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Economic growth, unemployment and skills in South Africa: An Analysis of different recycling schemes of carbon tax revenue

Jules Schers

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Economic growth, unemployment and skills in South Africa: An analysis of different recycling schemes of carbon tax revenue

Croissance, chômage et compétences en Afrique du Sud :
Analyse de plusieurs plans de recyclage
des revenus d'une taxe carbone

Thèse de doctorat de l'Université Paris-Saclay
préparée à AgroParisTech (l'Institut des sciences
et industries du vivant et de l'environnement)

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Thèse présentée et soutenue à Nogent-sur-Marne, le 21 Décembre 2018, par

Jules Christian SCHERS

Composition du Jury :

Frédéric LANTZ

Professeur, IFP School

Président, Rapporteur

Emilio Lèbre LA ROVERE

Professeur, Université de Rio de Janeiro (COPPE)

Rapporteur

Hyun Jin Julie YU

Research Officer, CEA-Saclay (I-Tésé)

Examineur

Rob DAVIES

Research Fellow, TIPS South Africa

Examineur

Franck LECOCQ

ICPEF, AgroParisTech (UMR 8568 CIRED)

Directeur de thèse

Frédéric GHERSI

Chargé de recherche, CNRS (UMR 8568 CIRED)

Coencadrant de thèse



Economic growth, unemployment and skills in South Africa:

Analysis of different recycling schemes of carbon tax revenue

Croissance, chômage et compétences en Afrique du Sud :

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PhD thesis of Jules Christian SCHERS

ABIES doctoral school, AgroParisTech (Université Paris-Saclay)

Supervisors: Franck LECOCQ and Frédéric GHERSI

***Centre International de Recherche sur l'Environnement et le
Développement -CIRED (UMR 8568 : CNRS, ENPC, CIRAD***

AgroParisTech et EHESS)

*à Georgia, who supported my PhD all the way,
... en aan Max, whose smile put everything into perspective.*

Abstract

This PhD thesis gives a numerical illustration of how a carbon tax affects South African GDP, employment, CO₂ emissions and socio-economic inequality. It uses a “hybrid” computable general equilibrium model of an open economy in a one-step projection from 2005 to 2035. It models second-best economies, notably skill-related rigidities in the labour market and in production of electricity. Seven scenarios for recycling of carbon tax revenue are analysed, plus an option to invest a part of tax revenue in improvement of skills of labour.

The analysis shows that under conventional assumptions about technological change, a carbon tax of around 100 ZAR₂₀₀₅ (18 USD₂₀₁₃) per tonne of CO₂ will have little negative consequences for GDP and employment, when combined with the right type of tax revenue recycling: Labour subsidies and company profit tax reduction likely lead to the best macro-economic outcomes, though do not reduce inequality. Additional measures are needed to reduce “energy poverty”. To achieve South Africa’s NDC of the Paris Agreement, a carbon tax rate of around 300 ZAR₂₀₀₅ or 55 USD₂₀₁₃ per tonne of CO₂ is necessary. However, this could have serious impacts on GDP growth. Also, without a change in the trend of increasing labour productivity, such lower GDP will lead to higher unemployment than in the reference case. An investment in skills of 7.5 billion ZAR₂₀₀₅ of annual Ctax revenue, with the objective of increasing access to high quality education and reducing the high skill labour shortage, is found to have a positive impact on GDP growth. However better calibration data is required.

The findings of this PhD thesis furthermore call for a thorough examination of what type of technological change could be expected for South Africa. Technological progress, consumer preferences and international circumstances limit the economy’s capacity to restructure and decarbonise and therefore to reduce negative consequences of carbon taxation for GDP growth. Proper assessment of future technological change is relevant for all sectors and inputs. Examples are given that show that energy and materials efficiency have an important role in future GDP growth under carbon constraints, because they determine the economy’s flexibility to reduce energy consumption and to substitute it, e.g. by labour. This finding normally holds not only for South Africa, but also for the rest of the world. These results also imply that international climate policy must coordinate technology transfer and that it has to take different potentials of nations to decarbonise into account.

Résumé

Cette thèse fournit une illustration numérique de la façon dont une taxe carbone pourrait affecter le PIB, l'emploi, les émissions de CO₂ et les inégalités socio-économiques en Afrique du Sud. Elle utilise un modèle d'équilibre général calculable « hybride » en économie ouverte par projection en un seul pas de temps de 2005 à 2035. Le modèle représente des économies de second rang, notamment des rigidités sur le marché du travail liées aux niveaux de qualification et dans la production électrique. Sept scénarios basés sur des modalités différentes de recyclage de la taxe carbone sont analysés, plus une option d'investir une partie des revenus de la taxe dans l'amélioration des qualifications de la force de travail.

L'analyse montre que sous hypothèse standard de changement technique, une taxe carbone de 100 ZAR par tonne de CO₂ environ a peu d'impact négatif sur le PIB et l'emploi lorsqu'elle est associée à un mode de recyclage des revenus approprié : subventionner le facteur travail et réduire les taxes sur les profits des entreprises pourrait conduire aux meilleurs résultats macroéconomiques, mais ne réduit pas les inégalités. Des mesures supplémentaires sont nécessaires pour réduire la « pauvreté énergétique ». Pour atteindre le NDC d'Afrique du Sud au titre de l'Accord de Paris, un taux de taxe d'environ 300 ZAR ou 55\$ par tonne de CO₂ serait nécessaire. Toutefois, un tel taux pourrait avoir un impact significatif sur la croissance du PIB. En même temps, sans changement de la tendance de croissance de la productivité du travail, ce PIB plus faible conduirait à un chômage plus élevé que dans le cas de référence. Une politique d'investissement de 7.5 milliards de ZAR de revenus carbone dans les qualifications de la main d'œuvre, avec l'objectif d'augmenter l'accès à la formation de haut niveau et de réduire le manque de salariés très qualifiés, pourrait avoir un effet très positif sur la croissance du PIB. Néanmoins, de meilleures données de calibration sont encore nécessaires.

Les conclusions de cette thèse appellent par ailleurs à un examen approfondi du type de changement technologique qui pourrait se produire en Afrique du Sud. Le progrès technologique, les préférences des consommateurs et le contexte international, limitent la capacité de l'économie à se restructurer et se décarboner et incidemment à réduire les impacts négatifs de la taxe carbone sur la croissance du PIB. Une véritable évaluation du changement technologique futur serait pertinente pour tous les secteurs et facteurs de production. Nous donnons des exemples qui montrent que l'efficacité énergétique et matières jouent un rôle important pour la croissance du PIB sous contrainte carbone, car elles déterminent la flexibilité de l'économie à réduire la consommation d'énergie et à la substituer au facteur travail par exemple. Ces conclusions sont à priori valables pour l'Afrique du Sud mais également pour le reste du monde. Ces résultats impliquent aussi que la politique climatique internationale doit traiter la question des transferts de technologie et celles des potentiels différents de décarbonation sérieuse à l'échelle nationale.

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List of acronyms

AFD	<i>Agence Française de Développement</i>
BAU	Business-as-Usual
BoP	Balance of Payments
BU model	Bottom-Up, or partial equilibrium, or engineering-knowledge based model
BTA	Border Tax Adjustment
CEA	Constant Educational Attainment levels
CES	Constant Elasticity of Substitution
CFC	Consumption of Fixed Capital
CGE	Computable General Equilibrium
CIRED	<i>Centre International de Recherche sur l'Environnement et le Développement</i>
CO ₂	Carbon dioxide
COA	Coal mining sector of IMACLIM-ZA
COP21	Conference Of the Parties to the UNFCCC (see below), 21 st edition, held in Paris November-December 2015
CPI	Consumer Price Index
CSLF	Constant Shares of the Labour Force
Ctax	Carbon tax
CTL	Coal-To-Liquids
DIM	Domestic Income Multiplier
DoE	Department of Energy of the government of South Africa
EIN	Energy INTensive and other mining sector
ELM	External Labour Market
ELC	Electricity sector of IMACLIM-ZA
EKC	Environmental Kuznets Curve
ERC	Energy Research Centre, of the University of Cape Town (UCT)
e-SAGE	energy-sector module added South African General Equilibrium model
ESKOM	South Africa's national power generation & distribution company
FC	Final Consumption
Fi	Firms
GAS	Natural gas and other gaseous fuels sector of IMACLIM-ZA
GDI	Gross Disposable Income
GDP	Gross Domestic Product
GDP PI	GDP Price Index
GFCF	Gross Fixed Capital Formation
GHG	Green House Gas
GTL	Gas-To-Liquids
GOS	Gross Operating Surplus
Gov	Government (at all levels), by which in fact is meant the entire public sector
HDI	Human Development Index

HIV	Human Immunodeficiency Virus
Hh	Household class, <i>or</i> Households' (in an adjective sense)
HSS	High Skill Services sector of IMACLIM-ZA
IC	Intermediate Consumption
ILM	Internal Labour Market
IMACLIM	IMpact Assessment of CLIMate change policies (Crassous, 2008)
ILO	International Labour Organisation
IPCC	Intergovernmental Panel on Climate Change
I-O	Input-Output
IRP	Integrated Resource Plan
KLEM	Kapital – Labour – Energy – Materials
LNG	Liquified Natural Gas
LSS	Low Skill Sectors of IMACLIM-ZA
MACC	Marginal Abatement Cost (MAC) Curves
MEC	Minerals-Energy-Complex
Mt	Megatonne
NDC	Nationally Determined Contribution
NDP	National Development Plan
NERSA	National Energy Regulator of South Africa
NNI	Net National Income
OECD	Organisation for Economic Cooperation and Development
OIL	Crude oil (imports) sector of IMACLIM-ZA
O&M	Operation & Maintenance
PhD	Philosophiae Doctor (Doctor of Philosophy)
PJ	PetaJoules
PPP	Purchasing Power Parity
PV	PhotoVoltaic
QLFS	Quarterly Labour Force Survey
RCPI	Relative Consumer Price Index
RDEF	Revenue recycling through DEFicit reduction
R&D	Reseach & Development
REER	Real Effective Exchange Rate
REF	Refineries sector of IMACLIM-ZA
RGOV	Revenue recycling through increased governmental final consumption
ROW	Rest of the World
RP	Reference Projection
RSA	Republic of South Africa
RSUM	Revenue recycling through a lump-SUM transfer
RTaY	Revenue recycling to redaction of Taxes on production (Y)
RTIF-fix	Revenue recycling reducing Taxes on Income of Firms, with fixed profit margins

RTIF-low	Revenue recycling reducing Taxes on Income of Firms, with lowering of profit margins
RTSC	Revenue recycling reducing Taxes and Social Contributions on labour
RVAT	Revenue recycling reducing VAT
SA	South Africa
SAM	Social Accounting Matrix
SASOL	South Africa's main international integrated energy and chemical company
SATIM	South Africa TIMES model
SLM	Segmented Labour Market
StatsSA	Statistics South Africa
SU tables	Supply and Use tables
SNI	Sustainable National Income
tCO ₂	tonne of CO ₂ emissions
TD	Top-Down, or macro-economic, often CGE, model
TFP	Total Factor Productivity
TIMES	The Integrated MARKAL-EFOM System (of IEA-ETSAP)
TRA	TRANsport service sector in IMACLIM-ZA
UNFCCC	United Nations Framework Convention on Climate Change
UCT	University of Cape Town
USD	United States Dollar
VA	Value Added
VAT	Value Added Tax
ZA	South Africa
ZAR	South African Rand

Technical Summary

Introduction and methodology

Backgrounds

South Africa faces a double challenge of developing economically and reducing its greenhouse gas emissions at the same time. Its main economic problem is high unemployment and inequality. One of the causes is a shortage of high skilled labour, and another often mentioned cause is what is called the “Minerals-Energy Complex” which reinforces inequality and creates disadvantageous economic conditions for labour intensive sectors.

South Africa is both likely to suffer from climate change – economically, and in terms of human health and ecologically –, and at the same time a big contributor to climate change. In terms of climate change the Republic of South Africa has made clear in its Nationally Determined Contribution to the Paris Agreement that it wants to take its responsibility to reduce its greenhouse gas emissions, given the right availability of support. The country is therefore developing climate change mitigation policies, and as a part of that has it is working on the implementation of a carbon tax.

Electricity production plays a big role as it is responsible for a bit more than half of South Africa’s GHG emissions, and almost two thirds of energy use related CO₂ emissions. In 2005 about 45% of electricity was consumed by energy sectors, mining and heavy industries. However transport and industrial processes contribute strongly as well.

Some policy strategy documents try to integrate economic and climate change policies. Nevertheless, the National Development Plan¹ still treats economic development and climate change in rather separate manners. However, without a low-carbon development path South Africa risks lock-in of polluting infrastructure with the costs for the South African society. It is important to correctly inform the debate about SA’s options for low carbon development. Improving economic modelling is part of improving such knowledge and insights, which is why this PhD thesis presents a macro-economic analysis of a South African carbon tax and its revenue recycling.

Research question and differences with other studies

This thesis tries to answer whether the objectives of economic development and climate change mitigation can be combined through the implementation of such a carbon tax and especially the recycling of the revenues which it generates. It also looks into the possibility to reduce the “skill’s shortage” as a way to create low carbon growth. The premise is that no mitigation policy can be successfully implemented without taking into consideration South Africa’s concerns about growth, employment, and inequality. The main research question therefore is:

¹ See: National Planning Commission, 2011.

How could climate policy influence South Africa's economic development? What order of magnitude could be expected from such policies in terms of socio-economic impacts and environmental impacts?

This question has been studied elaborately in scientific literature. Studies find differing degrees of economic impacts, and in some case economic benefits, for South Africa's economic development of climate change mitigation policies, mainly carbon taxation.

Compared to these studies this thesis proposes changes in economic modelling, particularly the inclusion of second-best economies for price setting in the labour market. It uses the IMACLIM framework of dual accounting of physical and economic flows in a "hybrid" I-O matrix of the SA economy for the modelling of energy use, allows for the application of an "engineering" view on future productivity or intensity of factors and inputs; and secondly, for estimating technological coefficients of future electricity production ("engineering" input and factor intensities) on the basis of a BU-model. Also, the present study uses a simulation model rather than intertemporal optimisation, synonymous to perfect foresight, as most studies do. Furthermore, it highlights complications in describing the role of skills in an economy and in CGE modelling. Finally, this thesis offers a detailed evaluation of the economic mechanisms of structural and technological change through which carbon taxation and recycling of its revenue could contribute to low carbon growth.

Methodology for analysing growth, environmental constraints, and development

Growth within environmental limits

To decide on what model to develop the question of how the interaction between environmental limits and economic growth is understood needs to be answered. This topic has received attention in economic sciences for more than a century. A selective review of scientific literature in this area leads to the conclusion that it is unlikely that when moving from a state of polluting growth to one of environmentally sustainable growth, a short-time drag on economic growth can hardly be avoided. The reason being that lack of regulation has promoted the use of technologies which externalise environmental costs. Environmentally sustainable "technologies" are therefore likely (still) less productive, which means that they are more costly. This does not mean growth needs to stop, because in theory technological progress can still continue. In the long run, growth will even be higher, because in the long run economic disadvantages of scarce or destroyed resources would have reduced growth too while obliging to perform the transition to sustainable capital against higher costs.

The conclusion is that the central issue is to foresee and integrate technological change in a macro-economic model.² In the context of modelling technological change, an important issue is how to account or model inertia in the modes or technologies of production and consumption. A proposed innovation to capture technological change is to model it endogenously. These models however often fail to provide a basis for how to calibrate them, at least one applicable to South Africa.

² Other measures, such as investment in R&D or evaluation of intelligent ways of influencing investment through mechanisms such as green bonds were unfortunately out of scope for this thesis.

More traditional production functions calibrate price elastic technological change on the basis of cost shares of factors, which are considered unreliable for representing the trade-off between capital and energy use. For the purpose of relatively long term prospective macro-economic modelling common to the analysis of climate change policies, Gherzi and Hourcade (2006) propose the use of technological coefficients informed by engineering knowledge, or energy system bottom-up models as a better way to project technological change in a (top-down) macro-economic CGE model.

To model economic behaviour and technological change they propose the macro-economic equilibrium framework IMACLIM. The reasons for the choice of this framework are:

- It uses dual accounting of physical volumes and values of economic flows, which is better capable to represent technological change and incorporate insights from engineering and so-called Bottom-Up models, rather than a “factor-value shares”-only approach to modelling technology in production;
- It models second-best economies: for profit or price-setting (mark-up rates); in wage setting (wage curve and equilibrium unemployment); and through rigidities in technological change and consumption. This allows to better capture both costs and benefits from lifting and introducing second-best economic conditions;
- It uses myopic simulation and avoids intertemporal optimisation: the latter under-estimates costs and benefits of policies which aim at avoiding infrastructure lock-in.

Development, growth and technological change

To model economic growth in developing and emerging countries functions a topic of discussion is whether convergence is taking place in *per capita* GDP. However, the more important question appears to be whether the adoption or development of more productive technology is taking place. Views about this question differ, notably about the respective roles of government and the free market. The conclusion is that such technological development and the development of (new) industries cannot be taken as a given fact in a single country study, such as for South Africa. The question of how to model prospective technological change is therefore also relevant in this context.

A second-best labour market model with skill differentiation

Due to the problematically high rate of unemployment in South Africa, second-best economies in the labour market need to be a key element of any analysis of economic development and the policies which could impact it. Furthermore, considering that reducing the skill-constraint of the South African economy offers a potential for environmentally benign economic development, this feature of the South African labour market needs to be part of the analysis and modelling of this thesis.

To model the labour market, the wage curve (out of multiple theoretical models) is the most convincing and most useful model in the South African context. To model the skills shortage, a segmented labour market model is proposed with a *positional* definition of skill of labour for the following reasons: (i) Earlier work has shown that an approach which equals skills to the level of

educational attainment runs into the problem that the foreseen increase in the level of educational attainment of the SA labour force cannot be absorbed by the SA economy in a CGE, except under extreme assumptions about labour productivity³; (ii) Recent findings show that for the majority of South Africans the quality of the education is poor, something which can be expected to impact the South African labour force still in the coming decades; (iii) Several more sophisticated labour market models by level of skill could be imagined, but lack calibration data.

To model skill of labour two approaches are common: “Human capital” models, which consider labour as one factor with a changing average level of skill; and different types of “segmented” labour market models. Of the latter, multiple types have been identified. Most of these models are market-clearing wage setting models, but wage curves can be imagined too in some of these models. The informal-formal duality could be seen as a special case of a segmented labour market model, but it could to some extent be captured by sectoral disaggregation and having, three or four levels of skills. The latter seems to fit the reality in South Africa’s labour market best. Furthermore, to reflect recent trends of a global trade-off between low- and high skill labour, for a part explained from technological change, this thesis models demand for high skill labour complementary to capital.

The IMACLIM South Africa model

IMACLIM South Africa (ZA) is an open-economy “hybrid” CGE model, running a one-step *simulation* from 2005 to 2035, taking account of population dynamics, exogenous productivity gains for all factors and inputs of production. It has sectoral disaggregation in 5 energy sectors and 5 non-energy sectors which have been grouped on the basis of the criteria of intensity in energy consumption; exposure to trade; and the skill profile of sub-sectors. International trade is modelled through Armington (style) price elasticities;

Its hybridisation procedure consists of three steps: (i) Translating energy balances and other information into an input-output (I-O) table of energy flows mirroring in its composition the economic I-O table; (ii) multiplying this table with user-specific energy price data, creating an “energy bills” I-O table; and (iii) “hybridising” by imposing the “energy bills” I-O table on the economic I-O table and adjusting the latter to re-obtain a balance in Inputs and Outputs by sector.

Technology of production of all sectors except electricity is modelled with nested CES KLEM production functions that also differentiate between three levels of skill of labour of labour and capital. Exogenous assumptions about technological change through changes in factor productivities and input intensities are differentiated by sector, reflecting different potentials for technological innovation and efficiency gains.

Technology for production of electricity is modelled on the basis of outcomes of the TIMES South Africa model (SATIM). It consists of applying similar trajectories for energy prices (notably coal and

³ A previous study by the author, see : Schers et al (2015).

electricity) to IMACLIM-ZA and SATIM, and running the latter model with different scenarios for carbon tax rates, similar to the ones in IMACLIM-ZA.

The labour market consists of three separate segments by level of skill, each modelled with a wage curve for the relationship between rigid real wages, indexed on productivity, and unemployment. Demand for investment follows the capital intensity and the projected GDP growth. The endogenous interest rate allows solving the capital market.

Primary and secondary income distribution is modelled for four main economic agents: firms, government, households and the rest of the world (ROW). Households are further disaggregated into 5 income-skill classes, whose consumption behaviour is represented by nested-CES consumption functions. For each agent exogenous assumptions about saving, investment, and thus future (international) borrowing and lending are made, and debt accumulation is modelled as well.

Policy scenarios are analysed against a reference projection (RP) meant to be a *coherent* and *reasonable* economic future (disregarding impacts of climate change). The RP's purpose is to identify the impacts and key mechanisms caused by the carbon tax and different types of carbon tax revenue recycling, by separating these impacts from those of the rest of the prospective parameterisation. Because a part of parameters has been chosen *ad hoc*, parameterisation of RP is benchmarked against “normal” values for a list of “macro-indicators”. The parameters which in theory are most relevant for modelling growth and unemployment are: Productivity changes; trend in export volume; the evolution of international prices; higher elasticities for international trade; elasticities of production functions.

Analysis of carbon tax scenario results

Main carbon tax scenarios

Eight “main” carbon tax (Ctax) revenue recycling scenarios are analysed, and investment in skills is added as an option (see below):

- **RDEF**, revenue recycling through reduction of South Africa’s public debt – the rapid increase of which in recent years is currently perceived as an economic problem;
- **RVAT**, recycling through reduction of a sales tax – this is seen as a way to reduce the burden of a Ctax for South African consumers and generate economic activity;
- **RGOV**, models an increase in final consumption by government for more public services;
- **RSUM**, a *per capita* lump sum transfer to all households – this measure is proposed to as a pro-poor way of revenue recycling to citizens;
- **RTIF**, recycling via reduction of company profit taxes. There are 2 variants:
 - **“fix”**: In which companies do not change their profit mark-up rates (calibrated on BY data), and owners benefit from higher returns to capital;

- “**low**”: Mark-up rates decrease (e.g. due to pressure of competition) and firms only maintain returns to equity about constant, consumers benefit from cheaper products;
- **RTaY**, recycling via subsidies to production of non-energy sectors, to stimulate activity in non-energy sectors;
- **RTSC**, replacing charges for social security and pension contributions by a subsidy to labour.

All scenarios are analysed for two levels of a carbon tax: 100 and 300 ZAR₂₀₀₅/tonne CO₂ (resp. 18 and 55 USD₂₀₁₃/tonne CO₂); The outcomes of these scenarios are compared to a Reference Projection (RP), which is modelled with the objective of being a “reasonable” expectation for a business-as-usual socio-economic future of South Africa.

Reference projection (RP)

A first key outcome for the evolution of the South African economy from 2005 to 2035 in RP is an increase of CO₂ emissions of 55%, implying a rise in *per capita* CO₂ to about 11 tonnes per capita. This is paralleled by an economic growth 2.7% on average per year, or 125% over 30 years, which corresponds to growth of real *per capita* GDP of 80%. Together this translates into a decrease of CO₂ intensity of GDP of 31%.

This decarbonisation of GDP can mainly be seen as a response to assumed price increases for coal, electricity, imported oil, and refinery products. Electricity production and household private transport decrease their share in direct CO₂ emissions, while refineries, transport services and industrial sectors have an above average increase in direct CO₂ emissions. If one also allocates first-degree indirect CO₂ emissions from energy sectors and transport then also the energy intensive industries and other mining sector (EIN), increases its share South Africa’s CO₂ emissions (from 37% to 41%). Exports’ share also increases (from 7 to 8%), whereas that of households decreases (from 24% to 19%).

Employment increases by about 8 million jobs, causing the broad unemployment rate to decrease from 39% in 2005 to 24% in 2035. Technically, this reflects growth in real demand outpacing growth in labour productivity and the labour force, in other words: the labour force and labour productivity together grow less (82%) than total GDP (125%). Decreasing unemployment is accompanied by higher real wages, but mostly for high skill labour, and relative income inequality between the poorest and richest household class (resp. class 1 and 5) increases. Consumption budgets of median income and lower middle class (classes 3 and 4) increase relatively fast, slowly catching up with the richest households (class 5). Material standards of living improve for everyone when it concerns non-energy consumption. However, *per capita* consumption of energy goods (ELC and REF) does not increase much. Classes 1 and 2 experience respectively a decrease or no increase of *per capita* consumption of electricity.

An increase in trade balance surplus as a consequence of model parameterisation about net international income transfers and borrowing and lending goes in parallel with a slight (~10%)

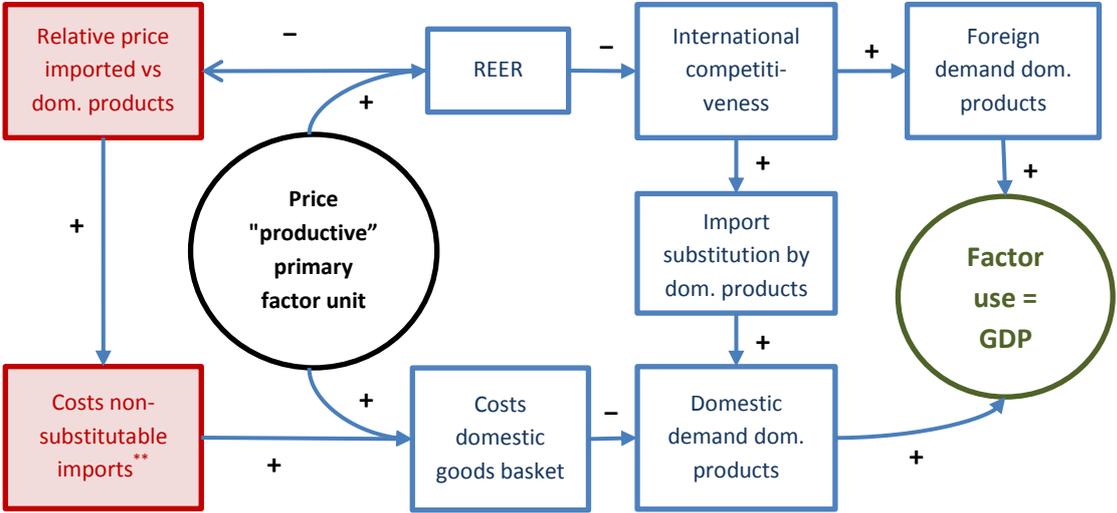
devaluation of the real effective exchange rate of the South African Rand.

Methodology for analysis of scenario results, and application to RP

It is not only the results which interest us, but also why scenario assumptions led to them. However, results for GDP growth and employment do not follow intuitively from assumptions of IMACLIM-ZA’s prospective parameterisation. Explaining outcomes of CGE models is difficult, because of the many feedback loops in the model. A crucial element to explain growth of GDP and especially employment is the fact that in RP (and many scenario results) GDP per worker grows more than labour productivity in volume terms.

What counts in IMACLIM-ZA is the evolution of the average price of primary factors’ *productivity* (in volume terms) relative to the average price of goods supplied to the economy – in an open economy model this ultimately means relative to the price of foreign goods. In the scenarios of this thesis, which have an approximately constant trade balance and current account over GDP, the real effective exchange rate (REER) expresses this relative evolution of the price of primary factor productivity relative to foreign prices and thus expresses international competitiveness. However due to rigid real primary factor prices, the price of primary factor’s productivity also determines domestic purchasing power and demand. Figure.0.1 thus expresses how the price of primary factors’ productivity relates to factor use, and thus to GDP growth relative to primary factors’ productivity growth in volume terms.

Figure.0.1 Causal loop diagram of how a change in primary factor prices over factor productivity impacts GDP



Explanation of the figure: A causal loop diagram shows how variables in a model are linked: a "+" sign with a connecting arrow indicates a positive relationship of a change in one variable on the other, a "-" sign a negative relationship; For IMACLIM-ZA this figure is conditional on a constant current account and trade balance (relative to GDP), as well as fixed price elasticities for international trade; One mechanism (in shaded boxes) in the scheme functions as a brake on the relation between GDP and productive primary factor unit costs: Non-substitutable imports would become too expensive if primary factor productivity would become very cheap.

The disadvantage of the REER as an explanation for GDP growth in scenarios is that its aggregate character makes it hard to link it scenario assumptions. I therefore construct another indicator that quantifies the change in domestic income relative to volume of goods supplied to the South African

economy (domestic output, Y , + imports, M), also conditional on the constant trade balance and current account found in IMACLIM-ZA's scenarios. Due to income growth equating to growth in demand, and therefore further increase of the volume of goods supplied to the economy, this indicator has the character of a multiplier, which is the reason that I call it the Domestic Income Multiplier (DIM). While I do not calculate the multiplier effect of this indicator, I do demonstrate that it correlates strongly with GDP growth results. The advantage of the DIM, compared to the REER, is that its 3 components and the fact that it can be calculated at the sectoral level enable showing how scenario settings lead to GDP growth results.

The DIM is calculated on a per worker basis, and consists of change in income per average volume unit of supply, multiplied by the change of the volume of domestic output over the volume of supply ($Y+M$). The latter is added, because domestic output generates more primary income per unit (value added plus indirect taxes) than average supply. The first term, growth of income relative to volume of supply consists of two elements: (i) Income growth thanks to cost reductions, meaning relative to the non-income parts of the cost structure of resources of a sector or the aggregate economy; and (ii) growth in the average value (price) of supply. The latter term is not easy to analyse. It can be considered a consequence of structural change and e.g. also of increase of primary factor prices' productivity (income) compensated by a decrease of the REER, meaning that it allows primary income to grow without causing cost increases and without negative consequences for international trade (e.g. growth of exports).

For the Reference Projection (RP) it can be shown that the increase in the DIM is driven for a large part by growth of value per unit of supply and by cost reductions in average production (see Table 0.1). It can be noticed that energy sectors increase their average price, but this has little negative consequences for international trade or for the ratio of income over costs in the supply of goods and services by other sectors, whose costs decrease thanks to import substitution and efficiency gains for materials & services inputs.

Growth of income relative to the volume of goods and services supplied to the economy causes GDP growth to exceed growth of supply per worker (which is found to be 23% in RP relative to base year (BY)) and growth of the labour force (34% vs BY), which – all other things equal – would translate into a growth of volume of supply of 65%. However thanks to the cost decreases and structural change captured by indicators like the DIM and the REER, GDP grows 125% in RP. Per worker, GDP growth turns out to be 35% in RP. All in all, this means that the employed labour force increases 66% relative to base year (and the employment rate 24%), corresponding to the mentioned 8 million jobs. Trade-offs in production and in the labour market cause this increase in employment to be slightly more concentrated in medium and high skill jobs than in low skill jobs.

Table 0.1 Calculation of DIM by sector for RP, vs BY

	Energy sectors	EIN	MAN	LSS	HSS	TRA	Aggregate economy*
Value per unit of supply	+64%	+0.1%	-5.4%	-2.2%	+6.1%	-0.6%	+4.0%
<i>Total resources relative to income****</i>	<i>+12%</i>	<i>-1.8%</i>	<i>-6.7%</i>	<i>-7.0%</i>	<i>-6.4%</i>	<i>-9.0%</i>	<i>-5.2%</i>
Income relative to total costs****	-11%	+1.8%	+7.2%	+7.5%	+6.8%	+9.8%	+5.5%
Primary income over supply volume**	+47%	+1.9%	+1.4%	+5.2%	+13%	+9.2%	+9.7%
Share of domestic output in supply	+0.9%	+3.5%	+10%	+0.1%	+0.2%	+0.1%	+1.9%
Multiplier for domestic income per unit supplied*** (DIM)	+48%	+5.5%	+11.1%	+5.2%	+13.5%	+9.3%	+11.8%

Comments: * Supply concerns total resources, in volume terms it consists of Y+M, whereas for energy sectors it is measured by dividing the value of supply by a price index for total energy resources. For the aggregate economy the volume of supply measures GDP growth. The values of average units of supply has been calculated as change in per worker values; ** The change in final demand per unit of supply is calculated by multiplying: (1+ change in value per unit of supply) * (1+ change in income relative to total resources); *** Multiplying the change in final demand per unit of supply times the change in the share of domestic output in supply gives the GDP multiplier per unit of supply; **** Income relative to total costs is the inverse of total resources relative to income.

Structural change favours growth of EIN, MAN, LSS and HSS sectors, relative to energy sectors and transport services (TRA). Decomposition analysis of the economic structure shows that domestic demand plays an equally large role in SA's GDP growth, with manufacturing (MAN) and labour-intensive sectors (LSS and HSS) seeing final demand to grow faster than exports, while the opposite is true for export-oriented energy sectors and the energy intensive industries & other mining (EIN) sector.

The decreasing CO₂ emission intensity of SA's GDP can be seen as partly a consequence of this structural change between sectors, with the volume of output growing more in MAN than in the more energy intensive EIN and TRA, and more in HSS than in the relatively more energy intensive LSS. However, most importantly, demand for electricity decreases. This is also caused by increasing energy and materials & services efficiency in production. Though not all sectors are equally capable to decrease their own emission intensity: HSS and MAN decarbonise more than EIN and LSS, while the direct CO₂ emission intensity per unit of output of REF and TRA also hardly reduces. This capacity of sectors to decarbonise is of significant impact for the results of carbon tax scenarios next.

Results of main carbon tax policy scenarios

Big differences were found between carbon tax revenue recycling (Ctx) scenarios in terms of GDP growth, CO₂ emissions, and employment. Differences in CO₂ intensity of GDP and income inequality, on the other hand, were not very big in most cases. Table 7.1 summarizes a comparison of Ctx scenarios with the reference projection (RP). It shows that two revenue recycling schemes result in much lower GDP and employment losses than other scenarios, while they obtain higher reductions in CO₂ emission intensity of GDP. It concerns the scenarios with revenue recycling into a reduction of profit taxes if followed by a reduction of profit mark-up rates (RTIF-low) and with revenue recycling into labour subsidies (RTSC). But, their CO₂ emissions are still higher than in other scenarios, because the relative size of their reduction of CO₂ emission intensity of GDP is smaller than that of growth of GDP. Income inequality of the richest over the poorest household class, finally, only changes in the

RSUM scenario, which sees the *per capita* income difference between the richest 10% of population and the poorest 20% being almost halved.

Table 0.2 Comparison of key results for Ctax scenarios with reference projection for 2035 (RP)

Scenario	GDP in 2035 vs RP	CO ₂ emissions, vs RP	CO ₂ emission intensity of GDP, vs RP	Employment (nr of jobs), vs RP	Hh class 5 over class 1 income gap, vs RP
Ctax rate 100 ZAR₀₅/tCO₂					
RDEF	-11%	-26%	-16%	-11%	-4%
RTIF-fix	-10%	-25%	-17%	-10%	-2%
RSUM	-10%	-25%	-16%	-10%	-29%
RGOV	-10%	-25%	-17%	-10%	-3%
RVAT	-6%	-22%	-17%	-6%	-1%
RtaY	-6%	-22%	-17%	-6%	-1%
RTIF-low	-4%	-20%	-17%	-4%	-1%
RTSC	-5%	-21%	-17%	-3%	-2%
Ctax rate 300 ZAR₀₅/tCO₂					
RDEF	-32%	-56%	-34%	-33%	-13%
RTIF-fix	-30%	-54%	-35%	-30%	-9%
RSUM	-28%	-53%	-35%	-28%	-48%
RGOV	-27%	-54%	-36%	-27%	-11%
RVAT	-18%	-47%	-36%	-17%	-5%
RTaY	-17%	-47%	-36%	-16%	-5%
RTIF-low	-14%	-45%	-36%	-13%	-4%
RTSC	-13%	-45%	-37%	-10%	-5%

Analysis of carbon tax scenario results

Analysis of results of carbon tax revenue recycling scenarios shows that the choice of revenue recycling schemes has a considerable impact on GDP growth, but that apart from the differences in GDP growth, the differences in CO₂ intensity and employment intensity of GDP between scenarios are relatively small.

The difference in the DIM between Ctax scenarios and RP is roughly proportional to the difference in GDP between Ctax scenarios and RP (see Table 0.3). Note, furthermore, that difference in the DIM vs RP also correlates to difference in the REER vs RP. Some deviations in this relationship can be associated to differences in the trade balance surplus. A break-down of the DIM shows that all scenarios suffer from substitution of domestic production by imports, which is roughly proportional to the REER. Furthermore, all scenarios except RVAT face a decrease in the average value of the supply of goods relative to RP. In RVAT this value increases, but the economy suffers more than in other scenarios from average cost increases (in the resource structure of goods).

Results show two categories of Ctax scenarios: One with relatively low GDP growth (RDEF, RTIF-fix, RSUM and RGOV), and one with medium to relatively high GDP growth (RVAT, RTaY, RTIF-

low, and RTSC). First of all, one can observe that low growth scenarios (RDEF, RTIF-fix, RSUM and RGOV) mainly reduce labour costs (income) per unit of GDP to absorb the increase in tax income due to the carbon tax. In parallel, costs for imports per unit of GDP increase in these scenarios, something which could be expected on the basis of the for South Africa's competitiveness detrimental evolution of the REER. On the other hand, costs for inputs of materials & services per unit of GDP decrease compared to RP, but this is a consequence of the decrease of unit labour costs (gross wages) in their production. Energy costs per unit of GDP do not increase more than in the four scenarios with higher GDP. This can be explained for a large part by the higher REER, which reduces import prices, and therefore the relative cost of OIL imports.

Table 0.3 Change in the DIM, its 3 principal elements, and in GDP and REER, for R300 Ctax scenarios vs RP

Change vs RP for R300 Ctax scenarios	Low growth Ctax scenarios				Medium to high growth Ctax scenarios			
	RDEF	RTIF-fix	RSUM	RGOV	RVAT	RTaY	RTIF-low	RTSC
iv. DIM*	-5.3%	-5.5%	-6.0%	-5.2%	-3.6%	-3.4%	-3.2%	-3.0%
v. GDP	-32.4%	-30.2%	-27.6%	-27.5%	-17.6%	-17.2%	-13.9%	-12.7%
vi. REER	+10.4%	+10.6%	+11.3%	+10.4%	+5.0%	+4.9%	+3.6%	+2.8%
vii. Trade balance over GDP	+1.8%	+0.6%	-1.3%	+0.1%	+0.1%	+0.3%	+0.1%	-0.1%

* DIM = Domestic Income Multiplier; It measures domestic income per unit of goods & services supplied to South African markets relative to BY. It is calculated by multiplying elements i to iii (more precisely: $1 + iv = (1+i)*(1+ii)*(1+iii)$).

Moving on to the four scenarios with medium to low GDP losses relative to RP (RVAT, RTaY, RTIF-low and RTSC), one observes that RVAT and RTaY manage to avoid a forced decrease in labour costs through a reduction of other taxes. In RVAT the cost of (or expenditure on) imports remains high though, whereas in RTaY, the recycling of carbon tax-driven price increases per unit of GDP is incomplete (we will see why this is the case in the next sub-section). RTIF-low assumes a reduction in profit mark-ups and therefore in Net Operating Surplus, which absorbs the largest part of the carbon tax-driven cost increase. Finally, the RTSC scenario shows a decrease in labour costs per unit of GDP, but this time it is not the consequence of a forced decrease in net wages, but due to carbon tax revenue being recycled into labour subsidies.

A successful revenue recycling mechanism proves to be one which manages to translate this cost increase for energy and energy-intensive sectors into a sufficiently big cost decrease in especially labour intensive sectors, thereby maintaining purchasing power close to the level of RP and lifting possible negative consequences for the trade-off between domestic and foreign products. The four low growth scenarios offer no such kind of cost reductions, and their type of revenue recycling rather represents a kind of an income transfer or a subsidy to final consumption. Still, any revenue recycling mechanism can achieve this only up to a limited extent, because of rigidities in intermediate and final consumption, especially of energy products. And, without any sudden drastic improvements in productivity with the introduction of a carbon tax – beyond price-elastic substitution of energy in production modelled with common elasticities of substitution, the consequence is that GDP growth will be (at least temporary) lower with carbon taxation.

Also important is that none of the economically well-performing scenarios manages to seriously reduce inequality. Only the RSUM recycling mechanism does. The reason is that no scenario achieves a radical change in high vs low skill employment and salaries, or of wages vs interests (property income). Structural change towards labour-intensive sectors and labour as a factor in production is insufficient to generate more low and medium skill employment. Furthermore, unemployment is not eliminated and not everybody can work. Therefore, without any additional compensation or measures against income inequality or for high energy bills, the impacts of a carbon tax on household final consumption “energy poverty”, here measured through the amount of final energy consumed by person, of the poorest two socio-economic household classes is expected to stay at its BY level for 2005.

Investment in skills

Results of both skill investment approaches show that a 7.5 billion ZAR₀₅ annual investment in education and training, financed with carbon tax revenue, only needs to achieve a small improvement in either high skill labour supply, or in output productivity of factors and other inputs to have a significant impact on South African GDP. In case such an investment increases the access of a large number of South African students to the high skill job market, GDP in 2035 ends up 4 to 6% higher than in cases with similar carbon tax revenue recycling but without an investment in skills.

If on the other hand the investment in skills does not change the positional character of the labour market, e.g. because the quality gap in education or other social barriers are not diminished, then the hypothesis was that it would at least improve output productivity thanks to having better trained workers. In this case, the impact of the investment can be positive if productivity gains are combined with wage moderation. However, the investment should focus on skills improving material and energy efficiency gains, as they are more effective in reducing the CO₂ intensity of GDP than further increasing labour’s output productivity.

Alternative scenarios

Alternative scenarios have been studied to consider the role of foreign carbon taxation and Border Tax Adjustment if South Africa would not apply a carbon tax, and also to analyse the comparability of different scenarios, their carbon tax rates and economic impacts, regarding differences in CO₂ emission reductions obtained. This led to the following findings:

A separate analysis of four scenarios shows that results for GDP growth and employment of the RTSC scenario remain the best, even if the carbon tax rate is increased to such an extent that South Africa’s NDC is achieved, which translated in IMACLIM-ZA to an emission target of 350 Mt of CO₂ emissions in 2035. This analysis shows that the carbon tax required to achieve South Africa’s NDC lies above 300 Rand₂₀₀₅ per tonne of CO₂, or well above the currently planned carbon tax rate (at 120 Rand₂₀₁₉ per tonne of CO₂, excluding exemptions).

Table 0.4 Comparison of key results for NDC objective vs reference projection for 2035 (RP)

Scenario	Carbon tax rate (ZAR ₀₅ /tCO ₂)	Total '05-'35 GDP growth	CO ₂ emissions	CO ₂ emission intens. of GDP	Employment (nr of jobs)	Hh class 5 over class 1 income gap
RSUM	255	-27%	-49%	-30%	-27%	-46%
RVAT	314	-19%	-49%	-37%	-18%	-5%
RTIF-low	325	-18%	-49%	-38%	-17%	-5%
RTSC	339	-15%	-49%	-40%	-12%	-6%

A second additional question was: *How would different international climate policy regimes affect the impacts of South Africa's carbon taxation and Ctax revenue recycling options?* Were the Rest of the World to levy a carbon tax with similar consequences for relative prices of products as a unilateral carbon tax in South Africa would have (the average for all Ctax scenarios in IMACLIM-ZA), then this is slightly positive for South African GDP growth and even more so for employment. However, the difference is relatively small. The influence of international trade and foreign Carbon taxation or Border Tax Adjustments (BTA) on South African economic growth however was likewise found to be small, unless a very aggressive BTA is applied.

Another question asked was: *What happens if industries achieve different levels of energy efficiency?* In this *ex post* analysis the energy efficiency gains found in IMACLIM-ZA were compared with values found in scientific and grey literature. On the basis of a report published by the Department of Environmental Affairs⁴ an inventory was made of the potential for CO₂ emission reducing energy efficiency gains by sector. In general, energy efficiency gains by sector found are on the high side in IMACLIM-ZA, but lower for the energy-intensive EIN sector. Alternative assumptions about future energy efficiency potentials were modelled through exogenous energy efficiency improvements. These new energy efficiency estimates increased GDP growth in selected carbon tax scenarios. However, to realistically model industrial sector's energy efficiency gains for South Africa corresponding to engineering insights, there is a lack of technology assessment studies.

A last scenario analyses *ex post* how results look like under an alternative assumption about wage indexation with productivity. In this case GDP growth and employment turn out higher for both the reference projection and carbon tax scenarios, but the relative impact of carbon taxation on growth and employment turns out to be smaller than in the main scenario results presented above. These results show that there is considerable uncertainty for the absolute size of outcomes for GDP growth and employment due to the way the wage curve is modelled, but conclusion of comparison between scenarios stays the same.

⁴ DEA (2014): "South Africa's Greenhouse Gas (GHG) Mitigation Potential Analysis"

Discussion and conclusion

Reflections on the methodology

At several occasions assumptions were necessary in modelling and scenario building, first of all to reduce model complexity and secondly to deal with a lack of calibration data. The following assumptions potentially cause uncertainty around, or bias in, modelling results:

- A first limitation to the modelling outcomes is modelling production through (nested) CES functions and exogenous productivity improvements (for all sectors except the electricity sector) instead of using Bottom-Up model information: This is not the ideal way to represent technological change for a few decades into the future;
- This study does not assume that carbon taxation leads to changes in exogenous (price-independent) labour-productivity improvement, while a general perception is that environmental technology is more labour intensive, e.g. organic agriculture versus agro-industrial production methods. Were this the case, then the main Ctax scenarios might underestimate employment, though not necessarily GDP;
- Descriptions of household consumption behaviour for South Africa are based on an *ad hoc* approach, and recent econometric studies of South African household behaviour could not be integrated in this PhD thesis anymore;
- There is uncertainty about the correct values for future elasticities of substitution in international trade, the relative evolution of prices between different foreign goods, and the price-inelastic trend in volume of world trade, but it is not possible yet to see whether there is a bias towards over- or underestimating impacts of carbon taxation or its revenue recycling;
- The interpretation that skills of labour are purely positional is probably, though very likely describing the current situation in South Africa's labour market well, a position that is too extreme for the longer term future, but no better alternatives were available;
- The model for the capital market (investment, capital formation, returns on investment, net borrowing and lending) might be too flexible, and might exclude the possibility of under-utilisation of capital or stranded assets, or responses of investment to change in the rate of returns or dividends and interest (on financial capital);
- An *ex post* comparison of SATIM runs and IMACLIM-scenarios showed a big difference in the amount of electricity produced. This could impact the share of existing and planned coal-based power generation in total power generation. Depending on expectations about the 2035 SA electricity market, the carbon intensity of electricity production in IMACLIM-ZA could range between 10% lower and 41% higher;

- On a more strategical level one has to keep in mind that results do not take into account feedbacks of climate change on the economy. Also, indirect economic and social impacts, e.g. for productivity, of revenue recycling has not been studied. This could cause underestimation of the benefits of the scenarios for more governmental spending (RGOV) and a lump-sum transfer to households (RSUM).

Comparison to other studies and theory on growth under environmental constraints

Other studies on carbon taxation in South Africa (Altieri et al., 2015; Alton et al., 2014; Merven et al., 2014; Van Heerden et al., 2006; and Devarjan et al, 2009) find smaller economic impacts of a carbon tax, or they find higher disadvantages or benefits of international carbon taxation or BTA regimes than found in this thesis. These differences can be explained from differences in how GDP growth is modelled, and in assumptions about investment, technological change, and more fundamental modelling differences, like the fact that many models use intertemporal optimisation while IMACLIM-ZA is a myopic simulation model. Also, in several of the mentioned studies energy efficiency comes “free of charge”, whereas in IMACLIM-ZA energy efficiency is achieved in a trade-off with capital and labour intensity, though sometimes to easily achieved. Without negative to zero cost alternatives for fossil fuel-based energy use, carbon taxation makes production more expensive. Whether this is a question of too much optimism in the other models concerning technological progress, or on too pessimist assumptions in IMACLIM-ZA is unknown because hardly any study is available on the cost of energy efficiency improvements in South African industries.

The difference between standard neoclassical Computable General Equilibrium (CGE) models and IMACLIM-ZA is that the latter is not an optimisation model and does not assume perfect markets: It allows capital and labour prices to be non-optimal in terms of welfare or GDP. Profit mark-ups are assumed constant and average real wage is assumed rigid through a wage curve indexed on the consumer price index. IMACLIM-ZA therefore finds bigger impacts on GDP and employment than many other models, and finds revenue recycling schemes that reduce the costs of labour (relative to its productivity) to be an efficient way to reduce the excess burden of a carbon tax. This is notably the case for revenue recycling into labour subsidies and for investing a part of carbon tax revenue into reducing the gap in the labour market between high skilled labour and other labour.

IMACLIM-ZA assumes that the carbon tax does not suddenly unlock a hidden potential of zero- to negative-cost options for more energy efficiency which would lead to abandoning fossil fuel-based energy use in production and consumption. A second way in which the South African economy is “attached” to energy use is through exports and household final consumption, which do not easily replace energy products, or products of energy-intensive sectors, by energy-extensive & labour-intensive products. This “attachment” to fossil fuel-based energy use manifests itself in limited substitution of energy by other factors of production. The consequence is higher production costs per unit than before the introduction of a carbon tax, and a “growth drag”. In view of this “attachment” to

energy, a decrease in real income (purchasing power of factor payments) can only be limited if carbon tax revenue recycling leads to cost reductions for labour or capital, and price reductions, of other products than energy or energy-intensive products. This promotes decarbonisation of production and helps maintain real income and international competitiveness high.

Answer to the research questions

The central question of this thesis was: *How could climate policy, notably a carbon tax and the use of the public revenue which it generates, influence South Africa's economic development? What order of magnitude could be expected from such policies in terms of socio-economic impacts and environmental impacts?*

The main conclusion is that a carbon tax and its revenue recycling could have something in-between almost no impact up to a significant negative impact on South African GDP growth, varying between scenarios analysed in this thesis. The order of magnitude of impacts on GDP growth varies between almost a double dividend, for a 100 Rand₂₀₀₅ carbon tax recycled into labour subsidies and with an investment in skills of labour that reduces the high skill shortage, and as a worst-case scenario the case of a 300 Rand₂₀₀₅ carbon tax is purely recycled into reducing the public deficit, with a GDP one third smaller than reference GDP in 2035 (of 125% above GDP in 2005). In these cases CO₂ emissions vary respectively between a reduction of 18% and a reduction of 56% relative to reference CO₂ emissions, which consist of a growth of South African CO₂ emissions of 55% compared to base year data (for 2005).

These results depend strongly on the choice of revenue recycling mechanism, but also on the type of technological change that is foreseen. The best way to recycle carbon tax revenue for GDP growth is by doing it in such a way that costs of domestic production are reduced in other sectors than the energy and energy-intensive sectors which see their average prices increase due to carbon taxation. Revenue recycling that stimulates technological change away from the use of energy or energy-intensive products, and that promotes the use of labour turns out to result in the best combination of economic and environmental development. This is notably the case for revenue recycling in the form of labour subsidies and in the form of a reduction of taxes on profits, on the condition that companies render the benefits to consumers and reduce their profit mark-up rates.

Results for broad unemployment vary in the same way as results for GDP growth, though there is some variation in the labour intensity of GDP between different revenue recycling schemes. Findings vary between hardly any impacts on unemployment (measured by its "broad" definition) in the case of a R100 carbon tax recycled into labour subsidies with an investment in skills, *or* with optimal energy efficiency prospects. While on the negative end revenue recycling of a R300 carbon tax through a reduction of the public deficit leads to a doubling of the broad unemployment rate compared to that of the reference projection. It must be noted that this thesis analyses the specific expectation of a future

with continued autonomous labour-saving technological change of especially low skill labour, and that this development is assumed to be the same with and without carbon taxation, except for price-elastic substitution. With price-elasticities of substitution between factors and intermediate inputs effectively being smaller than 1.0, this means that no fundamentally different pathway of technological development is foreseen under carbon taxation.

Carbon taxation does not seem to influence income inequality very much, which depends on other aspects of the economy, such as the relative size of labour and capital income, the rate of returns on capital, the growth in employment by skill, and finally social security and pensions. Only recycling of carbon tax revenue into a lump-sum transfer to households radically reduces (almost halves) income inequality. Poverty, in contrast to relative inequality, is affected by carbon taxation though. Without further assumptions about increases in social security, and with insufficient increases in low skill jobs, the lowest household income classes see little progress in their purchasing power of energy products compared to 2005, except in the lump-sum transfer scenario.

The results presented in this thesis depend on modelling and scenario assumptions (e.g. simplifications inherent to modelling), and some of these assumptions can be expected to cause over- or under-estimations of the socio-economic and environmental impacts of a carbon tax and its revenue recycling. One of the two most significant causes for bias in the results is the way in which the labour market has been modelled. This might lead to an overestimation of future cost of labour relative to labour's productivity, and thus leads to an overestimation of economic impacts of carbon taxation. The capital market, on the other hand, might be modelled too flexible, which might lead to an under-estimation of possible (negative) consequences for GDP growth and employment.

Policy implications

With the right type of carbon tax revenue recycling, South Africa can and should gradually introduce a carbon tax of at least up around 100 ZAR₀₅ per tonne of CO₂ (18 USD₁₃/tCO₂) considering that it likely has no significant impact on GDP and employment, while reducing CO₂ emissions considerably. The best macro-economic result is obtained when recycling carbon tax revenue into labour subsidies (RTSC) and reduction of profit taxes on the condition that it leads to lower profit mark-ups (RTIF-low), e.g. due to having competitive markets.

Reduction of value added taxes (RVAT) and taxes on production (RTaY) have been found less economically attractive than the first two options, but more attractive than carbon tax revenue recycling into one of the four measures that primarily increase income and expenditure: Reduction of the public deficit (RDEF), increased government-spending (RGOV), reduction of profit taxes in markets that are not combined with reducing profit mark-up rates (RTIF-fix), and a lump-sum transfer to households (RSUM). These four were found to have strong negative impacts on GDP and employment for a carbon tax rate of ZAR₂₀₀₅ 300/tonne CO₂ (18 USD₁₃/tCO₂).

Nevertheless, if one evaluates revenue recycling options against fixed emission targets, only the labour subsidies option stands out, and reduction of profit taxes, taxes on production, or VAT turn out to have similar impacts on growth and employment.

Analysis of the lump-sum transfer to households likely underestimates the macro-economic benefits of anti-poverty measures. Independent of whether there is underestimation of benefits, dedicated energy use-related anti-poverty measures should be part of the revenue recycling policy. The reason is that carbon taxes can – with current expectations about future technology – be expected to lead to more expensive energy supply and thus increase poverty of the poorest households, especially the unemployed and for other reasons not economically active people.

Were a part of carbon tax revenue to be used for an investment in skills with the objective of increasing access to high quality education and reducing the high skill labour shortage, then a strong positive impact on GDP growth can be expected: An investment of 7.5 billion ZAR₂₀₀₅ of Ctax revenue per year generated 4 to 6% additional GDP by 2035 in selected scenarios, while also reducing CO₂ emission intensity of GDP and income inequality. For a R100 carbon tax this reduces the gap in GDP with RP almost entirely. However more research is required as proper calibration data on educational investment, skills and productivity is lacking.

Low-cost energy efficiency and, in general, input efficiency improvements have been found to have a high potential to increase GDP growth and employment too, especially in the context of the introduction of a carbon tax. However, also here, more studies into energy efficiency potentials and their costs are required.

Analysis in this thesis showed furthermore that a carbon tax can contribute to South Africa achieving its Nationally Determined Contribution of the Paris Agreement of 2015 (COP21). A carbon tax rate of around 300 ZAR₂₀₀₅/tonne CO₂ (55 USD₂₀₁₃/tCO₂) would be required. The South African economy turns out to be very sensitive to a carbon tax. The reason is that a large part of its energy use is very cheap, namely that of coal, while the economy's CO₂ intensity is very high. Furthermore, relatively standard values for elasticities in consumption and international trade do not allow for a major restructuring of the South African economy. This points at limited possibility to change roles in the global economy, and casts doubts on the current focus in international climate policy on national and local approaches. Two things are required: First of all, international coordination of carbon taxation, possibly including consumer-oriented carbon taxes with differentiation in carbon tax rates between types of final consumption (e.g. holiday air travel versus clean infrastructure and technology investment). Secondly, transfer of technology, and knowhow and experience is required, as well as opening up of markets for, and protection of, new industries in trade regimes so developing economies can change their economic structure.

Future work

Industrial (or sectoral) energy efficiency has been identified to lack sufficient and applicable Bottom-Up studies. Without clear predictions for future technological change available, new approaches to inform macro-economic modelling and decision making should be considered. Possibly, expert- or stakeholder-based scenario-building could be developed. The link between the levels of education, job type and productivity need to be better conceptualised and studied too. For IMACLIM-ZA it might be interesting to model skills of labour by separating skill as a role in production, and skill of the workforce, and match the two through a “hiring procedure”-inspired labour market model. The description of future household consumption behaviour could be improved too, just like the model for the capital market, and behaviour for investment, rent-taking and setting profit margins.

1. Introduction

1.1. Challenges for South Africa's economic development

South Africa is an upper middle-income country⁵, the 28th national economy globally when measured in GDP PPP terms. The country has gone through an enormous transformation since it freed itself from Apartheid and held its first democratic elections in 1994. Since then, South Africa has advanced significantly in providing public and social services to its population, such as providing health care and education to its previously strongly disfavoured black African communities. It saw the number of people living below World Bank's poverty line decrease from 29% in 1993 to 16.5% in 2011. Similar progress (and a similar gap remaining to be closed) can be witnessed for access to electricity, which increased from 65% in 1990 to 85% in 2012.

But social challenges and problems remain: South Africa's Human Development Index lags compared to its economic richness: In 2014, with a HDI of 0.67, South Africa occupied a shared 116th position (together with El Salvador and Viet Nam) out of 188 countries.⁶ HDI progress in terms of education have for a part been undone by a decrease in life expectancy since 1990, obviously related to South Africa's HIV pandemic. But this trend in life expectancy has been reversed since 2005, and likewise there are signs that the increase in HIV among South Africa's population has been halted. Still, several generations, especially those now of working age and their children have been heavily marked by the epidemic.

With a Gini coefficient of 0.63 (in 2011)⁷ South Africa also has one of the highest levels of inequality in the world. Characteristics of South Africa's inequality are that it largely runs along racial lines, that it is most manifest in property, and that it is combined with one of the world's highest unemployment rates. Though Statistics South Africa (StatsSA) reports an increase in the number of people employed, from about 14 million in 2008 to 15.5 million in 2016, South Africa's official unemployment rate has risen at the same time, from 23% in 2008 to 27% in 2016.⁸ If one includes discouraged work-seekers, the so-called *broad unemployment rate* stood at 34% in 2016.⁹ The parallel increase in jobs and unemployment is also a sign that South Africa is struggling to absorb all young adults which freshly enter its labour market each year.¹⁰

All these issues are acknowledged in South Africa's National Development Plan (National Planning

⁵ According to World Bank's classification, see <https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups>; Furthermore, South Africa was in 2015 the 86th or 89th richest country in the world in average *per capita* GDP in PPP terms (out of 183 or 185 countries respectively, depending on whether one follows IMF's or World Bank's calculation), with a *per capita* GDP of 13.2 thousand international dollars, 12% below world average of 15 thousand int. dollars.

⁶ According to UNDP's Human Development Report 2015.

⁷ According to World Bank

⁸ Source Statistics South Africa website: http://www.statssa.gov.za/?page_id=737&id=1, accessed 02/12/2016.

⁹ Author's own calculations on the basis of data from the Quarterly Labour Force Survey Q3 2016. Statistics South Africa estimates its "expanded" unemployment rate at 36.3%.

¹⁰ South Africa's population is clearly aging, and the growth of South Africa's population of working age is expected to slow down on the basis of South Africa's demography: see Statistics in Brief 2016: <http://www.statssa.gov.za/publications/StatsInBrief/StatsInBrief2016.pdf>

Commission, 2011). In its Diagnostic Report the National Planning Commission listed the following:

1. “Too few people work;
2. The quality of school education for black people is poor;
3. Infrastructure is poorly located, inadequate and under-maintained;
4. Spatial divides hobble inclusive development;
5. The economy is unsustainably resource intensive;
6. The public health system cannot meet demand or sustain quality;
7. Public services are uneven and often of poor quality;
8. Corruption levels are high;
9. South Africa remains a divided society.”

The origins of South Africa’s inequality, poverty and previously very poor public and social services can be found in its history of Apartheid; A history that also shaped the country’s economic development. It contributed to an economy centred around what is called the “Minerals-Energy-Complex” (MEC), in which cheap labour and cheap energy contributed to the development of an export-oriented, state supported mining industry (Baker et al., 2014; Black, 2014; Hausmann, 2008; Wilde-Ramsing, 2013). This situation still largely continues nowadays, though it is bound to end some day due to falling *per capita* mineral resource exports, the ASGI-SA project¹¹ foresees (Hausmann, 2008). The MEC is also a part of the explanation for South Africa’s poor economic performance in other sectors, with particularly agriculture and manufacturing reducing employment between 1994 and 2007. For instance, Hausmann (2008) states:

“Instead, the first explanation is skills “mismatch” and inequality (geographically, in ownership, and in income), and the lack of structural change to correct for it are considered important factors. The lack of structural change is typically a consequence of disadvantageous conditions of trade for the sectors which could absorb low skill labour.”

This can be understood in the following way: The big role of export-oriented mining in the South African economy contributes to an often high-valued Rand, and (among other factors) to real exchange rate volatility, which is bad for the predictability of revenues for manufacturing and other tradable sectors. A second consequence of the MEC is a relatively big services sector, which puts a strain on South Africa’s scarce high educated labour force, and which drives up labour costs for other sectors too. One study found manager wages in South Africa in 2002 being about two and a half times higher than in Poland, whereas unskilled production worker wages were about the same (Clarke et al., 2007). Thirdly, a large services sector and a limited role of domestic manufacturing also contribute to

¹¹ ASGI-SA stands for: Accelerated and Shared Growth Initiative for South Africa (ASGI-SA), and consisted of an evaluation of South Africa’s economic development by an international panel of experts on a request of the South African government in 2005, and coordinated by the National Treasury.

a current account deficit, including a trade balance deficit. The reason is that it makes consumption prevail over investment. The only recent period of relatively high economic growth for South Africa, the mid 2000s, reflected this services-income oriented growth and could thus have been considered “non-durable” for this reason: Growth consisted mainly of growth in real estate value and final consumption, and not in productive capacity (Hausmann, 2008).

As a consequence of this economic and political history, unemployment is particularly high among low-skilled individuals, while there is a shortage of high-skilled workers (Black and Gerwel, 2014; Colclough et al., 2010; Hausmann, 2008). The precise form of this skills shortage is debated though, because some authors think that it is particularly a shortage of specific skills at all levels of education, and not a lack in the level of educational attainment (Daniels, 2007). Such precisions do not alter the fact that a lack of skilled labour increases labour costs, and that these shortages exist against a background of big differences in rates of unemployment by level of education: e.g. in 2013 the official unemployment rate for people with tertiary education was 9.9%, against 24.7% on average and 31.9% for people with incomplete secondary education (StatsSA, 2014a).

For completeness the importance of the MEC for South Africa’s low and medium skill unemployment, should be relativized a bit: Other causes play a role too in the weak position of manufacturing and the weak overall economic growth in South Africa. E.g., infrastructure bottle-necks and the low rate of household savings contribute to a lack of investment too. Another factor which hurts South Africa’s economic development is crime: One case study shows that crime adds a high “entry cost” to starting a business or running a successful businesses (Cichello et al., 2011). Another indication of causes outside the MEC for South Africa’s low and medium skill labour’s unemployment is that between 1995 and 2005 low skill job losses took place in all sectors, and not only in manufacturing. In other words: They were largely due to a changing skill profile of labour within sectors, and not so much due to a shift of employment between sectors, while the latter mechanism was the main cause of low skill job losses before 1995 (Banerjee et al., 2007). The latter observation also raises the question whether technological change has taken a new direction, or whether other factors play a role. Different sources point out that labour’s share in value added has decreased around the world, with technological change named as one of the important factors, because it leads to replacement of low skill jobs by more capital (ILO and OECD, 2015; Los et al., 2014).

In the context of these developments the structure of South Africa’s skill supply might seem worrisome. The skill shortage signalled above seems to be compounded by problems with educational quality, with an educational system providing high quality education to about a quarter of pupils and students, but very low educational quality for the rest of pupils and students (see Spaul, 2013). This poses important constraints on South Africa’s future economic development.

A question therefore is how to provide lasting and sustainable economic growth that can absorb South Africa’s for a large part poorly educated unemployed population.

1.2. South Africa's response to climate change

South Africa has started to experience several negative consequences of climate change, with increased frequencies of rainfall extremes and droughts, increased numbers of hot days, and sea-level rise. South Africa is also considered vulnerable to climate change because of social vulnerability and dispersed and poorly planned development (National Planning Commission, 2011). With water already being a scarce resource and soil often thin and sensitive to erosion, it is particularly South Africa's agriculture and forestry sector which will feel economic consequences of climate change first.¹² Crops most at risk include maize, apples, pears, wheat, barley and rooibos. Furthermore, a more generic rise of pests and of heat stress in animal husbandry should be expected. A lot however will depend on the capability to take adaptation measures. Consequences are expected to be felt especially between 2050 and 2100, with other countries on the African continent likely to be affected much more negatively than South Africa (RSA, 2011a). However, a lot is still unknown about both the direction and impacts of climate change in South Africa, as about the capacity to adapt to it and the cost to which damages can be avoided. The National Development Plan 2030 therefore proposed a strategy for the near future in which South Africa's economic and societal resilience is strengthened, and in which more research, studies and planning is done regarding climate change adaptation and modelling, on food security, on water resources, and on national disaster management (National Planning Commission, 2011).

Unlike most other African countries, South Africa cannot claim that it is not partly responsible for the historic rise in greenhouse gas (GHG) emissions. In fact, with its coal and partly coal-to-liquids based energy system, and energy intensive mining and industry sectors, South Africa is the 23rd most emitting country in the world according to World Bank data.¹³ South Africa is also one of the highest *per capita* CO₂ emitters in the world: In 2010 GHG emissions (excluding land use change) were estimated at 582.5 Mt CO₂-eq. This translates to approximately 11.5 Mt CO₂ emissions *per capita* (RSA, 2013a).¹⁴

The country is therefore aware of its responsibility to act on climate change and reduce its greenhouse gas emissions. In its Nationally Determined Contribution (NDC) for the COP21 in Paris, South Africa pledges to reduce its GHG emissions by 34% in 2020 and by 42% in 2025, relative to business-as-usual, and conditional on financial and technical support from the international community (UNFCCC, 2015a). In 2011, South Africa had already issued a Climate Change Response White Paper (RSA, 2011b), which included a carbon tax proposal planned for 2015 (see Box 1 for details on the strategy).

¹² As an example: Fruit farmers in the Western Cape are reported to have lost a quarter of their orchards due to Cape Town's 2018 water crisis following several consecutive years of low rainfall and a late political response. Hopes of restoring these orchards are dim, due to a lack of funds for reinvestment. At the same time 30 000 harvest season jobs are said to have been lost in the Western Cape in 2018. Source: Mail & Guardian, 22 March 2018. URL: <https://mg.co.za/article/2018-03-22-cape-farmers-lose-25-of-orchards-vineyards-as-result-of-drought> (consulted on 19 April 2018)

¹³ World Bank data, source: <http://wdi.worldbank.org/table/3.9#>, accessed 2/12/2016.

¹⁴ Other sources, such as World Bank quote lower numbers, which estimate South African greenhouse gas emissions excluding land use change at 456 Mt of CO₂ (or 9.1 tons of CO₂ *per capita*) in 2010.

Consecutive revisions and delays have led to a second version of the carbon tax bill released for public comments and treatment in parliament by mid 2018 (National Treasury, 2017; RSA, 2015). A date for the introduction of the carbon tax is to be determined at a later point, but should logically be well before 2022, in which year the carbon tax law demands a first review of the carbon tax. The carbon tax, however, is only one of several instruments by which the country aims to meet its mitigation goals. It will interact with other plans and policies, notably in the energy sector. In particular, the Government of South Africa has adopted a long-term electricity sector investment plan, titled the “Integrated Resource Plan” (IRP-2010, of which this thesis will use the updated version of 2013). Following massive power outages in the late 2000s it aimed at easing the tension between supply and demand of electricity (RSA, 2013b).

Box 1 Key elements of the South African mitigation strategy

The 2011 Climate Change Response White Paper outlines the following key elements of the South African mitigation strategy (IEA, 2013; RSA, 2011b):

- A National GHG Emissions Trajectory Range. The objective is that emissions increase from 374 Mt CO₂ in 2011 to 398–583 Mt CO₂ between 2020 and 2025, then plateau at 398–614 Mt CO₂ between 2025 and 2035, and eventually decrease down to 212–428 Mt CO₂ by 2050;
- Reduction targets for key sectors (based on cost-benefit analysis);
- The requirement for actors of such sectors to submit mitigation plans, including actual carbon budgets for some companies in certain sectors and subsectors;
- Implementation of mitigation policies that support job creation and economic development;
- Implementation of economic measures, including carbon pricing — which could come in the form of a carbon tax (or in the form of emission trading for the entities covered by carbon budgets);
- Implementation of a monitoring system for GHG emissions.

The IRP therefore deals with the contributions of energy use to South Africa’s greenhouse gas (GHG) emissions. Direct CO₂ emissions from energy use make up the majority of South Africa’s GHG emissions (RSA, 2013a): An elaborate greenhouse gas emission inventory found that in 2000 CO₂ emissions were 76% of South African GHG emissions. Within this category energy use caused 85% (301 Mtonne of CO₂) of gross (or net positive) CO₂ emissions (354 Mtonne of CO₂).¹⁵ The remainder of gross CO₂ emissions consisted of industrial process emissions, while absorption of CO₂ took place in forestry and cropland use (reducing emissions with 21 Mtonne of CO₂). The CO₂ emissions from energy use itself consisted in 2000 for about 50% of emissions from the electricity sector (RSA, 2013a). Industrial fuel combustion contributed 13% and transport contributed about 12% to direct CO₂

¹⁵ Greenhouse gas emissions here include land use change and forestry. Percentages are based on author’s own calculations are based on data from the Department of Environmental Affairs and Tourism (DEAT), Republic of South Africa (from RSA, 2013).

emissions of energy use.¹⁶ Transformation of energy, especially Coal-to-Liquids, but also oil refineries and Gas-to-Liquids processes, contributed about 9% to CO₂ emissions of energy use.¹⁷ The CO₂ emissions from fuel combustion in commercial, public and residential buildings (mainly space and water heating plus cooking) contributed 2.5%, whereas gross CO₂ emissions from fuel combustion in agriculture, forestry and fishing contributed 1.2% (RSA, 2013a).

On the supply side, the updated IRP-2010 report of 2013 calls for the addition of new power generation capacity. Renewables, primarily wind and photovoltaic (PV) power generation, would constitute the largest share (via price-competitive procurement), followed by nuclear. Under the updated IRP-2010, the share of coal thus falls from 93% (current) to 46% of total electricity capacity in 2030.¹⁸ The plan furthermore contained further increases in regulated electricity prices, which have risen from ca. 0.25 South African Rand per kWh (ZAR/kWh) in 2005 to 0.65 ZAR/kWh in 2013, after approval by the National Energy Regulator of South Africa (NERSA) (Baker et al., 2014; IEA, 2013).

Improving electricity transmission links with neighbouring countries is also proposed as a strategy to reduce the pressure on the South African power generation system and provide access to low-carbon electricity (notably hydro-electricity from Mozambique and further away in Southern Africa). Increased capacity for imports of LNG is also part of the plan. On the demand side, the plan targets a 35% energy efficiency improvement, via energy efficiency and demand-side management initiatives. Energy efficiency gains, particularly in energy intensive industries and mining are also mentioned as objectives in the National Development Plan (National Planning Commission, 2011).

Given the high level of South African emissions, the set of policies capable of achieving the proposed mitigation targets are likely to have significant implications on the achievement of other economic, social or environmental goals.¹⁹ These side effects matter from a public policy viewpoint, because they constitute other channels by which the mitigation policy impacts welfare beyond the direct cost of the policy and beyond the benefits in terms of climate mitigation. Documenting side effects also matters from a political economy viewpoint, as policies to tackle these “side” effects often have wider public support than e.g. taxing energy, an example is reduction of local air pollution. The detailed design of mitigation policy packages – for example the way by which proceeds of a carbon tax are recycled – is central to limiting adverse side effects and to maximize co-benefits.²⁰

¹⁶ Direct CO₂ emissions consist of the emissions caused by burning of fuels within the sector. CO₂ emissions caused by the production of the electricity used in rail transport are therefore not included in the transport sector, and similarly from the direct CO₂ emission inventory of other sectors. CO₂ emissions from own power generation by industries is included in their inventory though, whereas this thesis allocates, in Chapter 4, all power generation CO₂ emissions, including own power generation by industries, to the electricity sector.

¹⁷ Others estimate the contribution of South Africa’s Coal-to-Liquids (CTL) plan higher, e.g. Burton *et al.* (2016) estimate CTL on its own to contribute 10% to South Africa’s CO₂ emissions.

¹⁸ Nuclear and hydro each account for 12.7% of total installed capacity, wind 10.3% and PV 9.4%.

¹⁹ The positive side effects are typically called “co-benefits” in the literature while the negative side effects are often denoted as “adverse side effects”. See Kolstad *et al.* (2014) and Ürge-Vorsatz *et al.* (2014) for recent discussions.

²⁰ In fact, the expression ‘side effects’ implicitly refers to a distinction between ‘climate’ policies, the primary goal of which is climate mitigation, and ‘non-climate policies’, adopted mainly for other reasons. As climate mitigation objectives become more stringent, and as the links between mitigation objectives and other goals become more apparent, this distinction between ‘climate’ and ‘non-climate’ policies is becoming increasingly blurry. This is important because it allows thinking about mitigation with a broader set of policy instruments. For example, the response of transportation emissions to carbon pricing in a city depends strongly on the shape of the city,

1.3. Research questions

The key issue for South Africa's economic development in the context of its climate change objectives is whether the country is capable of achieving the technological and structural change required to reduce the carbon intensity of its economy. The underlying idea is that no mitigation policy can be successfully implemented without taking into consideration South Africa's concerns about growth, employment, and inequality. This thesis therefore aims to explore the conditions under which mitigation policies create "win-win" situations and interact positively with South Africa's development objectives.

The aforementioned "technological and structural change" consists of the following: The first aspect is change in sectoral structure of the economy. Moving economic activity away from resource-depleting sectors towards activities which are based on sustainable use of renewable resources like renewable energy, or non-resource inputs such as labour and its accompanying characteristics (skills, knowledge and intellectual "capital") will make South Africa's economy less polluting. The second aspect is technological change, meaning change in "technology" of production: Most industries or sectors could, in theory, shift from non-renewable inputs to renewable and non-resource inputs. The third aspect is final consumption and trade: Macro-economic structure is determined by consumption in the sense that: A. consumption and trade drive demand for domestic output and thus the sectoral structure of economic activity, and B. certain types of consumption are directly polluting, for example the consumption of gasoline and diesel for the use of private motorized vehicles. Change of preferences in consumption from resource-depleting products towards "clean" products and services would therefore make it easier for South Africa to combine climate change and economic development objectives.

The central question for this thesis therefore is:

How could climate policy influence South Africa's economic development? What order of magnitude could be expected from such policies in terms of socio-economic impacts (see section 1.1) and environmental impacts (section 1.2)?

Before continuing this discussion by treating the sub-questions to which this thesis formulates answers, I would like to emphasize that the research questions are set within a certain "*thinking framework*" from which the central question of mitigation and economic development will be *approached*. The reason to mention this explicitly is to create awareness of the fact that – though a necessity in all research and therefore mostly taken for granted – this framework determines the questions we ask. It is the window through which we look at a problem or question. Awareness of the fundamental perspective helps seeing this work in a larger context: It helps both not to over-interpret the findings of this research by considering its analysis to be "omnipotent" and to tell

which itself results from a broad set of urban policies (*e.g.*, transportation, zoning, fiscal policies, housing, *etc.*). Playing on this set may thus have significant implications for mitigative capacity in the medium term, even though the underlying policies would not be classified as 'climate' policies.

everything there is to know about climate policy; and it helps not to diminish the findings' importance by dismissing its modelling approach or assumptions as unfamiliar – as other studies too have a frame through which they look at the world. In the case of this thesis the underlying framework is that I approach the question of South Africa's development and climate change objectives with a toolbox of the economic sciences, specifically the methodology of computed general equilibrium (CGE) modelling. This approach is particularly of interest, because it proposes a methodology by which macro-economic interactions and feedbacks can be studied, in relation to different fiscal policies, technology of production and different types of structural change.

A next issue is selection in the policies that should be considered in this thesis. A wide range of climate and energy policies, government budget plans and tax policies could in theory be analysed. Studying all of them is probably worth many PhD theses. The focus of this thesis is on a carbon tax and its combination with different tax revenue recycling schemes that are considered relevant for South Africa and which represent different strategic axes for revenue recycling. More specifically, the tax revenue recycling schemes concern different parts of the South African society. They can be shaped as a tax reform favouring different groups (poor households, or consumers, or enterprises and their owners), or they can address different socio-economic concerns (public debt, competitiveness, poverty). The present analysis of carbon tax revenue recycling thus intends to inform the policy debate on carbon tax revenue recycling on its major orientations, next to identifying strategic issues to successfully achieve policy goals for climate change mitigation and economic development in connection to the introduction of a carbon tax. In brief, the carbon tax (C_{tax}) revenue recycling schemes analysed are (details follow in section 4.2.2):

1. Reducing public deficit: A high public (government budget) deficit and rising public debt are some of the major present-day economic concerns for South Africa;
2. Reducing a sales tax on products: The idea is that it stimulates domestic consumption, and also reduces the cost of living, thereby increasing demand, output and employment;
3. Increase government spending, either on administration, or on goods and services for the people of South Africa: the idea is an increase in public services;
4. A lump-sum transfer to all households on a per capita basis: the idea is to fight poverty and income inequality, and to compensate households for possible higher energy bills;
5. Reduction of company profit taxes, which works indirectly as a reduction of a capital tax, a reform which also has been analysed in many other studies. This option is introduced to simulate the macro-economic impacts of a reform that encourages investment and thereby GDP growth. It is performed in 2 variants:
 - a. A variant in which companies do not reduce their (fixed) profit mark-up rates after the tax break, thereby benefitting owners and asset holders;

- b. And a variant that could be considered to represent “competitive” markets in which firms reduce their mark-up rates parallel to the reduction in profit (or capital) taxes;
- 6. Reduction of taxes on production: Carbon tax revenue is recycled via subsidies to production of non-energy sectors, compensating them for higher energy bills – a scenario to reduce the burden on non-energy sectors and thereby stimulate domestic output, growth and jobs;
- 7. A reduction of charges for social security and pension contributions increasing all the way up to a subsidy to labour – the objective is to compensate for possible loss in activity and for increased costs of energy, and to directly aim at reducing unemployment, by making labour more attractive as a factor of production

The projections for South Africa’s economy in 2035 with these seven policy options are compared a Reference Projection’s outcomes for 2035 in which I assume neither a carbon tax, nor impacts of climate change. This comparison intends to answer the following question:

How do the different main carbon tax revenue recycling scenarios impact key indicators for the South Africa’s socio-economic development and CO₂ mitigation policy?

The key indicators to evaluate the results are:

- Change in total CO₂ emissions versus baseline, meaning: reference projection CO₂ emissions;
- GDP and *per capita* GDP;
- Broad unemployment rate;
- CO₂ emission intensity of GDP;
- Income inequality, measured by the difference in real *per capita* income between the poorest and the richest household class.

When suitable, these indicators will be accompanied by related indicators to provide additional insights on South Africa’s socio-economic development. More importantly, with the discussion of scenario outcomes I will answer the question which I consider most insightful for policy making:

How do the outcomes on key indicators follow from structural change, and through which mechanism do the main policy scenarios cause structural change?

From the discussion in section 1.1 it has become clear that the labour market currently contains constraints on South Africa’s economic development and that the unemployment rate is unacceptably high. This study therefore cannot avoid dealing with the aspect of how to improve South Africa’s labour market conditions. The most notable aspect that will be taken into consideration is the existence of a shortage of skilled labour. This shortage is assumed to make production in South Africa more costly, due to overheating of especially the high-educated part of the labour market. The question is:

Can a reduction of South Africa’s observed skill shortage provide a pathway for an economic development that is low in its carbon content? Is investment in skills an

interesting option as a way to use carbon tax revenue?

Finally, a last set of questions to be answered is about how the model's conclusions are sensitive to scenario and modelling assumptions. For this purpose alternative scenarios will be analysed and a sensitivity analysis will be performed in order to answer to the following questions:

How would different international climate policy regimes affect the impacts of South Africa's carbon taxation and Ctax revenue recycling options? How do assumptions and choices in model parameterisation affect the outcomes of scenario analysis?

Important aspects that will be considered are:

How do assumptions on international trade and about technological change impact model outcomes? How does the representation of South Africa's energy system impact results of such an analysis?

This kind of robustness and sensitivity analysis also helps to evaluate the chosen modelling approach itself, and though this is not the topic of this thesis, the exercise performed does shed some light on the functioning of energy-economic models. The outcomes of scenario analysis and sensitivity analysis will therefore also be used to reflect on questions like how one could incorporate growth mechanisms in a macro-economic model, and e.g. how one could correctly model their socio-economic impacts such as employment and inequality. How does the modelling *approach* chosen in this thesis impact the findings? What is the added value of the approach? These questions will be dealt with in the discussion and conclusion at the end of this thesis.

1.4. Existing studies on development and climate policy in South Africa

The present study is not the first study to look at the question of how the challenges for South Africa's economic development interact with the questions of mitigation measures for (and adaptation to) climate change, or *vice versa*. Almost obviously, South Africa's CO₂ intensity has been a topic of debate and scientific research since climate change became an international question in the 1990s. The discussion here starts with literature on a more strategic policy level, before discussing studies that analyse climate change mitigation policy with economic general equilibrium models.

Analysis for strategic policy orientation

The international scientific and policy communities on climate change tend to place climate change objectives above development objectives (Winkler et al., 2015). Winkler *et al.* argue that it is important to consider climate change mitigation and adaptation policies in coherence with development objectives in designing a strategy that achieves all policy objectives and which can be politically feasible in a developing or emerging country. In Winkler *et al.*'s approach, development objectives are the starting point for any policy development or economic planning, after which planned policies are adjusted in iteration until development objectives and climate mitigation objectives are jointly achieved.

In a more applied policy analysis Winkler and Marquard (2009) gather insights from a wide range of literature on South African climate change mitigation policy. They use insights from this literature to analyse how a combination of development and climate change mitigation could look like for South Africa. They review the potential in South Africa to achieve higher energy efficiency, for changes in the fuel mix, and for structural change in economic activity. Whereas the former two objectives entail a large variety of different investment programs (with differing degrees of economic viability), the latter point is addressed by proposing five different strategies:

1. Adjusting state incentives promoting or benefiting energy intensive industries, and shifting them towards low carbon industries;
2. Focussing decarbonisation efforts on non-energy intensive industries, as they would suffer less from global competition loss;
3. Develop policies that help energy intensive industries adjust to the conditions required by successful climate policy: e.g. measures that promote lower energy intensity, and international negotiations on the future place and international location of such industries;
4. Use general economic instruments, such as carbon taxes or other similar instruments which create a price signal to move the economy, sectors, or technology away from high energy intensity;
5. Focus industrial policy and investment strategies on promoting low energy- and low GHG-intensive industries.

The need for an integrated approach that combines development with climate mitigation is also expressed in plans of the South African government. Unfortunately, this is often only a marginal topic, and does not form the key message. The most important reference in this respect is probably the National Development Plan (NDP) 2030 (National Planning Commission, 2011). While it recognizes the need to restructure the economy towards a low carbon economy, and acknowledges the unsustainable, resource-intensive character of the current South African economy, economic structure is not a topic of the part of the report that discusses climate change mitigation actions (in the Overview section, p. 33). The NDP furthermore still reserves a central place for South Africa's resource-intensive sectors in its strategy for the economy (National Planning Commission, 2011, pp.38-42). Nevertheless, it must be granted that the NDP does envision increased efficiency, taxation of infrastructure use, and more intelligent stimulus for mining's down-stream industries (see NDP p.42). The plan also emphasizes the need to stimulate development of small- and medium enterprises, and to equip the labour force with a higher level of skills.

The combination of South Africa's economic and environmental objectives receives much more attention in South Africa's New Growth Path, of which the 4th national "Accord" is the Green Economy Accord (RSA, 2011c). The Accord is a voluntary agreement between government and major

social partners: Unions, businesses, and civil society. The Green Economy Accord's underlying philosophy is that climate change action provides an opportunity for the development of new economic activity and that the country can profit from its technological research and the economy's manufacturing base to generate new processes and products. It emphasizes the responsibility of government to create an enabling environment for businesses and citizens. The plan specifies twelve commitments, which are envisioned to account for 300 000 new jobs in green economic activity by 2020, as part of the 5 million envisioned in the entire New Growth Path. Commitments concern actions such as increasing use of renewable energy at home, for power generation, and in transport; facilitating "green" investment; making coal-based technologies cleaner; increasing energy efficiency in industry, services and residentially; more recycling; a modal shift to public transport and freight transport by rail; electrification and reduction of open-fire cooking and heating; and finally, using local employment, especially for the youth, and to develop the skills of the labour force. The Accord addresses a large part of the policy objectives proposed by Winkler and Marquard (2009).

The low extent of integration of environmental and economic strategy, at least at the highest political level, possibly signals a lack of political will to engage in a structural reorientation of the South African economy. Baker *et al.* (2014) analyse how different political and economic forces in South Africa might prevent the country to embark on an efficient and cost-effective implementation of policies and measures that will reduce South Africa's CO₂ emissions and that could avoid a lock-in of the South African energy system on coal use. The economic risks of such a lock-in are considerable. Not only should one think of an international trend of carbon footprinting of products and supply chains, but also, as Baker *et al.* point at, of carbon-content based evaluation of stock market value and investor portfolios. Also, there is a risk that importers of South African products, like EU countries, apply a border tax adjustment (BTA) scheme in case of absence of insufficient carbon pricing by South Africa or other countries (National Treasury, 2013). The biggest concern might be the long term economic costs, with costs of inaction falling onto all South African businesses and citizens. For example, Burton *et al.* (2016) project an increase in electricity prices due to stranded assets up to about 10% (between 2030 and 2045) if future constraints on South Africa's CO₂ emission budget would all be allocated to the electricity sector to spare SASOL's²¹ coal-to-liquids (CTL) operations.²²

As mentioned in section 1.1, historically, and up to the present, it seems that what benefits the South African Minerals-Energy-Complex (MEC) could be disadvantageous to inclusive economic development and even employment. Black (2014) argues that continuing the stimulus for energy intensive mining sectors prevents the economy to develop into a different, inclusive growth trajectory. He points at the historic causes for this development (as well as at other consequences of South Africa's history of Apartheid for the possibilities for people to develop new businesses and find jobs).

²¹ South Africa's main international integrated energy and chemical company, which also has exploration and production of oil and gas, and which in South Africa runs a Gas-to-Liquids (GTL) plant, as well as conventional oil refineries, chemical plants and some coal mines.

²² Author's own estimation on the basis of Figure 5 in Burton *et al.* (2016).

Black is therefore optimistic about the potential for policies for a low-carbon economy to have a more positive impact on employment than currently expected in estimates for employment of investment programs in renewables. The latter type of studies, like by Maia *et al.* (2011), only look at direct and first degree indirect employment impacts of investment programs, and they do not account for economic feedbacks on the entire economy, e.g. due to changes in production costs, prices and the structure of demand. These effects can be bigger than direct employment impacts.

CGE model analysis of mitigation policies

It is therefore important to evaluate mitigation policies including macro-economic feedback loops, and in consideration of the concerns about economic structure, to evaluate mitigation policies in combination with a certain vision on economic development. Using a macro-economic computable general equilibrium (CGE) model enables this kind of analysis. This kind of studies is data-intensive though, especially if one wants to look at sectors and policies in more detail. But, once a model is developed, more detail can be added, and scenarios for specific sectoral developments can be integrated in the general equilibrium analysis. This is also the strategy of this thesis, for which the methodology and the modelling tool will be further elaborated in chapters 2 and 3. This study, however, is not the first to embark on this mission, and there are probably few countries (both developed and developing) covered as broadly and with the same depth concerning the question of macro-economic impacts of a carbon tax.

Van Heerden et al. (2006)

One of the earliest analysis available is from Van Heerden *et al.* (2006), who ask whether revenue recycling from a carbon tax could generate a double or even triple “dividend” in South Africa. They use a static CGE model of the South African economy with 27 sectors and 48 household groups. To capture scarcity of skilled labour in South Africa, the model features a fixed and fully employed supply of high-skill labour, while supply of low-skill labour is elastic to real wage. There can be substitution between capital and labour, but not between aggregate factor volumes and intermediate inputs like energy. At this level the production function is modelled Leontief, though wages and rates of returns on capital can change. Calibrated on 1998 SAM data, the paper tests 4 environmental tax instruments and 3 revenue recycling schemes. All measures are analysed *separately*, thus creating 7 scenarios analysed for their impact on target variables.

The environmental taxes analysed are: 1. a tax on CO₂ emissions from consuming fossil fuels (carbon tax) of 35 ZAR₁₉₉₈/tonne of CO₂ (equivalent to 5 USD/tonne CO₂); 2. A fuel levy on the sales of coal, crude oil and gas equivalent to the carbon tax; 3. A tax on consumption of electricity equivalent to the carbon tax, but for CO₂ emissions of electricity use only; and 4. a broad energy tax that basically combines instruments 2 and 3 with the difference that the tax is levied on consumption of fuels and thus targets refinery products rather than coal or crude oil – this option is more advantageous for fuels from CTL plants, over which higher taxes are paid in option 2 due to the higher CO₂ emissions

involved in coal-to-liquids conversion losses. The recycling schemes are: A. a break in direct (income) taxes on labour and capital; B. a break in indirect (sales) taxes; and C. a break in sales taxes on food.

Van Heerden *et al.* find that marginal reductions of CO₂ emissions due to environmental taxes are larger than marginal increases caused by tax breaks. A carbon tax in combination with a food tax break is expected to cause the biggest reduction in CO₂ emissions. The reduction of the marginal excess burden of the food tax break is also bigger than the increase in any of the environmental taxes, thus creating a double dividend in terms of GDP growth. There is no double dividend for the direct tax break and the general indirect tax break. Finally, the combination food tax break and environmental taxes also leads to net marginal gains in low skill employment. The authors therefore find that this combination leads to a “triple dividend”. Marginal employment gains are also obtained with an indirect (general sales) tax break, but only in combination with a carbon tax or a fuel tax.

Devarajan et al. (2009, 2011)

Devarajan *et al.* (2009, 2011) ask how a carbon or energy tax will fare in a distortion-laden economy such as the South African. To do so, they first build a static CGE of the South African economy calibrated on SAM 2003 data. The model has 43 sectors and is combined with an econometrically estimated micro-simulation model for occupational choice and other household behaviour to analyse distributional impacts. 3 Labour skill levels (unskilled, semi-skilled and skilled) exist for 3 types of labour (formal, self-employed and informal) leading to 9 labour markets. Formal unskilled and semi-skilled labour is modelled through rigid wages, while formal skilled labour and all self-employed and informal labour are modelled as fully employed with market-clearing wage setting. Devarajan *et al.* test 3 policies to reduce CO₂ emissions by 15%: 1. A carbon tax, 2. A sales tax on energy inputs, and 3. A sales tax on products of energy-intensive sectors. Carbon tax revenue is recycled through a reduction of all indirect taxes (on production, sales, and imports). Sensitivity analysis is focused on different rigidities in production and the labour market.

The main result is that the choice of the type of environmental taxation is critical for employment effects: Sales taxes on energy or pollution-intensive commodities have more negative consequences for employment than a carbon tax. Relatively small welfare losses (a 96 ZAR₂₀₀₃/tonne CO₂ carbon tax leads to 0.3% welfare losses) are found regressive for a carbon tax and progressive for the two environmental sales tax cases. The reason lies in the composition of final consumption of different household income deciles: A carbon tax touches different product categories in a more equal way, whereas environmental sales taxes in combination with a reduction of all other indirect taxes can be said to be beneficial to products that are important for low income households. The strong employment impacts of the sales tax scenarios can be explained from the way Devarajan *et al.* model the labour market. This will be discussed and compared to findings of the present study in section 6.2. A last finding is that they find substitution possibilities between factors and labour market rigidities to be very critical for welfare and employment impacts of environmental taxes (Devarajan *et al.*, 2011).

Pauw (2007)

Pauw (2007) explores the possible impact of a carbon tax in combination with various mitigation scenarios on the South African economy for the period 2000 – 2015. The analysis is performed with a dynamic CGE model that integrates information on future technological change coming from a bottom-up (BU) model. The BU model, a MARKAL model,²³ estimates technology shares in electricity production and for the production of refined fuels, as well as energy efficiency gains. Technology shares are translated into fixed capital shares, while goods markets clear in such a way that capital is fully utilised. Energy efficiency in intermediate inputs of energy per sector is copied “costless” from the MARKAL model into the CGE model. Costless means that no increases in capital or other factor or intermediate inputs to production are required to achieve these efficiency gains. The MARKAL model furthermore determines the investment need for a long term (up to 2050) optimal (least cost) energy system. Differences in investment need relative to the reference scenario are translated into changes of the fixed investment rate target – savings adjust to generate this investment.

Pauw (2007) analyses the implications of 3 policy scenarios, which are combinations of policy measures resulting from the Long Term Mitigation Scenarios project (Winkler (ed.), 2007). These combined scenarios are respectively labelled “Start Now”, “Scale Up”, and “Use the Market”, with the former two consisting of a progressive set of investments and measures to reduce CO₂ emissions in the electricity and refineries sectors paid for by changes in income taxes. The latter scenario simulates a gradually increasing carbon tax, the revenue of which is recycled into a food tax break. Due to this set up, results are not comparable in terms of CO₂ emissions: By 2015 the start now and scale up scenarios result in a reduction of a bit more than 50 Mt of CO₂ emissions (or minus 8% or more) relative to reference path emissions of close to 600 Mt CO₂, while the use the market scenario results in a reduction of 100 to 150 Mt CO₂ (or 17-25%) relative to the reference path (Winkler (ed.), 2007).

The technological measures in the Start Now and Scale Up scenarios are respectively expected to lead to an increase in GDP of 0.2% and 1.0% (Pauw, 2007). This GDP growth is absorbed by investment requirements in the Scale Up scenario, leading to a slight decrease in (temporal) household welfare in 2015. In the Start Now scenario investment decreases relative to the reference case and gives way to an increase in (temporal) household welfare in 2015. The Use the Market scenario sees a decline in GDP of 2% by 2015. Pauw (2007) indicates that the main reason is a higher import bill due to faster substitution of domestic energy sources (mainly coal) by imported energy resources, namely oil (to produce refinery fuels) and natural gas (for fuel switching in non-energy sectors).

Employment effects for unskilled and semi-skilled workers, and wage effects for skilled and high-skilled workers are relatively synonymous to changes in GDP growth for the Start Now and Scale Up scenarios. However, for the use the market scenario, the 353 Rand per tonne of CO₂ carbon tax in

²³ The MARKAL (for Market Allocation) model is a linear optimization program developed by the International Energy Agency (IEA) to analyse trajectories for cost optimal energy systems from the point of view of a central planner.

2015 causes an increase in semi-skilled employment of about 3%, whereas unskilled employment is unchanged relative to the reference case, while wages in fully employed skilled and high-skilled labour segments decrease. Possibly, food tax breaks are beneficial for employment of unskilled and semi-skilled labour, because they reduce wages for these categories relative to average prices in the economy as these labour categories have rigid real wages (indexed on consumer prices). At the same time, decreased GDP growth translates in lower demand for skilled and high-skilled labour.

Alton et al. (2012, 2014)

Alton *et al.* (2012, 2014) explore the likely impacts of domestic and/or foreign carbon taxes on the South African economy. Using 2005 as base year, they analyse the trajectories of 3 policy scenarios up to 2025: 1. A domestic carbon tax; 2. A domestic carbon tax plus border tax adjustments; 3. A foreign carbon tax plus border tax adjustments in South Africa's main trading partners. Three recycling options are explored: A. uniform reduction in sales tax; B. reduction of a corporate tax imposed on capital earnings of domestic firms; C. scaling-up of existing social transfer programs benefitting households.

Alton *et al.*'s CGE model, e-SAGE, bears similarity to that of Pauw (2007), the main differences are that it is recursive dynamic with sector-specific capital and allocation of new capital by sector, elastic to (recursive) periodic sectoral profit rates. Capital shares of energy sectors are not forced exogenously as in Pauw (2007), but technology shares in electricity generation and the refineries sector are endogenous. Intertemporal profit maximisation (between periods) determines profit mark-ups with the objective to clear the capital market (full utilisation of capital). Wages clear medium and high skill segments of the labour market, while low skilled and unskilled labour is unemployed with an upward-sloping labour supply curve. A CES function determines substitution between capital and aggregate labour at the sectoral level. Growth is modelled exogenously and determined by total factor productivity (TFP) growth and change in factor use per sector. Capital availability is driven by fixed exogenous saving rates for households (who earn all factor income) accompanied by an exogenous inflow of net foreign investment. This foreign investment is fixed at an absolute amount in the foreign currency, and therefore variable with the exchange rate.²⁴ Net debts and assets seem not to be tracked in e-SAGE. Finally, Alton *et al.* (2012, 2014) assume energy efficiency gains that depend on the increase of energy prices and on the speed at which capital stock is renewed.

Alton *et al.* (2012, 2014) find that a carbon tax of 210 ZAR₂₀₁₀/tCO₂ (145 ZAR₂₀₀₅/tCO₂) by 2025 leads to approximately 36% decrease in GHG emissions relative to BAU (41% when deducting net exported emissions). However, taking into account the original Integrated Resource Plan (IRP) for electricity production of 2010 leads to a decrease in emissions of only 30% compared to their "revised baseline". Depending on the baseline, both findings can be considered consistent with South Africa's NDC. GDP losses of their domestic ("production") carbon tax in 2025 range between 0.7% and 1.7%

²⁴ Foreign investment plus the trade balance add up to zero.

relative to BAU (depending on the recycling option). The standard carbon tax revenue recycling mechanism in e-SAGE is a reduction of a sales tax, which obtains medium outcomes compared to the two other scenarios for carbon tax revenue recycling: A social transfer to households and a reduction of corporate tax rates, which respectively obtain lower and higher GDP growth outcomes. But, they find a trade-off in the choice of the recycling option between revenue distribution and economic growth, with the social transfer leading to less poverty and inequality, something that a corporate tax break does not achieve.

Merven et al. (2014)

Merven et al (2014) use the e-SAGE model of Alton et al. (2012, 2014) one step further and link it to the partial equilibrium South African TIMES bottom-up energy system model (SATIM) developed by the Energy Research Centre (ERC, 2013) at the University of Cape Town (UCT). Merven *et al.*'s study focusses on power sector CO₂ emissions, and therefore does not show economy-wide outcomes for CO₂ emissions, and uses the electricity sector version of SATIM (SATIM-E). They compare, for the period 2010 to 2040, a business-as-usual reference scenario with the introduction of a carbon tax – starting at 48 ZAR₂₀₁₀/tCO₂ (5 USD/tCO₂) and increasing to 120 ZAR₂₀₁₀/tCO₂ (12 USD/tCO₂) in 2025²⁵, and to two scenarios that achieve emission reduction through increased renewable energy deployment compared to the electricity sector's updated Integrated Resource Plan 2010-2030 (IRP): One scenario concerns a medium-sized investment (RE1) and one a more ambitious renewable energy program (RE2).

The carbon tax scenario in the linked SATIM-e-SAGE model leads to modest impacts on GDP (-0.7%) and employment (-2.6%) by 2040, while power sector CO₂ emissions in 2040 turn out approximately 5% lower compared to their reference. Merven et al (2014) do not report on CO₂ emissions of the rest of the economy, but do report that the carbon tax leads to an electricity price in 2040 that is approximately 15% higher than in their reference scenario, which should motivate higher energy efficiency in the rest of the economy, just as the carbon tax itself. A comparison with Alton et al. (2012, 2014), might give a clue of the total emission reduction that could be expected from Merven et al.'s carbon tax rate, assuming that their parameterisation of e-SAGE is similar to that of Alton et al. (2012, 2014). The latter find that a carbon tax between 10 and 15 USD/tCO₂ leads to a greenhouse gas emission reduction by 2025 for the entire economy of between 20% and 30% in e-SAGE.

Under conservative assumptions for costs of renewable energy, Merven et al (2014) find that the RE1 and RE2 scenarios lead to slightly more negative GDP projections compared to the introduction of a carbon tax. RE2 also results in more negative consequences for employment compared to the carbon tax scenario, despite lower electricity prices. The explanation might be connected to the fact that the carbon tax is recycled into a sales tax reduction, and therefore leads to output growth in non-energy intensive sectors, such as agriculture and the food industry. The RE1 and RE2 scenarios do not offer

²⁵ Alton et al. (2012, 2014) model a carbon tax starting in 2012 with a value of 3 USD/tCO₂ and increasing to 30 USD/tCO₂ in 2022.

this possibility of revenue recycling, but they result in lower power sector CO₂ emissions and a lower electricity price compared to the carbon tax scenario, in which power generation hardly reduces its CO₂ emission intensity. The higher electricity price and other increased costs of fossil fuel-based energy use with carbon taxation likely motivate higher energy efficiency in all sectors in e-SAGE (see the discussion about energy efficiency in e-SAGE above).

The macro-economic difference between scenarios reduces a lot if more optimistic future cost decreases are assumed for renewable energy technology. This suggests that their model predicts that South Africa is under-investing in renewable electricity generation if future cost decreases of renewables turn out more optimistic, as they currently seem to do (Wright et al., 2017). Their outcomes suggest that it would be better in this case to decarbonise electricity generation than other sectors.

Altieri et al. (2015)

Another approach is taken in the Deep Decarbonisation Pathways Project (Deep Decarbonisation Pathways Project, 2015), for which Altieri et al. (2015) perform the analysis on South Africa. Altieri et al. (2015) do not analyse the implementation of a carbon tax, but work with cumulative CO₂ emission budgets, optimally divided between a budget for the power sector and one for the rest of the economy on the basis of a BU (partial-equilibrium) analysis with SATIM-F (in a one-time iteration with e-SAGE to improve GDP and energy demand forecasts). They consider two economic visions, tested by means of introducing “shocks” relative to reference assumptions of the linked e-SAGE – SATIM-E model, and analyse how both visions turn out economically in respecting the cumulative emission budget.

The first vision they test is one in which they manipulate the model in such a way that investment is increased in low skill labour-intensive & CO₂ emissions-extensive sectors, such as agriculture, furniture, and glass products, but also the “other services” sector. This automatically implies somewhat lower new capital formation in other sectors, because their investment is exogenous, savings-driven. The second vision they test is one in which they increase strongly the number of high and medium-skill level workers entering in the job market. In this way, they hope to undo the skill shortage which is characteristic of South Africa’s mineral exports and services sector intensive economy (see discussion of the MEC above). Altieri et al. (2015) show that South Africa achieves considerable GDP increases in both scenarios: GDP per capita is almost three times higher than in 2010, and highest for the low skill investment-structure scenario. This scenario also achieves the highest reduction in unemployment, but (counter-intuitively) inequality is slightly higher for this scenario than for the high skill scenario, with slightly more people in the lowest income household class (18%) than in the second, high skill labour, scenario (17%).

Differences with the approach of the present study

Compared to these studies this thesis proposes a few methodological differences in how to model

macro-economic developments. Firstly, the model in this thesis is a simulation model, and not an optimisation model that assumes perfect primary factor markets. It also means that the model in this thesis does not use perfect foresight in optimising economic behaviour (maximising household welfare or minimising system costs to society). Furthermore, the methodology of the present study (see Chapters 2 and 3) makes use of end-user specific prices and a system of mark-up pricing – profit margins therefore do not adjust to clear the capital market. The assumption of perfect rational expectations and market clearing are thus avoided. Lastly, the model in this thesis uses financial consistency in the capital market and tracks (international) stocks of financial assets, and models its impact on the trade balance and exchange rates.

Secondly, the model assumes imperfect labour markets (with unemployment) for all skill segments of labour and skills to be positional, meaning that it is the relative degree of educational attainment that determines the type of jobs one can apply for, and not the absolute level of educational attainment obtained. This reflects mentioned problems with educational quality (Spaull, 2013). Furthermore relevant for labour market modelling is that carbon tax revenue recycling is analysed in the context of continued labour-saving technological change, while other studies rely on factor neutral productivity gains. Productivity gains are defined in volume terms and include efficiency gains in intermediate inputs.

Thirdly, the Input-Output table on which the model in this thesis is calibrated uses dual accounting of energy flows, and for instance also for the physical capital intensity of production (see chapters 2 and 3). This enables a more precise evaluation of technological change. Regarding the incorporation of bottom-up modelling results or engineering insights, by combining exogenous changes in the production technology frontier with CES substitution. The latter is the case for all sectors except the electricity sector. Regarding power generation the model of this thesis assumes, in contrast to Devarajan et al (2011) and Van Heerden *et al.* (2006), rigidities in power generation based on bottom-up model runs of SATIM. The combination of bottom-up and top-down modelling is therefore similar to that of De Pauw (2007) or Alton et al (2014). However, it is less elaborate than that of Merven et al (2014) and Altieri et al (2015).

Finally, the present study includes yet unexplored revenue recycling options, particularly wage subsidies and government budget deficit reduction. Also, the analysis looks into the reduction of company profit taxes, but combines this with different assumptions about how profit mark-up rates respond.

1.5. Thesis outline

This Ph.D. thesis continues with a discussion of the theory and methodology of modelling the question of economic development, employment and environmental taxation through macro-economic modelling (Chapter 2). Chapter 3 continues with a description of the IMACLIM South Africa model

(IMACLIM-ZA), which is the tool for the analysis of the policy questions of this thesis. In Chapter 4 I discuss the Reference Projection, the basic policy scenario settings, and their projections. I explain the results and relate them to different aspects of the modelling of the behaviour of the South African economy. Chapter 4 also includes a discussion about potential impacts of an investment in skills of labour. Findings are put into a larger context in chapter 5, which discusses alternative assumptions for the policy scenarios such as varying carbon tax rates to achieve comparable CO₂ emission levels and different assumptions about foreign or international climate change policies, how energy efficiency affects the results, and finally how sensitive results are to model parameterisation. Finally, Chapter 6 discusses the limitations of the present analysis, how it compares to previous studies, and to the theory about growth and development under environmental constraints. Chapter 7 concludes by answering the research questions presented in this Chapter.

2. Theory for a CGE model for analysis of carbon taxation, growth and employment

The objective of this chapter is to present the theoretical considerations on which the methodology for the analytical model of this thesis, presented in Chapter 3, is based. This chapter does not present a comprehensive treatment of literature and theory regarding macro-economic modelling. It discusses a selection of literature and ideas that are important for the foundation of the IMACLIM framework, and for modelling the question of the macro-economic impacts of carbon tax revenue recycling in South Africa in particular. Because the IMACLIM framework has been developed as a correction of applied prospective neoclassical CGE modelling, the focus of this Chapter will be on the reasons to deviate from the neoclassical approach.

The chapter consists of two parts: The first part (section 2.1) asks the question why economic growth under environmental constraints is best modelled with a dual accounting framework for values and quantities of flows in an economy, and why technological change is best modelled exogenously in the present analysis for South Africa. The second part (section 2.3) discusses the options for modelling the South African labour market and its rigidities, in particular a skill shortage. In between, section 2.2 treats the question whether particular assumptions should be applied to model development.

2.1. Growth, environmental constraints, and technological change

This section does not present a comprehensive summary of literature on CGE modelling of the question of growth and environmental limits or taxation or regulation. It only discusses a selection of literature, to underline a few issues that motivate important modelling choices of this thesis. To set the stage, this section starts by briefly providing some insights on the measurement of economic activity and how it relates to environmental limits (in sub-section 2.1.1). In particular, the role of technological change and of the timing of mitigation and adaptation measures is discussed. This discussion serves in identifying the requirements that prospective macro-economic models should ideally meet in order to inform policy making on economic development within environmental constraints. This section continues with how neoclassical CGE models address the question of growth within environmental constraints, and discusses some of its weaknesses (in 2.1.2).

This leads to the conclusion that a dual accounting or “hybrid” approach to CGE modelling that also takes into account second-best economies would be most appropriate to address the question of growth within environmental constraints, such as the present analysis of carbon tax revenue recycling in South Africa. This section then presents the IMACLIM framework that is used in this thesis and how it addresses the mentioned shortcomings of a neoclassical approach (in sub-section 2.1.3). Finally, I pay special attention to how economic growth is modelled in the IMACLIM framework (in 2.1.4), which supports the analysis and understanding of the macro-economic results of scenarios in Chapter 4.

2.1.1. Modelling economic development under environmental constraints

Introduction

This thesis addresses the research questions presented in chapter 1 with a methodology of quantitative macro-economic modelling that takes into account a large number of feedback loops within an economy. A rich body of scientific literature serves as an inspiration for the development of such a model. One of the early ground-breaking works in this literature on economic growth and (in this case) constraints on energy resources was a treatment of possible impacts on the British economy of scarcity of domestic coal resources in the second half of the 19th century (Jevons, 1866). According to Missemer (2012, 2013) Jevons was a pioneer in introducing important concepts such as intergenerational equity. He analysed how taxation of coal use and the recycling of revenues of such a tax could improve Great Britain's economic future and the welfare of future generations in anticipation of increasing costs of coal. Jevons' study can be positioned at the start of what became a large area of research on how regulation and taxation could be used to improve the economics of man's use of resources and the environment. This question has become a central topic in economic research, especially in the last quarter of the 20th century, at a time when pollution and resource depletion started to receive important societal attention.

Nowadays, there are multiple approaches for macro-economic analysis of environmental constraints. Each approach has its own focus and therefore specific advantages and disadvantages depending on the question to be analysed. In this thesis I work with a dynamic computable general equilibrium (CGE) model, which is particularly suited to study medium-term future, dynamic macro-economic developments under certain expectations of technological change.²⁶ Before developing the argumentation that leads to the methodological choices later in this section, it might be good to take a step back and take a bit of a broader look to get a sense of the interplay between economic development and environmental constraints.

Measuring economic and environmental development

While the world faces many important environmental problems, few seem to be perceived as dangerous to the future of human civilisation as man-made climate change. The predominant political and scientific response to this problem however often tends to consider climate change mitigation without taking into consideration the development paths that contribute to GHG emissions, and the development paths that could be an alternative (Winkler et al., 2015). The most common definition for development nowadays is that of sustainable development, which was the principle concept of the Brundtland Report (WCED, 1987).²⁷ Sustainable development is often presented as a balanced

²⁶ Some examples of other approaches than CGE modelling to prospective macro-economic modelling are Dynamic Stochastic General Equilibrium models (Christiano et al., 2018), I-O or SAM models (see a discussion by Perrier and Quirion, 2017); macro-econometric models (Lehr et al., 2012; Scasny et al., 2009); Goodwin-Keen models (Giraud et al., 2016; Keen, 1995); and (also) System Dynamics models like the World3 model that Meadows *et al.* (1972) used for their well known, forward looking analysis of growth and technological change and environmental limits: "Limits to growth".

²⁷ The Brundtland report states: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: 1. the concept of 'needs', in particular the

development that takes into account environmental, social and economic objectives, though this definition never appears in the report itself.²⁸

For the present study on carbon tax revenue recycling in South Africa, the social pillar of sustainable development is only analysed in a relatively narrow sense by looking at income inequality and unemployment. This thesis thus limits the analysis to economic development and its relation to the environment.²⁹ Concerning these last two aspects, the Brundtland Report emphasizes the importance of economic growth at several instances, but economic growth is only considered a “means” to realize the primary dimensions³⁰ of sustainable development (Holden et al., 2014): “Sustainable development clearly requires economic growth in places where such [human] needs are not being met. Elsewhere, it can be consistent with economic growth, provided the content of growth reflects the broad principles of sustainability and non-exploitation of others. But growth by itself is not enough.” (WCED, 1987: part I, Ch.2)

Economic success is generally considered to represent progress in welfare or, in a more restricted definition, the extent to which human needs or wants are being fulfilled. As a measure for economic development, this thesis makes use of the *per capita* GDP indicator. It is recognized that this indicator has serious limitations, and that it is not a good guide for long term policy making (Van den Bergh, 2009). The incapacity to take into account environmental concerns and their impact on future generations is one of these deficiencies. Van den Bergh (2009) identifies several reasons why *per capita* GDP has an unfortunately big, partly self-fulfilling, and often misinforming role in economic decision making. He argues that none of the arguments in favour of GDP as an indicator for public policy making holds. However, implicitly, Van den Bergh recognizes a political motivation for using the GDP indicator, namely that GDP growth enables to postpone politically difficult questions of welfare redistribution. Other arguments to explain why GDP is not being abandoned as an indicator are provided by Pottier, who points out that GDP growth is a politically *easy* short-term solution for a reduction in unemployment, and high GDP often equates to geopolitical influence (interview with A. Pottier in: Thiry and Gueret, 2015). Though many alternatives have been proposed in literature (see for instance the Sen, Stiglitz, Fitoussi report; Stiglitz et al., 2009), the possibility to replace GDP in political decision making by other indicators is in practice limited, at least for the time being. The present study thus uses GDP as an indicator for economic development, amongst other indicators (see section 1.3).

The scope for environmental policy evaluation in this thesis is, for more practical reasons, restricted to

essential needs of the world's poor, to which overriding priority should be given; and 2. the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.” (WCED, 1987: part I, Ch.2)

²⁸ Different proposals for the measurement of sustainable development exist (OECD, 2004). A politically accepted concretisation of the concept of sustainable development can be found in the United Nation's 2030 Agenda for Sustainable Development, often referred to as the 17 Sustainable Development Goals (SDGs) (United Nations, 2015).

²⁹ Development that is both economically and environmentally durable could be considered equivalent to what is called “viable development” within the concept of sustainable development.

³⁰ Herman Daly's primary dimensions are: “safeguarding long-term ecological sustainability, satisfying basic human needs, and promoting intra-generational and inter-generational equity” (Holden et al., 2014).

CO₂ emissions from burning and transforming fossil fuels in South Africa (see also the introduction in Chapter 1). This is partly a consequence of choice, namely to focus on the role of energy supply and demand, leaving aside the role of land use and agriculture in the economy (which would be worth a PhD thesis on its own), and partly to reduce the modelling effort on the amount of greenhouse gasses involved in the use of fossil fuels (e.g. methane) with the objective to focus on macro-economic modelling.

Environmentally sustainable national income

One of the partial solutions to the deficiencies of *per capita* GDP as an indicator for economic progress which Van den Bergh discusses, is worth considering into more detail: It is the Sustainable National Income (SNI) indicator (De Boer and Hueting, 2004; Gerlagh et al., 2002a; Hueting and De Boer, 2001; Tinbergen and Hueting, 1991). What is interesting about the SNI is that it provides an intuition on how GDP, or in their case Net National Income (NNI)³¹, and environmental constraints might be linked through time.³² The application of the concept of the SNI in a macro-economic general equilibrium model (Gerlagh et al., 2002a; Hofkes et al., 2004) offers a perspective on what economic models should be capable of analysing when they deal with the question of economic development and environmental constraints.

The SNI is the achievement of the pioneering work by economist Roefie Hueting who considered that increasing use of the environment caused competitive use of environmental functions, which qualify as scarce goods (Hueting, 1974, 1980).³³ Up to a certain extent this reduction of environmental functions can be done sustainably. For instance, agricultural use of land means that there is some reduction in ecosystem services or biodiversity, which is not dangerous for ecosystem survival if it is on a limited scale. This corresponds to the idea of the natural system's carrying capacity.

However, environmental functions' scarcity is not priced correctly for several reasons, among which the fact that the environment is considered a public or "free" good, and the fact that its value for future generations is hardly taken into account in economic transactions in the present. Partially and indirectly, such loss of function has been given a market value, but in such a way that it leads the System of National Accounts (SNA) to measure it as an increase of welfare. One of Hueting's examples is the loss of outdoor space to play for children due to the use of streets for motorized transport (Goodland, 2001): Medical expenditures by households or government (e.g. due to reduced health of children or in case of accidents) or for playgrounds are measured as a part of GDP in this case, while the welfare loss of the environmental function of space for children to play is not taken into account. The same logic applies to larger scale environmental problems like the loss of air quality,

³¹ Net National Income (NNI) is Gross Domestic Product (GDP) minus consumption of fixed capital (capital amortisation costs) and adjusted for transfers of primary income to or coming from the rest of the world.

³² A personal reason for me to start this discussion with Hueting's work is that my encounter with his work was the first time that I discovered a perspective on how economic analysis could deal with environmental questions and combine the questions of the time left to restore environmental sustainability and the question of how much of present-day economy was engaged in resources and the environment depleting activity, an encounter that ultimately led to my decision to start a PhD at CIREDE.

³³ Hueting takes his concepts of welfare, scarcity and marginal pricing from the economists Pieter Hennipman and Lionel Robbins.

reduced biodiversity and climate change.

To calculate the SNI, Hueting and De Boer (2001) propose to quantify scarcity and thereby the value of environmental functions by constructing each function's supply and demand curves. Demand curves consist of (actual and future) expenditures that express preferences for environmental functions.³⁴ Supply curves consist of present and future expenditure required to increase the availability of the original environmental function again, including costs to take away the causes for the loss of the environmental function and to neutralize accumulated past pollution. This thus corresponds to an abatement cost curve. Both curves take into account future expenditure or abatement costs, so welfare can be maximised intertemporal.

A "green" national income can be calculated by taking into account people's preferences for the availability of environmental functions that are not expressed in the market prices of goods. Due to a variety of approaches to determine human preference for the environment, multiple "green" national incomes are possible. However, a "sustainable" national income, Hueting argues, can be established relatively objectively: The principle of sustainable development (discussed above) can be translated into a minimum standard for the availability of the environmental function, adding a precautionary "safe margin" given our understanding of the environment of today. This sustainability standard translates into a very steep demand curve, and therefore a very high marginal (shadow) price, for the environmental function when the minimum standard is almost reached or surpassed (Hueting and De Boer, 2001). Likewise, a supply (or abatement cost) curve can be established scientifically on the basis of knowledge of costs of present-day available technology.³⁵ Finally, considering that the maximisation of a green or sustainable national income requires changes in activity, there will be an impact on markets for other factors of production and goods and services. Economic equilibrium therefore changes, implying that the calculation of the SNI, and the distance to NNI, requires a general equilibrium model (Gerlagh et al., 2002b).

Application of the SNI and the race against the clock

Analysis of the SNI, when extrapolated into the future, can teach us how much time there is left to act upon environmental degradation. To understand this, recall that the sustainable national income has to be lower than actual net national income that does not correctly represent the value of environmental functions, because actual expenditure on costs for abatement of loss of the environmental function are, as a part of economic activity, counted as income in the NNI.³⁶ Theoretically, one could extrapolate a "business as usual" (BAU) NNI and its corresponding SNI into the future (Figure 2.1), using for the SNI today's knowledge of the environment and the precautionary restriction to only make use of

³⁴ The expenditures that the demand curve considers include costs to compensate loss of the environmental function (e.g. purification of water for drinking), costs to repair damage due to such loss (e.g. health care costs), travel expenditure to enjoy an environmental function lost in ones' vicinity, as well as the resource rent of raw materials.

³⁵ The precautionary principle excludes the use of not yet operational technology for calculating the Sustainable National Income (SNI); Several authors discuss different methodological (in De Boer and Hueting's words: technical) issues in establishing the SNI. Choices regarding the role of trade have a big impact (Gerlagh et al., 2002b; Hofkes et al., 2004; Verbruggen et al., 2001).

³⁶ Note that this is the same in the calculation of the Gross Domestic Product (GDP).

presently proven technology (Huetting and De Boer, 2001). The transition to the SNI cannot be achieved immediately, because it requires changes in use of technology, in economic structure, and in the level of economic activity. A hypothetical feasible transition path (y_f) is therefore depicted as well. Figure 2.1 shows the inevitable collapse (decrease of y_b) if production (NNI) exceeds the sustainable carrying capacity of the environment for a certain amount of time. The figure shows that the pathway for intertemporal (optimal) welfare (w_b) collapses prior to collapse on the BAU pathway for NNI (y_b in the figure).³⁷ Intertemporal welfare (w_b) corresponding to BAU NNI decreases at some point in time due to loss of environmental functions causing such a loss of welfare or such an increase in reservations of national income for future restoration of the function that this exceeds welfare gains from growth in NNI (increase in y_b). At some later point in time, total net national income will be required to restore environmental sustainability: w_b is about zero then. Beyond this point, it is impossible to restore environmental functions, meaning that NNI has to collapse. This point in time has to be avoided and the issue at stake is therefore to timely embark on a transition path to sustainability, when still feasible (y_f).

Figure 2.1 Historic (y_a) and projected pathways (y_b) for NNI under BAU and its SNI counterpart in the year of investigation (y_s), plus a feasible transition path (y_f); Image source: Huetting and De Boer (2001)

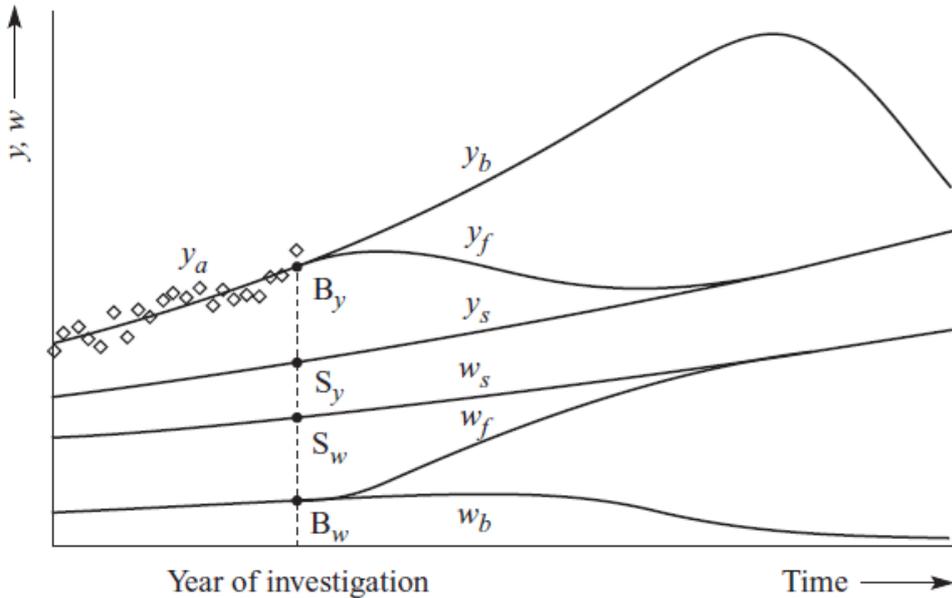


Figure 2.3 Actual standard national income observations (y_a , fictitious example) compared with the net national income (y) and a welfare indicator (w) on three optimal paths, calculated with a dynamic environmental economic model. The blocked path (index b) approximates the actual path (index a) by assuming incomplete expression of preferences for the environment. These preferences are assumed to be completely expressed on the unfeasible unblocked path (index s) and the feasible unblocked path (index f). The points B_y and B_w indicate the levels of national income y and the welfare measure w on the blocked path b in the year of investigation; S_y and S_w are the corresponding points on the unfeasible unblocked path s

³⁷ In the case of an absolute preference for environmental sustainability welfare is lower for the NNI (w_b) than for the SNI (w_s). The difference between national income and welfare is present plus anticipated future value of the loss of environmental function, which should not be double-counted as in national income measurement (see discussion above).

What is missing in Hueting's approach to answer the question about how much time there is left to make a transition to a sustainable economy is the role of technological dynamics. Future technology not only shapes the curves in the graph, but e.g. also takes into account lock-in of (unsustainable) capital. Prospective environmental-economic modelling should therefore be used to identify how feasible transition trajectories to a sustainable economy could look like. The less time there remains for a transition, the steeper the decrease of the NNI during the transition will need to be. The latter in turn causes doubt about the social sustainability of a transition (which is not taken into account in the SNI). Modelling of these technological dynamics is explored more into depth in the next sub-section. First, it might be interesting to consider what the expectations are concerning technological change and having a sustainable economy, and what can be expected in this respect for South Africa.

Expectations about technological change for cleaner production

Hueting (1996, 2010) thinks that it is very unlikely that growth can be combined with a reduction of negative impacts on the environment, at least in the short term. He points out that, historically, growth has come from the most polluting activities (energy intensive industries), which in a country like the Netherlands make up about one third of national income, while yet another part of the economy is complementary to these sectors. Hueting finds that the least polluting activities (mainly services, also a third of Dutch GDP) typically experienced low productivity growth in past decades. He furthermore argues that *if* environmentally "clean" technologies would have been more productive in a traditional sense, that is: in output per worker (labour productivity), *then* they would have been implemented automatically, because labour (including entrepreneurship and R&D) have by far been the dominant cost factor for production in the Netherlands. The latter supposes competitive markets and weak environmental regulation, causing environmental externalities not to be factored into production costs. Profitability has pushed the technological frontier to an unsustainable optimum.

Indeed, assuming proven technology, the Dutch national income is required to reduce between 20% and 50% to arrive at a sustainable level (Dellink and Hofkes, 2008; Gerlagh et al., 2002b; Hofkes et al., 2004; Verbruggen et al., 2001).³⁸ The gap between Dutch NNI and SNI has decreased over time, from 56% of NNI in 1990 to 42% in 2005, assuming sectoral shares in international trade to be constant. Decomposition analysis by Dellink and Hofkes (2008) showed that this reduction could be related to increased use and availability of cleaner technologies. Still, the absolute gap between the Dutch NNI and SNI hardly reduced, implying that the rate of deterioration of environmental functions attributable to the Dutch economy remained the same. (The question how much time there is left for a "feasible" transition is not answered in the mentioned studies.)

The analysis by Dellink and Hofkes suggests that the Dutch economy shows proper signs of an environmental Kuznets' curve (EKC), meaning that developed economies show *relative decoupling* of

³⁸ Variations are mainly caused by different assumptions about the treatment of international trade. An estimation of the gap between NNI and SNI for the entire world by Tinbergen and Hueting (1991) revealed that globally a similar relative change in world's output would be needed as has been found for the Netherlands.

GDP and pollution. The underlying assumption of the EKC is that cleaner technologies of production and consumption are developed once higher standards of living are achieved. But, both the principle of the EKC and Dellink's and Hofkes' (2008) SNI calculation might neglect the impact of resource use, because they do not seem to take into account the need for other countries to make production sustainable too.³⁹ Their findings are therefore slightly in contradiction to findings by De Bruyn et al. (2009) who signal growing "outsourcing" of pollution by the Dutch economy. The latter corresponds to analysis by Wiedmann et al. (2015) for the entire world, showing that once one takes into account global supply chains, lifestyles of people in developed economies hardly showed any sign of relative decoupling as suggested by the hypothesis of the EKC. Instead, pollution seems to have been outsourced, together with large parts of product supply chains, to Asian countries.

An important idea still lacking in this discussion, namely that of the Porter hypothesis: It suggests that environmental regulation could enhance competitiveness and stimulate innovation, thereby leading to higher economic growth (Ambec et al., 2011). Motivations for this phenomenon could, for example, be that people and organisations stick to habits and ignore alternative ways of doing things, or that a tax system and vested interests block new, more productive technology, as is demonstrated in studies in transition science (e.g. see Geels, 2002). Nevertheless, the Porter hypothesis is still strongly debated, and evidence is far from conclusive (Ambec et al., 2011).

However, the point here is not to discuss how big the untapped potential of clean technological progress is, but to show that that knowledge about technological change has a very important role to play in the estimation of future economic growth under environmental constraints. It should therefore be made explicit to analyse and understand future GDP growth.

Implications for South Africa, and the role of labour productivity

The objective of this thesis is not to elaborate a SNI for South Africa. The findings just discussed, on Dutch and global sustainable incomes and those on outsourcing of pollution (by De Bruyn et al. (2009) and Wiedmann et al. (2015)), are rather a warning sign about the possibility to combine GDP growth with a reduction of CO₂ emissions. The South African economy namely depends, despite its large service sector, more on energy intensive industries and resource extraction than the Dutch.⁴⁰ This implies that the gap between net and sustainable national income can be expected to be larger for South Africa than for the Netherlands. However, for South African employment Hueting's (1996, 2010) prediction that limiting pollution increases employment provides hope. Hueting observes that with currently existing technology environmental damage can only be reduced by reducing activity or by bringing in *more labour or time* to perform activities. The latter requires a reduction of output per

³⁹ They assume either fixed world prices (SNI1), which seems too optimistic considering that they show that internalizing the environmental externality to make a large part of production more expensive; In the other case they assume constant sectoral shares in international trade, which would mean that international demand for Dutch services would remain relatively high, whereas domestically the share of services in GDP decreases due to lower income elasticities in household final consumption.

⁴⁰ South African mining and industry, including manufacturing, account for 26% of South African gross value added according to the SAM 2005 (StatsSA, 2010a), against only 12% of in the Netherlands (in 2014). For services these numbers are 66% for South Africa and 77% for the Netherlands. See <http://www.clo.nl/indicatoren/nl0002-bruto-toegevoegde-waarde-en-werkgelegenheid> (accessed October 2016)

worker, meaning a decrease in labour productivity, which also implies a decrease of real income.⁴¹ An example of time use to make consumption or production less polluting is travel time: Slower transport tends to be less polluting. In brief, labour will be more needed as a factor of production to substitute for energy use and capital.

2.1.2. Building blocks for a dynamic CGE model representing growth under environmental constraints

The question of the Double Dividend of environmental taxation

Within the field of CGE modelling, neoclassical and new-Keynesian models take a central place. The neoclassical CGE model is the point of departure for a series of CGE models that work with assumptions that deviate from that of perfect market-clearing or first-best economies. An important question for the analysis of GDP growth under environmental constraints is whether a “strong” double dividend is possible when revenue of a new environmental tax is used to lift other obstacles for obtaining optimal welfare. A strong double dividend is defined as recycling of revenue of environmental taxation that leads not only to better environmental outcomes than under the pre-existing tax system, but also has zero to negative net costs to society (Goulder, 1995).⁴² The latter for instance means an improvement of GDP or of material welfare.

To be able to generate a double dividend, one has to assume pre-existing distortions or deviations from an economically optimal equilibrium (that produces maximal welfare). Strictly neoclassical models assume only first-best economies, assuming perfect markets in combination with the rule of positive but diminishing returns to factor additions, primary factor income equates to the factors’ marginal productivity (first-best economies). Models are solved using welfare maximisation. Factors typically considered are labour and capital, though other factors, like human capital or land, can be added to the model. Marginal productivity can have lower limits in economic equilibrium, which follow from behavioural specifications. For instance, in the case of capital payments a “natural” interest rate causes a lower bound in marginal productivity, while marginal labour productivity is often bounded by the minimal wage rate for which people would want to work as defined in household’s utility function (the labour supply-leisure function). Except for these lower bounds, strictly neoclassical models only consider taxation to be increasing the marginal productivity against which factors can be engaged in production. If a tax increases the minimal level of productivity for which it is economic to engage factors in production this translates into GDP losses, because less productive factor use is pushed out of use for leading to negative returns. An implicit assumption is that payment for, or production of, the public good by government or a public sector does not contribute to productivity. Later adjustments of neoclassical production functions, especially from the 1980s onwards, take into account other

⁴¹ On the other hand, it might be strange to worry about declining labour productivity in times when some, for instance the Netherlands’ Scientific Council for Government Policy (see Went et al., 2015) expects that capital of new technology will increase average labour productivity so much that a part of the labour force, whose skills have become obsolete, likely has no further role on in production.

⁴² In a “weak” double dividend revenue recycling leads to higher welfare than recycling of environmental tax revenue into a lump-sum transfer to an aggregate household, which in a neoclassical CGE model inherently reduces welfare by altering the labour-leisure decision for utility maximisation by the household towards lower economic activity.

market distortions than the minimal wage rate and the natural interest rate, and often abandon the idea that markets can be perfect, and often – but not necessarily – see a role for government’s provision of public goods to solve market failures.⁴³

Though the analysis of how the interaction between environmental taxation and distortions affect welfare can be traced back to, for example, the works of Jevons (1866) and Pigou (1938), more recent analysis of the question of environmental taxation and the double dividends originates from the early 1990s. Goulder (1995) provides a discussion of the state of literature at the time and reasons that the highest chance for a strong double dividend, if attainable, lies in using environmental tax revenue to reduce the pre-existing tax that has the highest marginal excess burden on welfare. The motivation for this point of view Goulder finds in the literature of his time, which pointed out that for the US capital taxes had the highest excess burden. He then adds that fossil fuel taxes will raise costs of production of capital goods, whose production is intensive in energy according to US data, and that a strong double dividend is therefore unlikely for the US (Goulder, 1995).

Goulder’s model, however, assumes a perfect labour market, and can therefore not take into account possible gains of lifting labour market constraints to economic activity. Bovenberg and Van der Ploeg (1998) show, with a theoretical model, that under certain conditions an imperfect labour market, with rigid wages causing involuntary employment, could lead to a “triple” dividend (resembling Goulder’s “strong” double dividend) in which social welfare is increased through an increase of environmental welfare, employment, and profits. The two conditions they find are: 1. That labour and is a good substitute for pollution or environmental degradation; 2. That pre-existing pollution taxes have not eroded the potential tax base. The latter is assumed to make achievement of higher environmental benefits costly, specifically if income of a third (fixed) factor (next to labour and environment) is too low to be used to raise additional public revenue, or if this third factor is a better substitute for pollution than labour.

This thesis analyses whether circumstances and a mechanism for a double or triple dividend, as identified by Bovenberg and Van der Ploeg, exists for South Africa, but it does this with a different kind of model (see sections 2.1.3 and 2.1.4 next). Section 2.3 provides further discussion of the relevance of labour market rigidities and labour market policies for the estimation of costs and benefits of environmental taxation or other environmental policies.

Criticism on the neoclassical production function for analysing environmental constraints

Some economists think that one should not use neoclassical or new-Keynesian production functions at all when analysing growth under environmental constraints, for instance from Georgescu-Roegen (Daly, 1997). His argumentation is that neoclassical production functions assume substitutability

⁴³ This approach is often called new Keynesian economics (Heijdra, 2009). A part of new Keynesian economic analysis deals with CGE models to analyse how market distortions or second-best economies have an impact the macro-economy. Some well-known economists whose work is considered to be new-keynesian are G. Mankiw, D. Romer, J. Stiglitz and P. Krugman. For a brief introduction and further reading on second-best economies, see: "Theory of Second Best", International Encyclopedia of the Social Sciences, Encyclopedia.com, <http://www.encyclopedia.com/social-sciences/applied-and-social-sciences-magazines/theory-second-best> (accessed April 6, 2018).

between inputs, such as capital and resources, or between different types of capital, such as natural and man-made capital, without in any way capturing the limits to substitution. With neoclassical production functions therefore, growth could continue, and dematerialize, ad infinitum based on artificial capital. However, in reality there are limits posed by the earth system and the laws of physics, chemistry and biology.

Another criticism expressed by Georgescu-Roegen and others is that neoclassical production functions only take into account priced goods and thus do not measure the role of non-priced goods such as clean air in production. Third, the aggregate form of the production function only measures the world by the model's numéraire, often a volume index unit of GDP, without taking into account what the physical state of an input or factor is (Daly, 1997).⁴⁴ As a consequence, the neoclassical production function is not capable of measuring additions to or losses of GDP due to improvement or degradation of resources and the environment (for instance soil degradation or improvement). (Recall that Huetting sought to solve this issue.)

Robert Solow and Joseph Stiglitz accepted an invitation by Herman Daly to respond to the criticism on the neoclassical production function in a special issue of *Ecological Economics* (1997): They both argue that neoclassical models work in specific circumstances to analyse specific questions for a specific period of time (e.g. 50-60 years), and that until then resources had mostly not been sufficiently important or constraining to model GDP growth and (material) welfare (Solow, 1997; Stiglitz, 1997). They do not claim that the neoclassical production function is a universal (fundamental) description of production. Given this constraint of temporal validity of their models, Solow and Stiglitz think that substitution possibilities between capital and resources exist and should be modelled. Solow furthermore emphasizes that one needs transparent and applicable models to analyse questions of economic growth and environmental scarcity. He thinks that this justifies working with measures like factor shares in CGE modelling.⁴⁵ Stiglitz emphasizes that the usefulness of analysis with CGE models is that they shed light on how policy can make markets perceive economically optimal prices or information about scarcity of resources.

Indeed, Daly's proposal that resources should be constant when added to a neoclassical production function, considering the limits to the earth system (Daly, 1997), might be correct from a fundamental point of view, but does not correspond to the reality of production within a limited time horizon, which only uses a sub-set of all the earth's natural resources. The question should indeed be how realistically production functions can capture substitution of use of limited resources, and whether

⁴⁴ In neoclassical economics, also the "utility" of goods is supposed to be captured by price. This is a criticised concept, for several reasons: Firstly, it is not capable of capturing the "utility" of the "free" economy, meaning non-monetarised exchanges of goods and services and benefiting from free "experiences" such as the aesthetics of a landscape or a view. Secondly, some people argue that it is not capable of capturing the "utility" or quality of software products of recent years, notably the "free" applications (see different viewpoints on this matter by Bodea (1994) and by Derviş and Qureshi (2016)).

⁴⁵ Solow also refers to work which does incorporate the role of environmental amenities in production. A conceptual example of a typical neoclassical model that distinguishes between different environmental inputs is discussed in Appendix E.1, which presents a discussion of the potential for green growth from a neoclassical perspective by Smulders et al. (2014).

Solow's and Stiglitz' assumptions about substitution possibilities might not be too optimistic (Pearce, 1997), especially in the light of developments in the state of the environment and resources since the 1970s. It might exactly be the temporal validity of the neoclassical or new-Keynesian models that might not be very convincing, at least: not anymore.⁴⁶ Daly (1997) correctly points at the fact that the environmental challenges all need to be dealt with in the first half of the 21st century. Presently, 20 years after Daly, Solow and Stiglitz's debate on Georgescu-Roegen's criticism of neoclassical models, scientists take exceptionally strong political positions on environmental questions, while sounding the alarm that there is a great insufficiency of action (Ripple et al., 2017). Three examples:

- Total global marine fish catch has been decreasing since the mid 1990s despite increasing fishing efforts (Ripple et al., 2017), which could be a sign of nearing collapse;
- Vertebrate abundance is at less than half of 1970 nowadays (Ripple et al., 2017) whereas in the case of insects there are reports of regions with insect populations having declined more than 70% since 1992 (Schwägerl, 2016; Vogel, 2017);
- The vast majority of climate change mitigation action scenarios require a peak in global CO₂ emissions between 2020 and 2030 (directly followed by a steep decline) to avoid very dangerous climate change by keeping global post-industrial temperature rise below +2°C (IPCC, 2014). In the meantime, net additions of fossil fuel-based power plants continued in recent years despite increasing renewable power generation, and total fossil-fuel based power generation capacity is foreseen to grow at least until 2040 even when taking into account new policy proposals (IEA, 2017, Ch.6). Fossil fuel-based energy use's role is furthermore expected to remain much larger than that of renewables in growing future energy needs for heat generation and transport (IEA, 2017, Ch.7).

One urgent question therefore is how to model the "time of grace" as Opschoor calls it (1997) in the mentioned special issue of *Ecological Economics* (1997) on Georgescu-Roegen, before physical *and technological* limits reduce not only intertemporal, but also temporal welfare.⁴⁷

Criticism of the neoclassical treatment of technological change

Lack of a representation of physical limits is not the only criticism on neoclassical production functions. Even their capacity to capture the degree of substitution between primary factors and other inputs to production within a limited time frame is far from ideal. Notably for substitution between capital and energy, Ghersi and Hourcade (2006) and Hourcade et al. (2015) argue that neoclassical production functions cannot represent technological change, especially not in the case of anticipated strong technological change that is considered necessary to make energy supply and demand respect climate change mitigation objectives.

⁴⁶ Possibly, the technological progress in energy and material efficiency achieved in the 1980'ies and 1990'ies and its counterpart in political progress in regulating environmental problems from the local (air and water pollution) to the global level (ozone layer) might have fed Solow's and Stiglitz idea at the time that their models had sufficient analytical capacity.

⁴⁷ In other words, the race against the clock which one implicitly finds in the analysis by De Boer and Hueting (2004).

In neoclassical models, elasticities of substitution between factors and other inputs to production are calibrated on historical cost share data. According to Gherzi and Hourcade (2006) there is a gap between the standard neoclassical notion of capital stock measured as the gross operating surplus (GOS) part of value added (VA), and the capital intensity measured by the array of successive capital vintage structures. They point out that the cost share of capital could only represent a technologically meaningful quantity if its price were to reflect its marginal product. They argue that the latter is often not the case for energy technology. They for instance point out that investment choices in energy-use equipment often do not follow rational information about prices (Jaffe and Stavins, 1994). Here one could also add that marginal abatement costs curves are path-dependent (Kesicki, 2012) and that their shape changes with circumstances. Such circumstances could be changes in economic structure, or in relative prices, which implies that the elasticity of substitution between capital and energy cannot be constant. Gherzi and Hourcade (2006) furthermore emphasize that path-dependency of developments in technology and infrastructure also limits future substitution possibilities between factors.

Even if cost share-based estimates of elasticity of substitution between capital and energy did correctly represent past substitution behaviour, Gherzi and Hourcade (2006) doubt that this estimate is useful for describing future price-elastic substitution behaviour between capital and energy. They demonstrate their point by showing the gap between, on the one hand, changes in energy intensity estimates for production and consumption under carbon taxation for CES functions of energy-capital substitution, and, on the other hand, the substitution found in two engineering-based partial-equilibrium (bottom-up, BU) models. The functional form of a CES function is in most cases not capable of capturing the engineering knowledge-based dynamics of substitution between capital and energy. This also leads to different estimates for macro-economic costs and/or benefits of (for instance) carbon pricing (Gherzi and Hourcade, 2006).

Lastly, Gherzi and Hourcade criticize the idea that one could estimate costs and benefits of policies through intertemporal optimisation, assuming either a forward-looking invisible hand of the market like is the case in many neoclassical models, or through an all-knowledgeable central planner who minimises the costs of energy to society as is the case in many partial-equilibrium models. Both approaches under-estimate the costs and benefits from facing or overcoming second-best economies.

As an alternative to model technological change in a macro-economic model, Gherzi and Hourcade propose a methodology based on dual accounting (hybridisation) of data on values and on physical volumes of economic flows, thereby allowing to capture physical intensities or efficiencies of energy use and capital use in production (Gherzi and Hourcade, 2006). The alternative methodology they propose is the basis for the IMACLIM framework, the approach on which the modelling of this thesis relies, and which will be discussed in the next sub-section (2.1.3).

Other aspects of modelling growth and technological change: Investment, consumption and trade

Two last aspects of GDP growth deserve mentioning for a comprehensive treatment of the question of

economic growth under environmental constraints, namely the role of investment in new “clean” capital and the effects of changes in consumption and international trade.

Growth, investment and formation of “clean” capital

That investment in productive capital, especially in technologically advanced capital, and in R&D would necessarily be optimal is far from evident.⁴⁸ For example in a discussion of the role of finance for economic growth with technological change that allows to respects climate change mitigation objectives. For example, several studies show that due to the “shareholder” regime for managing companies of the last 20 years, profits are nowadays directed much less than in the past to re-investment in productive capacities of firms or into R&D, and that as a consequence, productivity gains are diminishing (Hourcade et al., 2015).⁴⁹ There is a large literature on ways to re-direct finance so investment can ignite a new wave of innovation and technological progress, such as risk-reducing guarantees to increase investment in new productive capital, e.g. in renewable energy and for higher energy efficiency (see for instance: Hourcade et al., 2012; Zhengelidze, 2011).

Related to the proposal for measures that stimulate investment in new, clean technologies is the concern that environmental taxation such as carbon taxes negatively affects socially optimal economic growth when there is myopic investment behaviour (see for instance De Bruyn (2013)). The idea is that carbon taxation increases the costs of producing new clean or renewable capital if there is not yet a non-polluting alternative to produce new capital. Installing a price signal for investment to prepare or in parallel to the introduction of a carbon tax is something which could help avoid overly detrimental effects of carbon taxation on productive capital as argued by De Bruyn (2013). Perrissin Fabert (2014) proposes a system for such a price signal for investment that only penalizes investment in polluting capital, namely through a system of carbon credits on central bank loans to public and private banks.

However, the question of investment behaviour is left out of this thesis. Integrating it into the present analysis would require a detailed representation of investors’ decisions, as well as a representation of the financial sector (to model policies dedicated to investment, such as “de-risking”). This is beyond the scope of this PhD.

The role of consumption and trade in structural change

The question of consumption has not yet been very important in the discussion in this chapter so far, while consumers make choices that are critical for society’s impact on the environment. An important question could be how fast households adopt new, environmentally-friendly technology and lifestyles.

⁴⁸ The build-up of experience and an industry to improve production of new technology, e.g. through economies-of-scale.

⁴⁹ Their analysis is partly put into doubt by other economic analysis: Wolf (2015) identifies various other reasons for why companies potentially do not invest in productive assets and save instead. But other analysis is relatively supportive of Hourcade et al.’s analysis. E.g. Chang (2014) also refers to data showing that companies retain less profits in favour of returns to their shareholders. He also blames this lack of re-investment of profits into firms on the short-term shareholder-CEO interaction, leading to neglect of durable investments in company survival. Chang also points out that in recent years profits in finance have been higher than in industrial companies, thereby favouring investment in financial products rather than in productive capacity. Finally, another indication for the real impact of finance on productivity is found in analysis by Borio *et al.* (2015) at the Bank for International Settlements who point at even negative consequences for productivity of non-productive credit booms.

If price signals are required to stimulate either more sustainable behaviour, or more technologically advanced consumption, one could expect that real household income might be negatively affected. If on the other hand changing consumption is only a matter of changing preferences coming from habits, e.g. through peer-to-peer “*learning*”, then the consequences for real income do not need to be negative and might even be positive (e.g. when diet preferences change towards largely vegan diets). Consumption furthermore plays a role in its trade-off with savings, which is important for investment and/or for the current account. In fact, measures to increase savings are also part of the recommendations to improve South Africa’s economic growth prospects discussed by Hausmann (2008) and in the National Development Plan 2030 (National Planning Commission, 2011).

A similar impact on the structure of production can be attributed to changes in trade, meaning in substitution between domestic production and imports, and due to the height and composition of exports. Two policy strategies are proposed through which trade could contribute to a more sustainable economic development for South Africa, being: Improving economic conditions for manufacturing sectors, and ending stimulus for resource-depleting industries (Hausmann, 2008; National Planning Commission, 2011; Winkler et al., 2015). It is therefore relevant to correctly model changes in trade. The model description in Chapter 3 (in particular section 3.2.2) shows how this question is dealt with in this thesis, and scenario results are analysed from the perspective of the interaction between structural change and international trade in Chapter 4.

2.1.3. The IMACLIM framework for modelling technology, energy use and growth

The IMACLIM framework that is used in this PhD thesis and its dual accounting of values and quantities of economic flows is a response to the neoclassical approach of CGE modelling. The framework offers a solution for the weaknesses of the neoclassical production function discussed in section 2.1.2, specifically how to represent medium- to long-term technological change in a macro-economic model. The IMACLIM framework can, thanks to its methodology of accounting for physical quantities, also be considered a step forward for analysing the question of the “race against the clock”, defined in section 2.1.1 above. The current sub-section presents the framework’s general philosophy (its *rationale*), followed by a discussion of two key characteristics: The hybridisation procedure and the integration of Bottom-Up (BU) modelling integration.

The “rationale” of the IMACLIM framework

As discussed above, Gherzi and Hourcade (2006) argue that the smooth mechanisms at play in micro-founded consumption and production functions are ill-suited to represent the complex dynamics that underlie the substitution between energy, capital, labour and other non-energy factors and goods. Gherzi and Hourcade propose the use of engineering (bottom-up) modelling-based approaches in the representation of energy systems. For them, this is the key to a sufficiently detailed macro-economic (top-down) representation of technological change and of the trade-offs between factors and inputs of production for economic analysis of energy and climate policies. To allow for the integration of

bottom-up (BU) approaches within a comprehensive top-down (TD) coverage of the economy they consider it necessary to combine physical quantities and values of flows and stocks in an economy (Gherssi and Hourcade, 2006). As an example, this allows introducing rigidities and asymptotes linked to the vintage structure of capital.

Gherssi and Hourcade's approach of hybridisation and integration of an engineering-based framework in a top-down model is called the IMACLIM framework. The IMACLIM family of models is based on an input-output (I-O) framework, firmly anchored in national accounts data, that forms a macro-economic shell in which partial equilibrium analyses of energy markets can be embedded in a way that is consistent with the general macro-economic equilibrium (Crassous et al., 2006; Ghersi, 2003; Hourcade et al., 2010). Here "equilibrium" is not meant in an economic textbook-sense of perfect market-clearing, defined by profit and utility maximisation of respectively producers and consumers. Instead, it is meant in a more restrictive sense of consistent accounting of economic activity to allow for a proper assessment of the feedbacks between energy and non-energy markets.

The IMACLIM framework exists in two forms: IMACLIM-R models, like IMACLIM-R Monde (Crassous et al., 2006; Hourcade et al., 2010; Waisman et al., 2012), and IMACLIM-S models (Gherssi, 2003, 2015). IMACLIM-R models are *recursive* dynamic, with modules for energy supply and demand that are technologically detailed and that track the vintage structure of the capital stock for energy systems. IMACLIM-S models run a succession of static economic equilibria. Technological change in these equilibria is either informed by exogenously defined dynamics. Or – in the case of change in technology for supply, transformation and end-use of energy – technological dynamics are represented endogenously by reduced forms that simulate BU model behaviour, or by soft-linking with BU models via iterative exchange of variables (Gherssi, 2015).

In IMACLIM-R models, the emphasis tends to be on the evolution of technologies in each sector and its interaction with aggregate GDP growth, whereas IMACLIM-S models tend to focus on socio-economic detail and therefore tend to focus on distributional issues (see for instance: Combet, 2013, 2014; Le Treut, 2017), but this is not a strict separation. In fact, in-between versions exists like in the case of IMACLIM-S Brazil in which soft-coupling with other models allows for some recursive dynamics (Lefevre, 2016).

Hybridisation, capital costs and mark-up pricing

The hybridisation procedure combines macro-economic I-O data as provided by Social Accounting Matrices (SAMs) coming from national bureaus of statistics, with data on quantities and prices of in production, transformation & use of energy coming from energy balances in official energy statistics, though other data sources or estimation methods can be used as well. Data about quantities of energy and user-specific energy price are combined to generate "energy bills" by user, which can be a productive sector or an economic agent in final demand. (Section 3.1.2 explains how energy bills are combined with SAM I-O tables in the hybridisation procedure.)

Hybridisation generates the *technological coefficients* for energy intensity, i.e. the consumption of energy in physical-quantity terms over the output of energy and non-energy sector.⁵⁰ Hybridisation, or dual accounting, helps to distinguish *energy-only* activity of energy sectors, while in the System of National Accounts energy sectors often also include non-energy activities by energy companies (e.g., real estate services and business consultancy). Furthermore, it provides a possibility to introduce more detail on energy use and energy technology than available in SAMs, which might even aggregate energy sectors with non-energy sectors (like refineries and chemical industry).

Furthermore, the use of user-specific energy prices from energy statistics or other data sources allows greater accuracy in the estimation of the relative price impact of energy taxes or of other changes in the cost structure of energy products as compared to another common practice in environmental-economic modelling; Namely, to derive energy prices implicitly from adding environmental satellite accounts without statistical correction of the economic values corresponding to these volumes.

User-specific prices are represented in IMACLIM models by taking into account user-specific product taxes and adjusting average output prices with user-specific margins. This does not imply that profit margins are differentiated by user, but it is a way to take into account differences in cost-structures by user. This non-homogeneity of cost structures by user could also reflect non-homogeneity in the composition of products going from a sector to a user, hidden in I-O data due to aggregation.

Separating capital amortisation costs from net profits (net operating surplus), finally, is another important element of the IMACLIM approach. As Ghersi and Hourcade showed (2006), calibrating a CGE model on capital amortisation costs allows price-elastic substitution between energy and capital to resemble the trade-offs found in bottom-up energy system models closer than if the total value of capital income from I-O data would have been used. Furthermore, using capital amortisation costs allows modelling the future evolution of capital amortisation costs in line with changes in the price of machines, equipment and infrastructural capital (e.g. buildings, or railway infrastructure), and in response to changes that affect these prices (e.g. resource prices). A last advantage of mark-up price-setting is, in theory, that it allows modelling behavioural rules other than profit or utility maximisation, e.g. sticky or non-rational price setting. In IMACLIM models, the standard assumption is that net profit mark-ups are a fixed mark-up rate over the total cost of production.

Different possibilities for BU-TD model coupling

In their paper Ghersi and Hourcade (2006) represent BU model behaviour in their macro framework by estimating a reduced form (envelope) of the BU model. The reduced form gives the physical capital intensity of production (the amortisation of physical capital, also called Consumption of Fixed Capital, CFC), and the energy intensity of production and household consumption under different levels of relative prices. Compared to CES functions, these reduced forms lead to different estimates of the

⁵⁰ Note that IMACLIM South Africa, like all multisectoral CGE models, also generates technological coefficients for intermediate inputs of non-energy products by assuming an index for a sector's output volume.

carbon tax rate required to achieve a given mitigation target, and thus to different impacts on welfare and GDP.

Other approaches to integrate BU-model insights in TD-modelling exist. The main condition for consistently combining two models, also when indirectly with a reduced form, is that there will be “sufficient” convergence of the variables that both models have in common, e.g. energy supply and demand, energy prices, and the amount of energy-related investment. In theory, it is possible to control the consistency between these trajectories for different kinds of coupling of BU and the TD models. Bibas (2015) and Lefevre (2016) distinguish the following types of BU-TD model combinations:

- Fully *integrated* BU-TD models, which act as one model. IMACLIM-R is an example of such a model (Crassous et al., 2006; Hourcade et al., 2010; Waisman et al., 2012);⁵¹
- Fully or partially *linked* BU-TD models, which consist of two models that communicate in one consolidated simulation architecture on an automated and consistent basis – an operation often referred to as “hard coupling”. The SATIM–e-SAGE linked model is an example of this kind of model (Burton et al., 2016; Merven et al., 2014);
- “Soft-coupled” BU-TD models, where communication or exchange of information between BU and TD models is manually organised, and models are run until a set of variables converges, e.g. the IMACLIM-Brazil–MESSAGE linked model (Lefevre, 2016), and a multiregional IMACLIM-S model soft-linked to the POLES and TIAM PanEU BU models (Gherzi, 2015);
- Model combinations without any type of linking, in which trends estimated for technological change or micro-economic behaviour (from a BU model), or for macro-economic behaviour (from a TD model) are applied in the other type of model, e.g. the use of a trend for GDP growth and household income from a CGE model by a BU-model. In this category of model combination the behaviour of either model could also be estimated econometrically in relation to a limited set of variables and translated into a set of equations which approximates the other model’s behaviour endogenously. In that case, one can speak of a “reduced form” representation.

Reduced forms are lighter to use than coupled models. This is an advantage, as coupling (whether hard or soft) is often very time- and resource-demanding. However, in theory it results in combined models that can explore a larger set of assumptions or scenario hypotheses than reduced forms. Nevertheless, using a reduced form demands awareness of the assumptions used in each of the two models, meaning that one has to be aware whether there is consistency between the trajectories of the models used.

In IMACLIM South Africa, for this thesis, a simple version of the fourth category of model combination is applied: Primary and secondary factor intensities of the electricity sector (the before-mentioned technological coefficients) are obtained from BU model runs and are exogenously applied to IMACLIM-ZA. Details of the methodology are provided in Chapter 3 (section 3.1.3). In combining

⁵¹ For a comparison between IMACLIM-R and IMACLIM-S models, see: Bibas (2015), part I., Chapter 5 (p.237).

BU modelling insights into a top-down model I strive for sufficient consistency.⁵²

The condition “sufficient” is added, because the use of information from one model into another model is never perfect. Even when both the BU and the TD model show similar trajectories of shared variables, this does not guarantee that the BU model generates unbiased behaviour for the CGE model: In fact, as most BU models assume a social planner minimizing the overall costs of the energy system over the modelled time-horizon, BU model results likely diverge from the aggregation of individual energy-related decisions made by many economic agents in reality, and on which CGE models are calibrated. Other aspects relevant for the extent to which modelling architectures can be combined are the classifications of sectors, similarity in calibration data, length of simulation periods, and the time-step of interaction between both models. The appropriateness of model combination therefore needs to be assessed on a case-by-case basis, and in connection to the question that the modelling exercise is trying to answer. The impacts of model differences on the conclusions of a study should also be assessed (as it is done in section 6.1.5 in this PhD).⁵³

2.1.4. Modelling GDP growth in the IMACLIM framework

IMACLIM South Africa can be called an accounting-style CGE model. It does not use optimisation or the basic properties of the neoclassical production function to model the change between two macro-economic (technical) equilibria. How IMACLIM-S style models can still generate GDP growth therefore might deserve additional explanation, especially because the neoclassical production function is the fundament for most CGE models. Also, one of the advantages of the neoclassical approach was exactly that it allowed to model equilibrium in long-run steady states thanks to its basic assumptions, something which the classical growth models before were not capable off (Solow, 1987).

To facilitate this discussion about GDP growth this sub-section also introduces a few concepts that are used in the analysis of GDP and employment results in Chapter 4. However, before starting the discussion about growth, a short clarification is required of how “productivity” is defined: see Box 2.

Box 2 Technological coefficients and the definition of productivity

Two definitions of productivity are commonly used: The first is productivity in terms of value added over factor or input volume, and the second is productivity in terms of volume of gross output over factor or input volume (OECD, 2001a). The value added notion is more common, especially regarding labour productivity, where this definition is used in collective wage negotiations (OECD, 2001a) or to analyse the evolution of the share of labour in value-added (ILO and OECD, 2015). Also at an

⁵² Another methodology considered for establishing reduced forms for integrating SATIM insights into IMACLIM-ZA was to develop “reduced forms” on the basis of a large number of SATIM model runs, whose output could be used to econometrically estimate functional forms, which would represent the relative price-input demand-response behaviour of the BU model. In this way, the BU model is synthesized in a “space”, or range, of possible future production technologies (vectors of primary and secondary factor intensities). However, given time constraints this objective had to be abandoned.

⁵³ Either implicitly or explicitly, stand-alone TD (macro-economic) or BU (engineering) models incorporate visions about respectively technological change or economic development. Often the consistency between these assumptions and modelling results is not evaluated, whereas like Ghersi and Hourcade argue (2006) there is a number of reasons to think that they influence each other strongly in the case of an energy transition which is to be achieved as part of climate change mitigation policy.

aggregate level, for instance for decomposition analysis of annual GDP growth, the value-added notion is often preferred because it is easier to aggregate the value-added of multiple sectors than volumes of gross output.

The technological coefficients of IMACLIM-ZA represent factor use over volume of output. This is the inverse of the gross output definition of productivity growth (OECD, 2001a). Furthermore, as the IMACLIM framework allows primary factor prices to evolve differently from primary factors' gross output productivity (i.e., the change in the volume of output over the volume of factor use), the latter does not necessarily equal *value added* productivity growth. Such a deviation between the two for instance happens when there are efficiency gains for intermediate inputs (see the discussion in Box 3). Considering that value-added productivity seems the more commonly used of the two definitions of productivity, it might have been more correct to use "output productivity gains" in this thesis to signify an improvement of primary factor's productivity in terms of technological coefficients. However, for the readability this thesis uses the term "productivity" without the adjective "output". The reader thus has to keep in mind that by productivity in this thesis *gross output* productivity in terms of volume of output is meant, and not *value added* productivity of primary factors.

Another important distinction in vocabulary on productivity made in this thesis is that between Total Factor Productivity (TFP) and multifactor productivity. Officially, both terms can mean the same thing (OECD, 2001a), namely the residual in output growth that cannot be related to the increase in primary factor use. TFP is typically used in neoclassical treatments of GDP growth and is associated with technological change improving the productivity of labour and capital. The OECD however prefers the use of the term "multifactor productivity" – by which KLEM's multifactor productivity is meant⁵⁴ – to signal a certain modesty in the ability to interpret residual output growth, while the term TFP suggests everything is technical progress (OECD, 2001a). OECD argues that KLEMS (and TFP) productivity growth also measure output growth that has other causes than technological progress, for instance: Changes in efficiency, economies of scale, variation in capacity utilisation, and measurement errors. In this thesis, multifactor productivity is used to signal that not only output growth over primary factor use is meant. E.g., I also model output growth over intermediate inputs.

A comparison with the aggregate neoclassical production function of Solow and Swan offers a clear and insightful way to explain how economic growth is accounted for in the IMACLIM framework.⁵⁵ One reason is that the neoclassical production function offers a clear and simple model for growth, which is a useful departure point to explain more complicated economic mechanisms. There are three main differences in how GDP growth is modelled in IMACLIM-ZA in comparison to an aggregate

⁵⁴ KLEMS (Capital, Labour, Energy, Materials Services) multifactor productivity stands for productivity (of value added or volume of gross output) over a quantity index of combined inputs (factors and intermediate inputs) on the basis of a specific method of weighing (for more detail, see OECD (2001a)).

⁵⁵ There is a wide variety of approaches and assumptions for macro-economic modelling. However, besides for the reason given above, a second reason for comparison to the neoclassical production function is that the neoclassical perspective tends to be the standard discourse to discuss economic growth and the functioning of markets for primary factors and thus serves as an intellectual point of reference. It must be added furthermore that the discussion here concerns models with exogenous growth.

neoclassical production function, each of which I explain below.

In brief, the first difference relevant for modelling of GDP growth is that the IMACLIM framework does not assume perfect factor markets and takes into account rigidity in factor pricing, in this thesis specifically rigid wage rates and rigid profit mark-up rates (the impact of imperfect primary factor prices on growth is described next). The second difference with an aggregate neoclassical production function is that IMACLIM models include intermediate inputs in production functions and exogenous change in the intensity of intermediate input use in production. The third difference is that IMACLIM-ZA does not use optimisation and the basic neoclassical property of positive but diminishing returns to primary factor use. At the end of this sub-section I explain how despite this last difference the CGE model of this thesis is still capable of producing macro-economic equilibrium results.

Imperfect primary factor markets and prices

To see the relevance of the first of the three differences for modelling GDP growth, one first needs to have in mind how the neoclassical production function models growth: In a basic neoclassical production function (described by the general equation $Y = F(K,L)$), GDP growth depends first of all on factor endowment (e.g. the capital stock often modelled through a perpetual inventory method based on exogenous saving rates and a depreciation rate⁵⁶; and an exogenous labour force). Secondly, it depends on growth of Total Factor Productivity (TFP), which defines the ratio of value added over factor use, and which is assumed to represent technological change.⁵⁷ Factor prices (meaning factor payments, e.g. the rental rate for capital and the wage rate for labour) are flexible in order to clear factor markets. While primary factors are assumed fully employed (in use) in the neoclassical production function, their use can still change, which leads to changes in GDP: The availability of capital (if not fixed exogenously) can, for example, change after a change in the national saving rate or in foreign investment (in case of a model for an open economy). And, while the availability of labour is usually modelled exogenously, the use of labour can vary if a labour-leisure function is included.

I introduce a thought experiment to support the explanation of how growth is modelled in IMACLIM-ZA: Imagine, to simplify matters, an aggregate neoclassical production function with exogenous capital and labour endowment for primary factors, and without a labour-leisure trade-off. An increase of TFP means that productivity increases at an equal rate for both primary factors. In case of fixed primary factor endowment and use, marginal productivity will increase at the rate of TFP growth, and by consequence, primary factors' prices too.⁵⁸ When factors' productivity and prices change at the same rate, the price of primary factors' "productivity" does not change. By the latter I mean that the volume (of baskets) of goods that can be purchased with the rewards (payments) for the amount of

⁵⁶ An aggregate capital stock can be estimated with the perpetual inventory method on the basis of an estimated or assumed depreciation rate (OECD, 2009). In IMACLIM-ZA a similar method is used, though the capital stock is related indirectly to the amount of investment (linked to savings through net international borrowing or lending, with amortisation of capital linking the two, see section 3.4).

⁵⁷ This thesis presents a model with exogenous technological change. However, many models exist with endogenous technological change.

⁵⁸ In most neoclassical models however, the change in factor productivity will change the labour-supply leisure curve and the change in marginal productivity might therefore not be identical to the change in TFP, with factor endowment changing too.

primary factor contributions to production of an average volume unit of goods remains the same.

I now change the imaginary model and introduce a labour-leisure function. (The capital stock is still exogenously fixed.) In this case, TFP causes real wages to grow, which in a neoclassical model normally motivates households to work more. The rule of positive but diminishing returns to factor additions however means that these labour additions will be less productive than previously used labour, and wages therefore increase less than TFP to reflect that *marginal* productivity of labour increases less as well. What happens, in fact, is that the average price of labour's "productivity" decreases, justifying the increase in labour supply.

In a next step I introduce real wage rigidity, meaning that next to being indexed on productivity, wages are also constant in terms of the basket of goods that can be bought with labour income. If in this situation a labour tax is introduced, then like in the example of an increase of TFP equilibrium marginal productivity increases, however this time without productivity increasing. In other words, the price of labour's "productivity" increases, and the neoclassical rule of positive but diminishing returns requires that its marginal productivity increases as well – which now causes a decrease in the use of labour – i.e., unemployment.

This last example brings us close to the situation in IMACLIM-ZA and most other national IMACLIM models. Like in many CGE models, labour is modelled with an exogenously fixed endowment, and similar to the use of a labour-leisure function, the use of a wage curve (Blanchflower and Oswald, 1995) allows labour not to be fully employed. However, factor primary prices – i.e. the rates at which factors' contributions to production are paid – are imperfect, meaning that they do not clear factor markets and even more, that they do not necessarily evolve in the same way as factors' average productivity, as they do not need to reflect the factors' marginal productivity. For example, to set the price of labour, IMACLIM models tend to use a wage curve to model rigid wage-setting behaviour, while rigidity in capital rents is created through the use of rigid profit mark-up rates (see section 3.2.5).

However, the mathematical requirement of a (mathematical) macro-economic equilibrium implies that average primary factor productivity (in value added terms, see Box 2) still equals average primary factor "payments" (primary factor income plus government income coming from indirect taxes). This is obliged by the basic market balances for quantities and values of goods that are part of the general equilibrium (see Box 3). As a consequence, one factor being priced above its marginal productivity must be compensated by another factor being priced below its marginal productivity, all other things equal.⁵⁹ What therefore matters for growth is the rate of output over a *combination* of factors and other inputs, rather than considering factors individually.

Imagine now that, for whatever reason (for example exogenous changes in economic negotiation

⁵⁹ In other words, factor pricing that is above a factor's marginal productivity can be considered an excess burden which can be compensated by a negative excess burden by pricing another factor below its marginal productivity, in a given technological combination.

power), the owners or suppliers of one of the primary factors increase their primary factors' price, meaning the volume of products (or supply) that should be paid as a reward for primary factors' contributions to production. Unless other primary factors would reduce their price, this will lead to a decrease in output and to more primary factor under-utilisation. This decrease is stronger in models with rigidities like IMACLIM, than in models with a lot of flexibility (all other things remaining equal). While this mechanism is fairly clear for neoclassical or new-Keynesian models, it might deserve further explanation for a non-neoclassical model, which will be provided towards the end of this sub-section.

In conclusion, what matters in the IMACLIM framework is not necessarily the price of individual factors, but the change in total primary factor payments as part of production costs, relative to the change in output productivity. The consequence of divergence in the evolution of total primary factor income per unit of production relative to multifactor output productivity is that the average cost of production, and thus the average price of goods supplied to the South African economy, changes.⁶⁰ When this happens, a new macro-economic equilibrium is found in which output and GDP have changed. The demand-side perspective of the same story is that a change in the (real) average price affects domestic purchasing power and the international competitiveness of South African products alike, and thus changes final demand for domestic output and GDP.

Box 3 Productivity, primary factor prices, and divergence between gross output and value added productivity

As mentioned in the text above, mathematical equilibrium in a CGE requires that average factor productivity (in value added terms, see Box 2) equals the average purchasing power of factor “rewards” (payments). This is an evidence in CGE modelling, but might need some clarification for a non-economist audience. Clarifying this for IMACLIM-ZA (and similar non-neoclassical, non-optimisation models) in this Box also sheds light on how cost reductions lead to GDP growth, and what other causes for GDP growth could be hidden in TFP of an aggregate production function.

First of all, one has to bring into mind that CGE models assume equilibrium in the markets for goods & services. IMACLIM models are no exception to this rule: Equilibrium in the markets for goods & services means that all goods produced and imported (together: total resources or supply) fulfil domestic intermediate and final demand plus demand for exports (together: total uses or demand). This is shown in *Eq.a* for a sector and product *i*, with final demand consisting of household (FC) and government (G) final consumption and investment (I):⁶¹

$$Y_i + M_i = IC_i + FC_i + G_i + I_i + X_i \tag{a}$$

⁶⁰ To talk about goods & services supplied to the South African economy is more relevant than talking about goods produced, because goods & services supplied to the economy include imports, which are relevant because it is the weighted average price of domestic and imported goods which determines the average price of goods that can be purchased in South Africa – and not only the price of domestically produced goods. However, the sign of the change in the average price per product supplied to the South African economy is normally the same as that of the change in the average price per product produced, because the price elasticity for the trade-off between imported and domestic goods is usually positive (Dimaran et al., 2002).

⁶¹ The naming of variables in this box uses the same naming as used in the beginning of Chapter 3 for the model overview (section 3.1.1).

Through the supply of goods primary income is earned. It consists of: value added (VA_i) plus indirect taxes (product taxes for sales of product i to user j , $TaxPr_{ij}$). Primary income also equates to the total value of Y_i and M_i , sold at average end-user price $\langle pUse_i \rangle$, minus the costs for imports, $M_i * pM_i$, and intermediate consumption, $IC_i * pIC_i$ (Eq.b):

$$VA + TaxPr_{ij} = (Y_i + M_i) * \langle pUse_i \rangle - M_i * pM_i - IC_i * pIC_i \quad (b)$$

The focus of macro-economics is on economic value, because value has the convenient characteristic that it offers a way to aggregate non-homogenous goods. However, the purpose of value is to refer to a volume of goods & services, or more precisely: the volume of a basket of goods & services. What this says, is that income represents the possibility to acquire a physical volume of (baskets of) goods & services. This can be seen when one combines Eq.a and b to obtain (Eq.c):

$$VA + TaxPr_{ij} = (IC_i + FC_i + G_i + I_i + X_i) * \langle pUse_i \rangle - M_i * pM_i - IC_i * pIC_i \quad (c)$$

Replacing average end-user price $\langle pUse_i \rangle$ in Eq.c by user-specific prices gives (Eq.d):

$$VA + TaxPr_{ij} = IC_i * pIC_i + FC_i * pFC_i + G_i * pG_i + I_i * pI_i + X_i * pX_i - M_i * pM_i - IC_i * pIC_i \quad (d)$$

The elimination of $IC_i * pIC_i$ gives (Eq.e):

$$VA_i + TaxPr_{ij} = FC_i * pFC_i + G_i * pG_i + I_i * pI_i + X_i * pX_i - M_i * pM_i \quad (e)$$

Of course, aggregating Eq.(e) gives two standard definitions for the measurement of GDP (Eq.f): namely the income approach (left-side of Eq.f), and by measurement of final demand (right-side):

$$GDP = \sum_i (VA_i + TaxPr_{ij}) = \sum_i (FC_i * pFC_i + G_i * pG_i + I_i * pI_i + X_i * pX_i - M_i * pM_i) \quad (f)$$

A similar aggregation is possible for Eq.b, and if one additionally expresses GDP as a primary factor's *value-added* productivity, meaning: relative to the volume of a factor's use in production, this gives (here shown for labour, L) (Eq.g):

$$GDP / L = \sum_i (VA_i + TaxPr_{ij}) / L = \sum_i [(Y_i + M_i) * \langle pUse_i \rangle - M_i * pM_i - IC_i * pIC_i] / L \quad (g)$$

From Eq.g it should be clear that GDP per worker (the most common definition of labour productivity, see **Box 2**), as an example of primary factor productivity, is equal to the average income ($VA + TaxPr$) per primary factor unit, and that this corresponds to the (average) amount of domestic production minus imports and intermediate consumption per primary factor unit (here: labour). Also, Eq.g shows that GDP per worker does not need to evolve in the same way as *gross output* labour productivity, which is Y/L (the same holds for GDP and output Y over capital or any other input): Gains in Y/L cause an increase in GDP/L – all other things equal – but it should be clear that other changes can also increase GDP per worker: The latter, growth of *value-added* labour productivity, which is equivalent to TFP in a neoclassical model with exogenous labour endowment, can also stem from an increase of Y and/or M over L , and from a reduction of M , IC relative to the volumes Y and to L , or from a reduction of pM , and/or pIC – i.e., import substitution, efficiency gains in intermediate inputs, and average reductions of prices of imports or intermediate inputs.

The role of intermediate input efficiency gains for GDP growth

The second difference between the IMACLIM framework and the aggregate the neoclassical production function is that the former takes into account intermediate inputs in the costs of production.

Inclusion of intermediate inputs is however not a unique feature of IMACLIM. Many neoclassical models also take intermediate inputs into account: Intermediate inputs can be added to an economy-wide aggregate production function as an explanatory factor for aggregate output growth over factor use, in the same way as other elements have been added to the neoclassical production function in the past included, human capital or energy efficiency for example, see a discussion by Baptist and Hepburn (2013).^{62,63} In the case of multisectoral neoclassical CGE models, contain a matrix for intermediate inputs (α) in sectoral production functions (typically, for i sectors, in the form of: $Y = \sum_i F_i(K_i, L_i, \alpha_i)$).

Neoclassical CGE models mostly model them as a constant ratio to output volume (e.g. see for instance Dervis et al., 1982). However, a feature that is rather rare in these models, and part of IMACLIM-ZA, is the use of exogenous *efficiency gains* in intermediate inputs.⁶⁴ A change in the use of, or in the prices of intermediate inputs has an impact on production costs, and therefore on total prices: For instance, if intermediate inputs' real (GDP price index deflated) prices decrease, or if the efficiency of their use increases, this translates into cost reductions, and thus into GDP growth (see Box 3).⁶⁵ When technological coefficients for use of intermediate inputs over output decrease, all other things equal, GDP should grow. This situation would be represented by an average reduction of IC_i over Y in Eq.(g) in Box 2 above.⁶⁶

This, like imperfect pricing of primary factors, affects production costs, and thus leads to an impact on GDP through *cost reductions*. This cost-reduction induced GDP growth in IMACLIM-ZA adds to growth from volume-based productivity growth of primary factors. The inclusion of intermediate inputs thus allows for a more explicit treatment of GDP growth and technological change, rather than the idea that all growth additional to growth of factor use is *disembodied* technological change, as pretended by the concept of TFP used in aggregate neoclassical production functions (see OECD, 2001a).

The role of cost reductions for GDP growth

In fact, efficiency gains in intermediate inputs are only one aspect which can add growth compared to growth by primary factor gross output productivity gains only. Eq. g in Box 2 showed that a decrease in imports per worker, and of (average) import prices (pM) and of (average) prices of intermediate inputs (pIC) should also lead to GDP growth per worker.

It is important to explore the meaning of Eq. g a little further, as not all increase of GDP per worker will lead to an increasing GDP: In theory, one could imagine (some exogenous) increase of primary

⁶² Note that all these elements reduce the “black box” of TFP.

⁶³ An example provided by Smulders et al. (2014) considers a neoclassical production function in which Resources (R) have been added as an input: See Appendix E.1 for a discussion.

⁶⁴ An example of a multisectoral CGE model with neoclassical production functions that does include efficiency gains for intermediate inputs is the applied multisectoral model for South Africa by Alton et al. (2014), which was developed on the basis of the Dervis et al.'s CGE modelling framework (1982).

⁶⁵ A demonstration of how intermediate input efficiency results in GDP growth is presented in Appendix E.3.

⁶⁶ With the price structure of IMACLIM-ZA of constant mark-up rates, this intensity-reduction leads to price reductions of goods, therefore also of pIC_i , and therefore to even more GDP growth.

factor prices (with primary factor productivity unchanged), and which increases $pUse_i$ without that it necessarily increases pIC_i to the same extent. This clearly increases GDP per worker, but obviously also unit prices of goods and services. In this case, growth in GDP per worker does not lead to GDP growth, whereas growth of GDP per worker through a reduction of intermediate input intensity of production does. The reason is that the latter leads to cost reductions for domestic output, whereas the former does not (relative to the price of primary factors).

The explanation for this result goes however beyond Eq.g in Box 2 and depends on wider general equilibrium impacts of changes in relative prices between primary and secondary factors (intermediate inputs) and foreign prices. Furthermore, Box 2 did not clarify how a change in primary factor prices relative to primary factor productivity and its impact on GDP can be modelled (in a technical sense) in a CGE model that does not use standard neoclassical properties or optimisation. Both these two questions are the topic of the next (and last) part of this sub-section.

Modelling growth in a non-optimisation model that does not use the basic neoclassical properties

The third difference between IMACLIM and not only the neoclassical production function, but in fact all neoclassical models are that IMACLIM does not assume perfect factor markets, and neither maximisation of profits and welfare. In theory, abandoning optimisation plus the rule of positive but diminishing returns to factor use seems to take away the direction for model solution that the neoclassical production function provided as an improvement of the instable classical growth models (Solow, 1987). However, the IMACLIM framework obtains similar impacts on GDP as the aggregate neoclassical production function in case primary factor prices increase relative to factor productivity.⁶⁷ A justified question therefore is how a more descriptive model of economic flows and quantities – without perfect factor markets, optimisation, and the basic neoclassical property of positive but diminishing returns – could be capable of finding an equilibrium and one that shows realistic consequences for GDP at an aggregate level when factor prices change?

For neoclassical and new-Keynesian production functions, the consequences for GDP of an exogenous increase of primary factor prices relative to primary factor productivity (all other things equal: For example: increases of taxes, or increased bargaining power of an economic agent) are quite clear and are obtained thanks to optimisation and the neoclassical basic rule of positive but diminishing returns to primary factor use. The discussion here shows that an accounting-style CGE model can obtain similar results if there are multiple sectors and if there is a possibility to express consumer preferences that reflect higher incomes, i.e. the improvement of purchasing power of a part of economic actors.

This is shown with the use of a few illustrations of plausible economic behavioural responses to

⁶⁷ By increased primary factor prices I mean increases of primary factor prices in terms of purchasing power, *or*: the average volume of (baskets of) goods and services that can be bought with the primary income (the rewards) per average unit of primary factor's contribution to production (including tax income). This could be called a "real" increase of the average price of primary factors relative to their productivity, as it concerns an increase in terms of the volume of goods and services that it represents. However, to avoid confusion with GDP or consumer price-index deflated prices, I simply call it an increase of primary factor prices relative to average factor (gross output) productivity, taking it for given that it concerns an increase in "real" terms.

changes in the average cost of production. The illustrations that follow furthermore show that growth impacts of the mentioned price changes are not only caused through international competitiveness, but also by domestic changes in purchasing power. Though I only discuss the specific case of increased primary factor prices, the illustrations given here are also valid for other causes of increased real average prices, e.g. a relative increase of import prices.

Before treating the case of multisectoral, non-neoclassical CGE models I first look at what happens in an *aggregate* and *open* economy accounting-style CGE model: In an aggregate open economy, an exogenous increase in primary factor prices that is not accompanied by an equal change in productivity can be modelled as a “real” increase in unit primary factor income, because it can be represented as a demand (by those who provide the primary factors of production) for higher payments (rewards) expressed in terms of the price of foreign goods. To see this, bring in mind that in an open economy the cost structure of supply⁶⁸ ultimately (when disregarding double-counting through the matrix for intermediate consumption) consists of costs for imports and of value added.⁶⁹ If factor prices (factors’ payment rates) increase in “real terms” this thus has to be relative to import prices, because all other values consist of primary factor payments – whose ratios are constant if there is no change in the rate of imports in total supply. An increase of factor prices relative to productivity here also means (see Box 5 in Chapter 4) an increase of domestic prices relative to foreign prices, and of the *real effective exchange rate* (REER), all other things equal – in particular that the current account and the broad capital account are constant over domestic GDP.⁷⁰ The increase in primary factor prices thus causes a reduction of international competitiveness. (The functioning of the REER in IMACLIM-ZA is discussed into more detail in Box 5 in section 4.2.)

However, the comparison to foreign prices is not obligatory. Consequences for GDP of changes in primary factor prices can also be modelled in non-neoclassical CGE model for a *closed* economy. However, conditional on either the inclusion of intermediate inputs, or on having *multiple* sectors with differentiation in consumer preferences between products:⁷¹

- In the first case, the inclusion of intermediate inputs, allows the accounting-style model to change the ratio between on the one hand intermediate consumption, and on the other hand value added (on the resources-side of the I-O table), and in parallel to value added on the uses-

⁶⁸ The cost structure of supply can also be called the cost structure of total resources in I-O modelling terminology. Supply or total resources consist of domestic production plus imports, and its cost structure is therefore not the same as that of domestic production. Something to keep in mind once results of scenario analysis are analysed in Chapter 4 is that also a change in the ratio of imports over domestic production can change the cost structure of supply.

⁶⁹ That all resources in ultimo consist of costs for imports and of primary income is clearest in the (theoretical) case that all products are either purely imported or purely extracted with only use of domestic factors (the latter implies that the sector’s resources consist entirely of domestic value added). Products that are produced with a mix of intermediate inputs of the other two sectors can be said to add value to imported value and to other domestic value added (including indirect taxes). When aggregating an I-O table for an entire economy, this becomes clear by the fact that at the aggregate level the value of intermediate inputs can be eliminated without creating disequilibrium, leaving the resources of an economy’s production to consist only of imports and value added (including indirect taxes).

⁷⁰ If the *market exchange rate* would be allowed to devalue however, the REER could remain constant – this depends on changes on the broad capital account and in the current account.

⁷¹ When neither of these two differences between sectors is present, the model will behave as an aggregate production function.

side: final consumption.⁷² Increasing the ratio between value added and intermediate consumption in an exogenous way when productivity does not change (decreases relative to primary factor prices) means that more output goes to final consumption and less to intermediary consumption. If the production function furthermore allows no or only little substitution of IC by (under-utilised) primary factors, then total output and GDP will have to decrease. In turn, this reduces primary factor use. The result is that a smaller number of providers of primary factors (capital owners or workers) earns a higher average income, while total average income and total income (and output) decrease;

- In the second case, if the model does not take into account intermediary consumption, but does include differences in consumer preferences for different products, a “real” price increase of primary factors without an equivalent increase in productivity means that a smaller amount of owners/providers of primary factors consumes on average a higher amount of the most preferred products. This implies that other owners/providers of primary factors have to accept that there are less preferred products available to them. However, because these products are “preferred” in consumption, all consumers will prefer to increase their budget and pay a higher price for these products. This comes at the expense of consumption of other products, meaning that output and the use of primary factors in these other sectors decreases. In total, less other products will be produced, and for the entire population, average income decreases.

Another way of presenting the last two cases is saying that consumption to be more concentrated in high valued or prioritised goods, which means reducing the use of factors producing low added value, or of sectors producing low valued output. In fact, the concept of increasing “real” primary factor prices means that those who increase these real factor prices have (obtained) a negotiation position that allows them to do re-define the volume of goods and services that they earn in exchange for their contributions to production. (See Appendix E.2 for a numerical illustration.)

The analysis could be extended by considering what happens if the increase in factor prices translates into higher prices in other sectors through intermediate consumption, e.g. when the products of sectors in which factor prices increase are also prioritised in intermediate consumption. Or vice versa, when import prices cause real prices to increase (at constant real factor prices) through increased import costs. Evidently, this situation could be imagined to be the case for energy carriers (electricity or fuels) in the short to medium term. In the open economy case the analysis could be extended by looking at what happens if import prices of non-substitutable imports increase.

A caveat is that behavioural responses to changes in primary factor and consumer prices can be complex and that there can be diverse feedbacks on output productivity through structural change. For instance, when people who earn income in a prioritised sector already have fairly above-average

⁷² The parallel change in the ratio of value added and the value of final consumption to the value of intermediate consumption is obliged by the general equilibrium rule that income equates final demand in a closed economy.

incomes (as e.g. is the case in crude oil extraction and refineries, at least in South Africa) spend additional income on products with low output productivity (low efficiency) like luxury goods (recall that GDP does not measure quality of goods or consumption) – the volume of output would decrease even stronger than just described. On the contrary, if income from people in non-prioritised sectors was mainly spent on consumption of luxury goods, and if this income and this type of consumption would be reduced in favour of income in prioritised sectors being spend on more efficiently produced goods, then the opposite effect might be observed, and an increase of real wage might lead to an increase in real GDP through this mechanism of structural change following on changes in income distribution.

The conclusion is that a non-neoclassical, multi-sectoral model without optimisation but with differentiation in consumer preferences – i.e., good-specific price and income elasticities – can model the impacts of an increase (or decrease) of primary factor prices relative to primary factor productivity and obtain a decrease (or increase) of *real* GDP as a consequence. The latter is a result similar to what the aggregate neoclassical production function obtains.

2.2. Intermezzo: Modelling technological change in developing economies

One of the most common notions on development is that of *convergence* in per capita GDP between developing and developed economies. A justified question is whether economic growth and, more specifically, productivity growth in South Africa should be modelled such that it reflects the idea of convergence. The discussion in this section will first show that this concept is not helpful to model the development of one specific country. This discussion will then motivate the choice to model economic growth for South Africa on the basis of exogenous assumptions for technological change.

The usefulness of convergence for applied economic modelling

The idea of convergence originated when economists applied the Solow-Swan growth model to developing economies and to inter-country comparison (Easterly, 2001, Ch.3). Their assumption was that the same technology should in principle be equally available around the world. Potential productivity gains from modernisation of technology should therefore be bigger in developing economies than in developed economies, and the neoclassical assumption of perfect markets then predicts that returns on investment would be bigger too. The rate of investment should, as a consequence, also be higher in developing countries, and finally the rate of GDP growth too. Due to the assumption of constant returns to scale the same can be shown for *per capita* GDP growth. Different studies then showed, in response, that there was no convergence between countries (Mankiw et al., 1992), and one study actually shows that over a century (from 1870 to 1990) national economies have diverged in terms of per capita GDP (Pritchett, 1997).⁷³ Observed rates of return on investment and rates of investment do not confirm the idea of convergence either (Easterly, 2001). Mankiw,

⁷³ Some still defend the idea of convergence. For instance Sala-i-Martin (2006) shows that income inequality decreased between 1970 and 2000, but this is on the basis of global per person income distribution, and not for cross-country comparison.

Romer and Weil (1992) therefore try to improve the neoclassical growth model by adding human capital. In doing-so they find cross-country convergence. But, the model with human capital does not stand the empirical test: Predicted rates of return on capital and human capital, as well as investment rates do not correspond to observed cross-country differences in labour productivity (Banerjee and Duflo, 2005). The assumption that growth of total factor productivity is homogenous everywhere, or that technology is equally available everywhere cannot be supported, neither that there is a homogenous market for capital (Banerjee and Duflo, 2005; Easterly, 2001). Banerjee and Duflo point at data showing that investment options with high returns are available in developing economies, but that there is an enormous variation in rates of returns within countries. They add that the same is true for developing economies. To explain the misallocation of capital they point at various obstacles to the functioning of the capital market, for instance: too little government protection of firms; too much government intervention; problems with property rights or law enforcement; credit constraints; failing insurance markets; local externalities such as herd behaviour of people; family decision making; and possibly also negative impacts of poverty on decision making (Banerjee and Duflo, 2005). Easterly focusses on the role of a lack of availability of technology and the right incentives for people to develop businesses (Easterly, 2001).

The criticism on the application of the neoclassical growth model to developing economies does not readily translate into an alternative simple model for economic growth. Banerjee and Duflo (2005) develop the first elements for a model with a disaggregate production function, but they do not come up with a final proposal. Also, their model does not offer a solution for representing the question of how developing economies adopt new technology.

Alternative views on technological progress in developing countries

A question therefore is how the process of adoption of new technology works, and whether it could be modelled? In summary, the development or the adoption of new technology by developing countries seems not to be easily explainable or reducible to a few parameters. Situations seem to differ by country, and sectoral specificities and government policy seem to play a big role. Some hold the view that governments create too many obstructions for entrepreneurs, while others hold the view that active government policies are necessary for developing countries to obtain access to modern technologies of production. An elaboration of the latter point shows the complexities of the process of adoption of new technology in developing economies.

On the side of economists that think that enabling entrepreneurs is more important for development one could place Easterly (2001).⁷⁴ He makes his point by discussing the example of the Bangladesh garment industry, which profited first of all from a coincidence – the installation of a South Korean garment company in Bangladesh following US import restrictions on garments from South Korea –, but then followed up on this event with a clever combination of protectionist and free-market policies

⁷⁴ Easterly does not adhere to the view of completely free markets and zero government intervention, and holds the view that governments need to protect *niche* markets (Easterly, 2001).

that enabled Bangladeshi entrepreneurs to grow their garment industry. This idea of acquiring technological know-how and the accompanying skills to set-off a perpetual cycle of productivity increase resembles the hypothesis of disruptive innovation, about which Hart and Christensen (2002) argue that it is actually more likely to take place in a developing rather than in a developed economy, because they expect that in the latter country established companies, markets and consumer tastes have little appetite for new or more efficiently produced products. They use the example of the development of the electronics and motorized vehicle industry in Japan, which initially produced lower quality goods than American or Western European companies, but at lower costs.

On the side of people who hold the view that state-driven action is more important to start technological development in developing countries one could place the hypotheses of “Late Industrialization” by Amsden (Amsden, 1987; Seguino, 2014). On the basis of the example of the state-led economic development of South Korea they explain how South Korean companies gradually developed know-how and the necessary human resources (skills) that allowed Korean industries to increase their productivity and grow. H.J. Chang provides empirical analysis showing that periods and countries with stronger government intervention and industrial policy often led to better growth (Chang, 2006, 2011). Also research by Mazzucato (2015) shows that markets and companies in which innovations mature very often initially benefited from active government policy.

Before concluding this section, it is worth discussing one last notion about development, growth *and* the environment, which will inform the definition of the reference projection in section 3.6. It concerns the idea that developing economies could develop into post-industrial societies and skip the phase of industrialisation. Economist H.J. Chang thinks that this is very unrealistic: He points out that there are no real post-industrial societies, pointing out that the importance of manufacturing did not decrease much in developed economies (Chang, 2014). The reduction of the share of manufacturing in developed economies’ total value added (VA) can largely be explained from decreasing relative prices thanks to productivity gains, and much less from a reduction in the volume of output: If one were to calculate the share of manufacturing’s VA in constant prices, its share only decreased by 10% in Germany, France and Italy for a period covering the last decade of the 20th century and the first of the 21st century (Chang, 2014, Ch.7). In Finland, Norway, the US, and Switzerland it would even have risen. Furthermore, a part of the change in industries’ share in VA can be attributed to industrial firms outsourcing internal services, and thus also the value added associated with them.

Conclusion on modelling growth and development

The conclusion might therefore be that regarding the adoption of new technology and technological progress in a developing economy, especially a small open economy like South Africa, it is safer not to consider technological progress a given fact, as suggested by the neoclassical growth model. The complex mechanisms that could explain technological development seem only weakly related to prices and returns on investment. Developing a new model for this process is not the objective of this thesis.

As a solution, the choice is made to “exogenize” technological change for a reference scenario; including assumptions about change in productivity of factors of production (see section 3.6 below). The approach is in this sense similar to modelling technological change in regard of future energy supply and demand, as discussed just before. The only difference is that no Bottom Up models have been identified that could inform the technological change of economic sectors from the perspective of general technological progress. In theory, consulting sectoral experts could offer a solution, just like scenario building. In this thesis, the choice has been made to use a coherent set of assumptions is used to construct a realistic reference projection (see section 3.6).

2.3. A second-best labour market model with skill differentiation

Due to its highly problematic character any policy in South Africa needs to be evaluated, and possibly even designed, for its impact on the labour market. For such policy analysis to make sense it is important to capture the actual characteristics of the South African labour market. As discussed in Chapter 1, the South African labour market is characterised by a very high rate of unemployment, and its unemployment can hardly be considered voluntary (StatsSA, 2014a). Another important feature of the South African labour market is that the country’s economic development is hampered by a “skill mismatch”, more precisely: a lack of high skilled labour and of skills in less skilled labour (Daniels, 2007; Hausmann, 2008). One of the causes might be a strong gap in the quality of education, which is insufficient for the majority of South Africa’s population (Spaull, 2013).

In the first sub-section I discuss motivations and existing proposals for modelling second-best labour market features, especially wage-setting behaviour. The discussion continues in the next sub-section with a treatment of different proposals for models that deal with skills of labour. The topic of informal labour will also be briefly discussed. This section ends with a general summary of how the South African labour market will be modelled in this thesis. The full labour market model is discussed in the next chapter, in section 3.3.

2.3.1. Modelling labour market rigidities in wage-setting

Capturing second-best features of labour markets is also important for the analysis of climate policies. Babiker and Eckhaus (2007) and Guivarch *et al.* (2011) find significantly different impacts of climate policies on GDP between economic models that take into account labour market rigidities and models that do not. Both studies highlight the need to include these rigidities in energy-economy-environment models to better capture the costs of energy transition policies, and also to signal the need for accompanying policies in this area. Guivarch *et al.* also recognise that assuming a first-best labour market eliminates the possibility of finding win-win situations by replacing one economic constraint (in the labour market) by another constraint (on fossil fuel use). The same point is made by Smulders *et al.* (2014) and Gherzi and Hourcade (2006).

To model wage-setting under second-best conditions, a typical solution is to incorporate different

types of second-best economic behaviour that could explain deviations from market-clearing wage setting, and which would relate the wage rate and labour supply to other variables or parameters in the model. (I assume that demand for labour follows from production functions, given a set of relative prices for all factors and other inputs to production.) An alternative approach is to directly apply an econometrically estimated empirical relationship between wages and other variables or parameters of the CGE model without trying to explain this relationship theoretically. I motivate here why the latter solution has been chosen. To do so, I start by discussing the options for theoretical models of unemployment and second-best market clearing in the labour market.

Within the field of CGE modelling early models based their description of unemployment on an econometrically observed negative correlation between aggregate unemployment and the increase of nominal wages (Phillips, 1958). The suggestion was that nominal wages increase once unemployment falls below a natural rate, and that nominal wages decrease once unemployment gets above this natural rate. Others found a similar relationship between unemployment and price inflation (Romer, 2012): The assumption was made that price inflation and unemployment were negatively related and that this relationship could be used in policy making. But, by the end of the 1960s and in the 1970s a period of “stagflation” – a simultaneous increase of inflation and unemployment – meant the end of the conviction that the Phillips curve correctly explained unemployment.

As a response to the break-down of the Phillips curve, alternative approaches were developed to model unemployment and wage-setting. Some models tried to improve the model of the Phillips curve, for instance by assuming expected (future) inflation to determine an *augmented Phillips curve* (Romer, 2012), or even more complex treatments including the role of information on inflation (Mankiw and Reis, 2002). Other models assume that monetary policy has little to no role in the labour market, and seek to explain more structural or incentive-based reasons for shifts in the natural unemployment rate or for wages to deviate from market-clearing wage-setting (see e.g. a discussion of the field by Phelps, 1992). Fields provides an overview of such non-first best labour market models and distinguishes three categories (Fields, 2005):

- Institutional wage setting: Other forces than profit maximisation by firms or utility maximisation by households are considered to determine wage setting and cause above market-clearing wages. Models exist that treat the role of minimum wages, trade unions, public sector pay policies, multinational corporations and labour laws;
- Efficiency wage models: In these models firms are considered to offer above market-clearing wages for various reasons. Firstly, because higher pay leads to better motivated and more productive employees, secondly, because higher wages have other impacts on employee behaviour and thus on productivity: for instance a healthier life, reduced risk of shirking,

lower absenteeism, etc.;⁷⁵

- Supply-side models: These models build on the reasoning that the unemployed demand above market-clearing wages for rather opportunistic reason to have the chance to earn more once employed.

The above models in theory offer the possibility to include a variety of second-best conditions in the labour market, but their calibration on South African data is largely out of scope for this thesis.⁷⁶ The focus is on the analysis of carbon tax revenue recycling. From this perspective it is sufficient to rely on an empirically supported relationship between unemployment and wages.

In fact, availability of micro-economic data in recent decades allowed for the estimation of such an “empirical law” on the relation between wages and unemployment: the wage curve. It finds that there is a negative long-term relation between real wage and unemployment with an elasticity of about -0.1 (Blanchflower and Oswald, 2005; Nijkamp and Poot, 2005).⁷⁷ This relationship has been found to hold for 40 countries, despite quite different labour market conditions. The wage curve of Blanchflower and Oswald is compatible with several of the previously proposed labour market models, such as the union bargaining model and the efficiency wage model (Blanchflower and Oswald, 1995).⁷⁸ An advantage of using the wage curve is that estimates for South Africa are available (Kingdon and Knight, 2006).

2.3.2. On modelling of multiple levels of skill of labour

To analyse the impacts of a skill shortage on the South African economy, and how it might add to the costs of a carbon tax, it is necessary to characterize the factor “labour” by its level of skill. Another question this thesis tries to answer is whether it is worth investing in speeding up educational improvement. A model for supply and demand for skills of labour is therefore necessary. In this subsection, I summarize what knowledge and views currently exist to model the dynamics of the labour market by level of skill. I first discuss human capital models and conclude that they seem unsuited for the present study. Next, I discuss how segmented labour market models could be used instead.

Human capital models

Fields (2007), Schütt (2003), Heijdra (2009) and Romer (2012) present overviews of labour market models with changes in human capital that could be related to increasing education. The earliest

⁷⁵ Some examples of efficiency wage models are: matching models, job creation & destruction models, ranking models, and imperfect information models.

⁷⁶ Darmendrail (2008) evaluates the possibility to apply a set of theoretical models that could explain equilibrium unemployment (as discussed by Pissarides (1998)) to the IMACLIM-S France model. Her conclusion is that of non-competitive market models discussed the Search equilibrium model is the most interesting to apply. For the efficiency wage model calibration data seems to be lacking, while for the Union bargaining model a multi-sectoral model would be needed, which IMACLIM-S France was not yet at the time, except for energy sectors.

⁷⁷ Blanchflower and Oswald (2005) estimated a global average elasticity of the wage curve of -0.1. Nijkamp and Poot (2005) corrected their estimation and estimated -0.07 for their analysis, and -0.11 for all data they analysed themselves, with the spread between regions and countries staying within a range of -0.5 to +0.1.

⁷⁸ Whether the behaviour of the augmented Phillips curve would also correspond to the wage curve is not answered by Blanchflower and Oswald, because they find their wage curve describing a completely different relationship: a static relationship between real wage and unemployment, as opposed to a dynamic relationship between (wage) inflation and unemployment. Some authors suggest though that these two relationships do not necessarily contradict each other (Campbell, 2008; Montuenga-Gomez and Ramos-Parreño, 2005).

human capital models are those developed by Mincer (1958), Schultz (1961), Becker (1962), and Uzawa (1965). According to Schütt (2003) these early models were only concerned with explaining differences in income distribution with the level of educational attainment. Denison (1967) and Jorgenson and Grilliches (1967) were among the first to treat the role of human capital as a factor of production and showed how it could explain a part of economic growth. These early models assume that skill is a factor on itself and that aggregated skill of a labour force can be measured by the average level of education or work experience, or by the percentage of workers having obtained a certain degree. Increasing education (skills) leads to a higher volume of the human capital factor supplied to production, and in parallel to higher output per worker.

A problem of the application of such a human capital model to the present study is that one objective of the study is to evaluate impacts on inequality. This requires having multiple households and multiple labour factors, which can have different wage and unemployment rates. Moreover, in development policy in the past the concept of human capital was interpreted in the past in a too simplified manner, namely that increasing education would automatically lead to more growth. Empirical evidence does not support this hypothesis, since skills are only valuable in an environment that has an equivalent level of skill and technology (Easterly, 2001).^{79,80}

Segmented labour market (SLM) models

Theories about segmentation of the labour market can be traced back to 19th century economists John Stuart Mill and John Cairnes and early 20th century economist Pigou. In the 1940'ies and 1950'ies American institutionalists John Thomas Dunlop and Kerr developed the idea of an “internal labour market” (ILM) organised between big firms and unions, and separated from the “external” less-organised one (ELM), while colleagues like Kerr also developed ideas about institutional forces creating barriers in the labour market (Leontaridi, 2002). These ideas are further elaborated by more contemporary labour economists who propose different theories for segmentation of the labour market. Leontaridi (2002) discusses the dual theory of Doeringer and Piore, the radical theory of Wachtel, Edwards, Reich and Gordon, the job competition and queue theory of Thurow, and the career labour market theory of Okun. Though they explain labour market segmentation on a different basis, all theories arrive at the result of division of the labour market into two, three or more segments. The most common subdivision is that into: 1. a primary ILM of well paid jobs, with strong mutual investment in the employer-employee relationship, high recruitment costs and good career perspectives; 2. a secondary ILM, also organized by many institutional forces and rules, but in firms or positions that have less stable guarantees of demand for their output, less mutual investment, easier

⁷⁹ This is a critique which is shared by Lucas (1988) himself who observes that a part of human capital lies in the context in which it is applied, and which cannot be captured at an aggregate national level, and which can for instance be suspected in the geographic concentration of similar professions or industries in different parts of New York City. (For this point Lucas refers to the analysis of “The economy of cities” by Jacobs (1969).) The role of the city as a proof that skills “need” other skills is also one of the arguments Easterly uses.

⁸⁰ Schütt (2003) points at literature that suggests a link between human capital and the role of technological catch-up, which has been identified to be very important for economic development by Easterly (2001) and Amsden (1987), but none of these models is yet convincing. Also, I consider such an approach incomplete, because it doesn't provide a solution to the role of other important conditions for technological change such as entrepreneurial freedom (as suggested by Easterly) or active industrial policies (as suggested by Amsden).

entry and higher employee turnover; And, 3. the ELM with hardly any durable employer-employee relationships. Education and training can be seen to serve as a selection criterion for access to a segment according to several of the mentioned theories, but it is surely not the only criterion. Leontaridi also identify models for segmentation by industry, though often grouping industries within two or more categories. According to Dickens and Lang segmentation by industry makes sense, because there are wage differences that cannot be explained by characteristics of the worker or the job. Dickens and Lang (1988) find that that SLM studies generally arrive at explaining labour market behaviour (wage setting and unemployment) better than neoclassical single labour market models, despite the fact that the segments are only theoretical and mostly do not representing hard separations in the labour market. Leontaridi (2002) agrees that labour market segmentation is proven, but finds that the lack of a common theory of segmentation and of common definitions or methodologies to analyse segmentation of the labour market limits the application of SLM theories. The lack of consensus concerns particularly the lines along which labour markets are segmented, and in Leontaridi's opinion the field of SLM studies should focus on mobility between segments to arrive at a better separation.

Still many (possibly ad hoc) SLM models have already been developed. Fields (2005, 2007) strongly favours the use of SLM models to analyse labour markets with a strong informal character, because he finds a clear distinction in wage-setting behaviour between formal and informal labour. Informal labour is often an important theme in developing countries, though Sinha and Kanbur (2012) criticize a dualistic treatment of informality as they find that informality has a rather gradual character. Fields is aware of this gradual character, but prefers a simplified segmentation over no segmentation at all. He therefore carefully defines informal employment as labour without secure contracts, worker benefits or social protection. Fields (2007) identifies the following categories of segmented labour market models, mainly in connection to modelling informal labour:

1. *Integrated labour market model*: this model is considered multi-sectoral in the sense that it allows wage variation between economic sectors, but there is only one labour market that clears. Wages in all sectors move up and down with that in other sectors;
2. *Crowding model*: assumes a formal, high-wage sector to be the preferred sector for work, and assumes that anybody who cannot find employment in this formal sector competes for work in low-wage sectors. If for whatever reason formal sector wages increase, this leads to a reduction in formal jobs and therefore to more people looking for jobs in the low-wage sector, whose labour market then clears at lower wages than in the previous situation;
3. *Harris-Todaro model*: Is like the crowding model, but does model unemployment and has a spatial dimension that determines how people move between rural and urban areas in response to a certain perception of probability of income (wage);

4. *Banerjee-Newman model of occupational choice*: in which people with different levels of wealth choose between investing time and money in possibly attaining a higher level of occupation (and earnings), and according to these choices end up working in subsistence labour, wage labour, self-employment or as entrepreneurs;
5. *Non-competing groups model*: with two completely independent labour markets, and no mobility between them. Fields (2007) does not regard this category to have any theoretical meaning and prefers one of the other four categories.

More elaborate models exist as well, with multiple sectors and multiple labour markets. For instance Bouët *et al.* (2013) present a model with 34 economic sectors over four categories of activity: formal and informal activity, for both urban and rural areas. They define specific wage curves for two types of labour supply: skilled and unskilled. Finally, there are models that focus on the role of separate labour skill categories as factors in production. For instance, in a model about capital-skill complementarity by Krusell *et al.* (2000), or in a model in which demand for skills follows endogenous technical change, on the basis of profit driven R&D decisions and lock-in of technological change following from the size or availability of a labour-skill factor (Acemoglu, 2002).

2.3.3. A blueprint for IMACLIM South Africa's labour market model

As discussed in sub-section 2.3.1, the estimation of a theoretical labour market model is out of scope for this thesis, and the use of an empirically established wage curve for South Africa (Kingdon and Knight, 2006), in combination with production functions seems sufficient to model policies that affect wages and employment. This sub-section therefore focuses on the modelling of skill differentiation in South Africa. As mentioned above, disaggregating the labour market into multiple skill segments serves to study impacts of different directions of economic development on income distribution and to study possible positive impacts of a reduction of the skill constraint. This means that the preference goes to a segmented labour market model rather than a human capital model.

The first question then is how to define skill segments. There are reasons to define it along an informal-formal split, like in the models discussed by Fields (2005, 2007). This could have analytical value for the analysis of carbon taxation. For instance, carbon taxation could push a part of commerce and e.g. small mining activity into informality. On the other hand, possible revenue recycling through the reduction of certain taxes (e.g. profit taxes, labour taxes and value added taxes) might stimulate formal economic activity.⁸¹ Informal labour is has been found to be a significant part of the South African labour force: (for the years 2001, 2005 to 2007 and 2008 values from 18% to 36% of total employment have been found), with variations in estimates mainly depending on how informality is

⁸¹ First explorations in the direction of a model with informality have been made, for which I and colleagues at CIRED thank Marius Guerard for his work during his internship at CIRED. But, in the end work on the IMACLIM-ZA model focussed on other aspects of modelling the labour market. While informality is no longer a central consideration for the model, it needs to be mentioned that a segmented labour market model for South Africa which deal with a differentiation between formal and informal has been modelled by Davies and Thurlow (2010).

defined (Devey et al., 2003; Guerard, 2014; ILO, 2013; StatsSA, 2008a; Valodia and Devey, 2012). The share of informal activity in value added is typically a lot smaller though (8-12% according to Guerard (2014)) and informal labour income or value added are estimated to be significantly lower than in other developing and emerging economies in Africa, Latin America or Asia. A disadvantage is that a correct representation of informality – especially with the eye on taxation – requires not only a separation between informal and formal labour, but also between formal and informal activity (Guerard, 2014). This would in turn require a considerable set of assumptions to disaggregate national accounts data (which do not distinguish formal and informal activities). Moreover, the modelling of the behavioural choice of enterprises, and especially the foundation of informal enterprises seems complicated, considering that informality seems less a question of choice in South Africa compared to other countries due to entry-barriers, particularly crime (Cichello et al., 2011). Furthermore, another type of separation between labour market segments seems more appropriate for the objectives of the present study: This concerns a segmentation of labour according to skill. As mentioned, there are strong signals of a structural gap in the quality of South African education.

The next question is then how to apply the education-definition of skills? South African labour force survey data signals that there is a mismatch between the level of education people have, and the level of education that is associated with the type of job in which people are employed (see section 3.1.4). Furthermore, Spaull's analysis of the South African educational system, and earlier analysis of projections for employment by level of skill (Schers et al., 2015) motivate the choice to treat skill or education as a positional good. This point will be further elaborated in section 3.3.1 when demand and supply for skills of labour are discussed. This treatment resembles that of segmented labour market theory for institutional and behavioural reasons as in the primary vs secondary internal (ILM), versus external labour market model (ELM) discussed in the previous sub-section. It also holds resemblance to that of a crowding model, for the observed phenomenon that under certain circumstances better educated people crowd out the less educated (or older) workers (Fields, 2007). Resemblance to a theoretical model is not a justification, and it has to be emphasized that the modelling choice is an ad hoc solution to represent signalled problems in the functioning of the South African labour market regarding quality of education and a high skill shortage, while there is massive unemployment. The model for labour market segmentation therefore has little empirical foundation, but I am unaware of any existing empirically founded model on which to base a segmented labour market model for South Africa.

To simplify matters, I follow the South African labour force survey's categorization of job types (StatsSA, 2005): a 4-tier system which I simplify to one consisting of 3 labour factors (Table 2.1). Considerations of calibration and model resolution that will be discussed in section 3.3 furthermore oblige the treatment of skill segments as completely separated markets (segments), without exchange between the three groups. For each skill segment an aggregated wage curve is defined, and wages

across sectors evolve in parallel (as in the multisector integrated labour market model).

Table 2.1 Classification of job types by skill level and educational attainment in SAM 2005 and IMACLIM-ZA

Job type, 2005 SAM	Skill level, 2005 SAM	Skill level, IMACLIM-ZA	Corresponding educational attainment, StatsSA (StatsSA, 2005)
Legislator, Senior management, Professional	4	3 / High	University (graduate), or post-graduate degree
Technician	3	3 / High	Beyond high school education lasting 1 to 4 years, starting age 17/18, except university
Clerk, Service worker, Skilled ag. worker, Craft worker, Plant/machine operator	2	2 / Medium	Secondary education lasting 5 years, starting at the age of 13/14
Elementary occupation, Domestic worker	1	1 / Low	No education to primary education

Finally, regarding the role of informal labour the present treatment might allow for an *interpretation* of the low skill labour category of most sectors to be a proxy for informal labour. Signs that such an interpretation is acceptable are available in the SAM 2005 (StatsSA, 2010a) and South African Labour Force Surveys (StatsSA, 2005), which identify that the job type of Elementary occupations & domestic workers (skill 1 in the table above) to be very strongly present in the Domestic & other services sector, which has been associated with informal labour. This does not imply that this is the only job type or sector with informal labour. In contrary, StatsSA (2005) identified informal labour in all sectors. But, this interpretation of low skill labour as a proxy of informal labour matches the idea that formality is a rather gradual phenomenon in South Africa. For instance, Valodia and Devey (2012) point out that jobs can be formal to different degrees, and that there are some industries where large amounts of work are done by formal workers with little job security and social protection. Such an interpretation of formality would correspond to the idea of an “external labour market”, as proposed by different theories of labour market segmentation (see the discussion above).

In summary, IMACLIM-ZA can be said to go beyond the idea of a “perfect” labour market, and explicitly models labour by level of skill with corresponding wages and levels of unemployment. Still, a few ingredients are missing in the above discussion of the options for modelling South Africa’s labour market. The most important is that the relation between skill as a factor (or role) in production (demand for skills) and skill as a characteristic of the worker (supply of skills) needs to be defined. These questions will be discussed and defined for IMACLIM South Africa in Chapter 3.

3. The IMACLIM South Africa model

This chapter presents the IMACLIM South Africa model (IMACLIM-ZA), for which the previous chapter provided the main theoretical and methodological foundations. Section 3.1 presents an overview of the model, including its calibration. The discussion about calibration is focused on key characteristics of the IMACLIM approach, namely the hybridisation procedure, and the integration of bottom-up knowledge about technological change in the electricity sector. The sections thereafter give a more technical description of the model: Section 3.2 discusses supply of and demand for goods & services, including production functions, international trade, final consumption, and price setting. Section 3.3 presents IMACLIM-ZA's labour market, followed in section 3.4 by a discussion on distribution and use of income (including for investment and borrowing and lending) and of the capital market. Section 3.5 presents an overview of model constraints and variables. Finally, section 3.6 discusses the principles for, and estimation of prospective parameters common to all scenarios.

3.1. Application of the IMACLIM framework to South Africa

IMACLIM South Africa (IMACLIM-ZA) is a two-period, dynamic computable general equilibrium (CGE) model of the South African economy. The model used in the present study is an updated version of the model developed for a study for the French Agency for Development (*AFD, Agence Française de Développement*) (Schers et al., 2015).⁸² It has common features with previously developed IMACLIM-S models for France (Combet, 2013; Ghersi, 2003, 2015; Le Treut, 2017) and Brazil (Lefevre, 2016; Wills et al., 2014), namely “hybrid” data and “second-best” macro-economic behaviour.⁸³

This section starts by presenting a general overview of the IMACLIM-ZA model and especially its disaggregation in terms of sectors and economic agents (3.1.1). This is followed (in 3.1.2) by an introduction to the hybridisation procedure and its application to South Africa. Next, sub-section 3.1.3 discusses the use of bottom-up information of the South African TIMES energy model (SATIM) of the University of Cape Town (ERC, 2013) to model technological change in the electricity sector. This section concludes with a brief discussion of calibration data for income transfers and income distribution, and of demographic and employment data (in 3.1.4).

3.1.1. Overview of the IMACLIM-South Africa model

Each IMACLIM model has its own characteristics, specific to the country and the questions analysed. IMACLIM-ZA is, as mentioned, a myopic, open-economy CGE simulation model. It consists of a set of simultaneous, non-linear equations under MS-Excel. The model projects for 2035, in a single 30-year time step from its base year 2005, an image of the South African economy. It aggregates the

⁸² For reason of some small changes in the model architecture, the version of IMACLIM-ZA used for this thesis is called version 2 (v2).

⁸³ The modelling approach in this thesis probably resembles the line of thinking of Kalecki (1939), Fitzgerald (1990) and Taylor (1991), and might be identified as neostructuralist, or new structuralist (Lin, 2012), because it also includes neoclassical and new Keynesian elements.

economy into 5 energy sectors and 5 non-energy sectors (discussed below). Production makes use of 4 factors of production, next to intermediate inputs. These factors consist of one capital and 3 labour factors, the latter distinguished by the level of skill of the job type (or position) of workers (high, medium and low). Final demand for products comes from 5 household income-skill classes (defined below), government, investment (originating from all domestic agents), and exports to the Rest of the World (ROW). IMACLIM-ZA explicitly models primary and secondary income distribution, transfers, borrowing, and lending and debt/asset accumulation for the five household income-skill classes, firms, government and the Rest of the World. The model uses the common IMACLIM second-best approaches for price setting through the use of profit mark-up pricing, and models the labour market as second-best with real wages modelled as being rigid through the use of wage curves.

IMACLIM-ZA also uses the approach of dual accounting of quantities and values of energy flows within an Input-Output (I-O) table. This enables the ‘hybrid’ top-down (TD) – bottom-up (BU) approach described in chapter 2. Dual accounting is used for the integration of BU modelling results about future technology for electricity production coming from the South Africa TIMES (SATIM) energy system model (ERC, 2013) (details follow in section 3.1.2.).

Schematic overview

The objective of this section is to give a helicopter-view of the model. Figure 3.1 (p.64) shows a schematic representation of the model, showing, when moving from left to right, the links between technological coefficients for physical intensities of production and the I-O table in physical quantities, continuing via the vector of prices, margins and taxes to the I-O table in values, which in turn links to distribution and use of income by economic agents. More precisely, Figure 3.1 shows:

1. On the ultimate left the vector of technological coefficients of a sector j comprising of:
 - intensity of intermediate inputs of product i (α_{ij}) over domestic output of sector j (Y_j);
 - intensity of labour per unit of domestic output ($\lambda_{sk,j}$);
 - intensity of physical capital per unit of domestic output (κ_j);
2. The I-O table in quantities, and accounts for use of physical capital (amortisation) and labour:
 - Multiplying technological coefficients by sectoral output Y_j (a model variable, green-shaded background), gives respectively: Total quantities of intermediate consumption of product i by sector j (IC_{ij}); Labour force by skill sk of sector j ($L_{sk,j}$); And physical capital use of sector j (K_j);
 - Endogenous trade-offs in international trade determine the ratio of imports in a sector j (M_j) over domestic production (Y_j) and the amount of exports of a product i , (X_i);
 - Price-elastic trade-offs and budget-constraints determine the quantity of Household final consumption of product i (FC_i), while government budgets and prices determine the quantity of Government final consumption (G_i);

- The quantity of demand for products for investment (I_i) follow from equilibrium in the capital market (see section 3.4.2 below) and a vector (β), calibrated on Base Year data, for the amount of capital goods demanded over capital write-offs.

Together, intermediate consumption (IC_{ij}), exports (X_i), final consumption by households (FC_i) and government (G_i), and investment (I_i) make up the total demand or uses for a product i (Use_i), which (when $i = j$) equals the total supply or resource of a product (Res_j), which equates to the total of domestic production (Y_j) + imports (M_j). This constraint can be expressed as (Eq.1):

$$Y_i + M_i = \sum_{j=1}^n \alpha_{ij} Y_j + FC_i + G_i + I_i + X_i \quad (1)$$

3. To the right follows the I-O table in values, and its link to the (secondary) distribution of income (further on the right). The I-O table in values is the multiplication of the I-O table in quantity terms with vectors of user-specific prices (including margins and taxes). The Values I-O table consists of:

- *On the supply side (1st column):* Values of intermediate consumption of product i by sector j ($\sum_j(V_IC_{ij})$); Imports of products of sector j (V_M_j); Total labour costs by skill sk and sector j ($Wage_{sk,j} + SoCo_{sk,j} + PeCo_{sk,j}$); Total capital amortisation costs (Consumption of Fixed Capital, CFC_j); Net Operating Surplus (NOS_j) and Specific Margins (MS_j), and taxes on production (TY_j) all by sector j . Labour costs and capital costs and taxation of production together make up the Value Added of a sector (VA_j). Finally, one needs to add Value Added Taxes (VAT), excise taxes, other product taxes (or subsidies), and the Carbon tax (if applied) paid in total over products (and imports) of a sector (*together: V_TaxPr_j*). Adding VA_j and V_TaxPr_j give the total primary income of a sector, which is equal to the total Gross Domestic Product that can be attributed to a sector (GDP_j). And, $GDP_j + V_M_j + \sum_j(V_IC_{ij})$ equals the total value of supply of a sector, also called the value of a sector's total resources (V_Res_j).
- *On the demand or uses side (1st row):* Intermediate consumption is part of both the production account (1st column) and the uses account in the system of national accounts as well as here ($\sum_i(V_IC_{ij})$). Add to the latter the value of exports of products i (X_i), the value of final consumption by households (V_FC_i) and government (V_G_i), and of investment (V_I_i), and one obtains the total value of uses of product i (V_Use_i).
- For the I-O table in value terms, the balancing constraint is: $V_Use_i \equiv V_Res_j$ if $i = j$.

4. The I-O table in values connects to the income distribution by economic agent, also called the integrated economic accounts. The (almost) bottom-right of the figure presents how GOS, wages, labour charges (social contributions and pension contributions), and the total of taxes (minus subsidies) on production and products constitute total primary income by agent (5 household classes: Hh1-Hh5; government, G; and firms, F). Primary income by definition equals sectoral GDP_j (Eq.2):

$$\sum_{ag=Hh1-Hh5,G,F} (PI_{ag}) = \sum_j (GDP_j) \quad (2)$$

A first transfer of income takes place via rents over, or returns on, capital via interests and dividends (RK_{ag}). For each domestic agent (Hhs, Gov, Firms) these are calculated by multiplying the total (accumulated) net debt or assets of an agent by agent-specific endogenous interest rates ($\tau_{i_{ag}}$). In practice, this means a transfer from companies and government (both net indebted) to households and ROW (both net owners of assets). A second set of transfers consists of: Social security benefits from government to households; Pension benefits from firms (pension funds) to households; Income & property (revenue) taxes from firms and households to government; And other transfers.

The result of all these transfers is the secondary distribution of income, also called Gross Disposable Income (after taxation) by economic agent (GDI_{ag}). Agents use their GDI to consume (FC_{Hhs} and FC_{Gov}) or for Gross Fixed Capital Formation ($GFCF_{ag}$). Total expenditure is called agents' Budget (Bud_{ag}). Consumption and investment behaviour are defined in such a way that there is a difference between agents' GDI and their budget. For instance, for government a future budget deficit of -3% of GDP has been defined, whereas households' gross savings (income not used for FC) are defined in such a way that they exceed $GFCF_{Hh}$. The difference between GDI_{ag} and Bud_{ag} is the Self-Financing Capacity (SFC_{ag}), which equates to net borrowing or lending by agent. The accumulation of intra-periodic SFCs leads, assuming a linear evolution of interest rates between BY and projection year, to the projected net debts (or assets) by agent (D_{ag}). ROW is assumed to balance domestic SFC and debt.

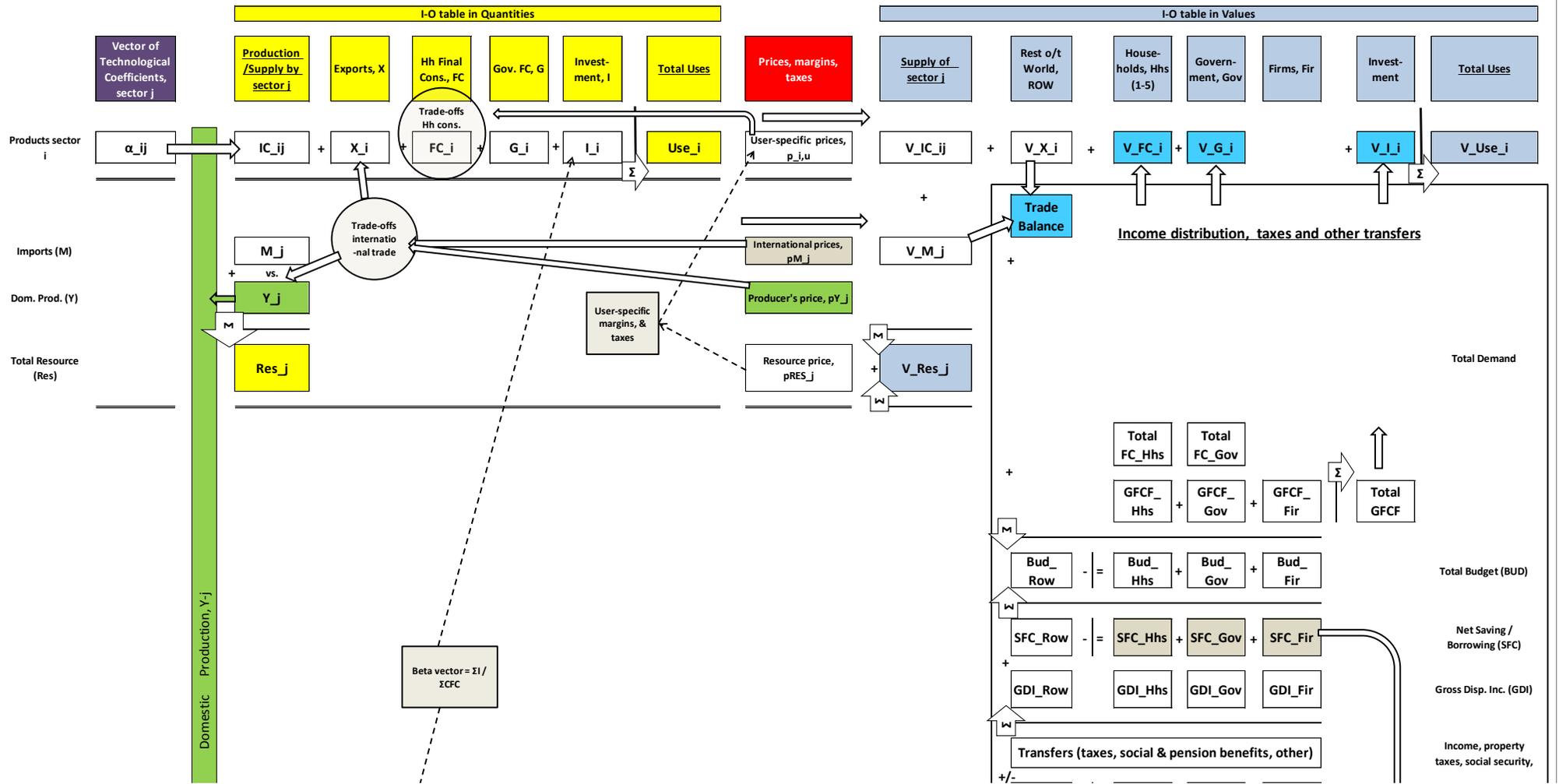
Sectoral disaggregation

The sectoral disaggregation of IMACLIM-ZA reflects a balancing act between the desire for increased modelling detail on the one hand, and data requirements, model complexity and transparency of results on the other hand. A first decision for sectoral aggregation concerned the energy production and transformation sectors: For primary energy, disaggregation by fuel type is based on similarity in physical properties (physical state, heating value) and a fuel's economic function, leading to the following categories: Coal and coal like energy carriers (e.g. lignite, coking coal, thermal coal); Crude oil (imports); and Gaseous fuels (natural gas, and coke ovens' and gas works' gas). For energy transformation a crude separation was made on the basis of types of energy products, distinguishing firstly power generation, transformation and distribution, and secondly refineries: oil refineries, coal-to-liquids plants (CTL), and gas-to-liquids plants (GTL).

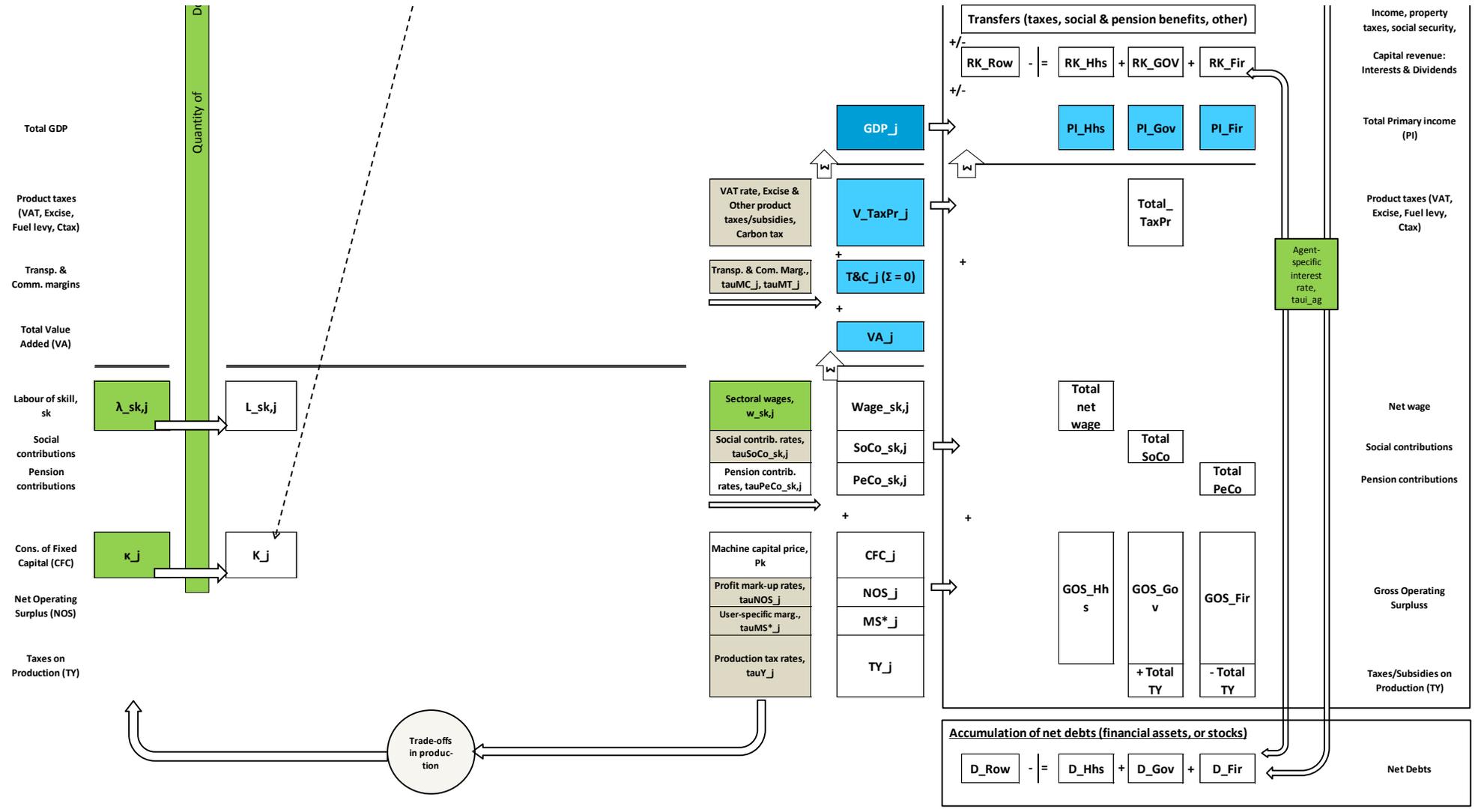
(Text continues after the figure)

Figure 3.1 Schematic representation of IMACLIM-ZA

Explanation: Green colour indicates a model variable; White is endogenous variables; Light-brown indicates (mostly) exogenously determined parameters; Bright blue indicates an element for the calculation of GDP (either income approach, or consumption approach).



(Figure 3.2 continued)



For non-energy sectors, a disaggregation that is relevant to the questions of this thesis has been based on the following criteria:

- Value added (VA) of a sector must be sufficiently large for macro-economic significance;
- The share of (SAM) energy consumption in total resources is an indication for the sensitivity of a sector to carbon taxation;
- With unemployment and a high skill labour-shortage as critical issues for the South African economy, total employment by sector is an important criterion. Also differences or similarities in shares of high, medium and low skilled labour have been taken into account;
- Finally, South Africa's demand for low and medium skilled labour depends for a large part on tradable goods (Hausmann et al., 2008). Exposure to trade, i.e. the share of exports in each sector's demand or of imports in a sector's supply, is therefore taken into account too.

Appendix B.3 presents data for the above criteria on which basis SAM sectors have been aggregated, coming from the Social Accounting Matrix (SAM) (StatsSA, 2010a) and Supply & Use tables (SU) (StatsSA, 2010b). Table 3.1 presents the aggregation of SAM sectors in 10 sectors of IMACLIM-ZA:

Table 3.1 Correspondence IMACLIM-ZA sectors to sectors in SAM 2005 (StatsSA, 2010a) or energy balance data

Sector	Full name	Corresponding sectors from South African energy balance data or SAM 2005
COA**	Coal	Coal mining
OIL**	Oil	Crude oil imports only*
GAS**	Gas	Natural gas, coke oven and gas works gas, gas distribution
REF**	Refineries	Refineries
ELC**	Electricity	Electricity, including own generation
EIN	Energy intensive industries	Gold & Other mining, Petrochemical industry, (Other) Non-Metallic Minerals, Basic iron/steel, Non-ferrous metals
MAN	Manufacturing	Food, Footwear & Textiles, Paper & pulp, Metals basic manufacturing, Electrical machinery, Radio, Transport equipment, Other manufacturing
LSS	Low skill sectors	Agriculture, Construction, Trade, Hotels & restaurants, Domestic & other services
HSS***	High skill services	Water, Communications, Financial intermediation, Real estate, Business activities, General government, Health and social work, Education
TRA***	Transport services	Freight transport by air, water and road, and public (bus and rail) and passenger transport services (road and air)

Comments:* Domestic oil production in South Africa is marginal and no future domestic production is assumed. ** There is little detail available about energy sectors in the SAM 2005 (StatsSA, 2010a), and energy sectors have been based on energy statistics and modelling, see discussion of hybridisation in sections 3.1.2 and 3.1.2. *** The transportation services sector and includes postal services (in Communication in SAM data) and own transport by companies, re-allocated to TRA on the basis of hybridisation with energy data.

The resulting values of the before-mentioned characteristics of these 10 sectors are given in Table 3.2. Energy sector and transport sector data could be obtained through the hybridisation procedure. Sectors that need to be disaggregated on the basis of energy statistics, compared to SAM data, were the electricity and natural gas sectors, as well as the refineries and other petroleum & chemical industries sector. In a similar way the transport services sector had to be composed on the basis of energy statistics too, so that it included own transport by other industries and the postal services, which is

included in the communication sector in SAM data. See section 3.1.2 and Appendix B.3 for details.

Table 3.2 Sector characteristics for aggregation criteria, after hybridisation

Sector	Description	Percent of GDP	Percent of employment	Pct high skill labour	Pct medium skill labour	Pct low skill labour	Energy costs / Primary income rate***	Pct X / total demand	Pct M / total supply
COA*	Coal mining	1.5%	0.5%	22%	66%	12%	0.02	41%	1%
GAS**	Gaseous fuels	0.1%	0.02%	26%	60%	14%	2.70	0%	32%
REF	Refineries	1.7%	0.2%	31%	53%	16%	1.78	11%	10%
ELC	Electricity	1.4%	0.5%	31%	62%	7%	0.91	7%	0.2%
EIN*	Energy int. ind. & other mining	11%	6%	22%	65%	13%	0.15	31%	12%
MAN	Manufacturing	13%	9%	26%	58%	15%	0.04	11%	32%
LSS	Low skill sectors	19%	47%	19%	46%	36%	0.04	9%	7%
HSS	High skill services	43%	32%	50%	40%	10%	0.01	4%	2%
TRA	Transport services	9%	6%	27%	64%	9%	0.45	9%	10%

* Own electricity generation in especially coal and other mining is part of ELC sector; ** Gaseous fuels besides imported natural gas are mainly coke oven and gas works gas, which are normally part of iron&steel industry; *** Direct energy over Primary income is measured in Rands of energy bills per Rand of primary income, which consists of Value Added + Tax income on products & production.

All energy sectors have relatively high energy bills compared to the primary income (value added plus indirect taxes) that these sectors generate with the exception of coal mining (8th column of Table 3.2). The reason is that coal mining's energy use is concentrated in after-sales transport, which is not included in the direct energy costs measure. Together, energy sectors (COA, GAS, REF, ELC) make up 4.7% of South Africa's GDP and 1.2% of employment. Following the energy sectors, the transport services sector (TRA) has the relatively highest energy bill. The transport sector forms 9% of GDP and 6% of employment, has about average exposure to trade with 9% of its demand consisting of exports and 10% of its supply consisting of imports. It provides by majority medium skilled jobs, and also has relatively much high skill jobs.

Next in terms of energy intensity are the energy intensive industries & other mining sector (EIN), with 0.15 Rand of energy expenditure for each Rand of primary income generated. It is strongly exports oriented, with exports equating to 31% of domestic output value. EIN makes up 11% of GDP and 6% of employment in hybridised data for 2005. Its labour demand consists in majority of medium skill jobs. Another sector, Manufacturing (MAN) is a sector in which South Africa imports a lot: import value is 32% of the value of domestic output. MAN employment has a similar skill profile as EIN and TRA, but with a slightly lower share of medium skill jobs. Low skill sectors (LSS) have been aggregated for reason of the high share of low skill jobs as part of their employment: 36%. The LSS

sector makes up 19% of South Africa's GDP, and provides an enormous 47% of total employment.⁸⁴ The high skill services (HSS) sector is the other large employer in South Africa offering 32% of 2005 employment, half of which are high skill jobs and it includes government and public services jobs (health care and education). The HSS sector offers relatively well-paid jobs (highest average after coal mining, refineries, and electricity): About 55% of its high share in VA goes to salaries (SAM data).

Household class disaggregation

The number of household classes has been set at 5 representing respectively, going from low to high expenditure per household: 10% (Hh1), 20% (Hh2), 20% (Hh3), 30% (Hh4) and 20% (Hh5) of population.⁸⁵ This aggregation has been chosen such that IMACLIM-ZA captures sufficient household detail to analyse macro-economic impacts on poverty and inequality, while respecting limited data availability. The SAM of 2005 presents income and consumption data for 12 household expenditure classes (StatsSA, 2010a), but the main constraint is the number of household classes in energy statistics, which only contain one aggregate household. Thanks to modelling by the Energy Research Centre for their South Africa TIMES (SATIM) energy system model (ERC, 2013), this can be increased to 3 income groups of households, additionally separated between electrified and non-electrified households for medium and low income group households. For the purpose of this thesis the choice is made to ignore the question of electrification, assuming therefore no inherent change in consumption behaviour related to energy access. Some limited additional assumptions have been made to disaggregate SATIM's 3 income classes into 5 household income classes to better capture income inequality. Another set of assumptions is used for the disaggregation of current and financial accounts data of households.⁸⁶ Details follow in section 3.1.4. Calibration of labour by level of skill over household classes, with corresponding wages, is also discussed in section 3.1.4.

3.1.2. Hybridisation: dual accounting of values and quantities of energy use

Procedure

As discussed above, the data hybridisation process is the basis of the IMACLIM framework. Its objective is to simultaneously and consistently track Input-Output tables both in monetary terms and in physical terms. This sub-section explains the methodology, common to IMACLIM models. An overview of sources and assumptions for its application to IMACLIM-ZA follows below, while Appendix B.3 presents the resulting hybrid I-O table for 2005 that is used to calibrate IMACLIM-ZA.

The hybridisation procedure consists, like in Combet (2013), of the following steps: (i) Creating Supply & Use tables in physical units; (ii) Creating an Input-Output (I-O) equivalent for energy sectors in the form of sectoral and agent-specific "energy bills"; and (iii) Hybridizing monetary and

⁸⁴ LSS employment, following from SAM data is by majority in Domestic & Other services, but also a large part of South Africa's 2005 employment can be found in Trade and retail (about 10% according to SAM data), in agriculture (7%), and construction (6%). A part of domestic & other services employment consists, according to SAM sector classification, of jobs in education. Assuming a skill profile similar to that of average public sector jobs (government and health care), the education sector has been transferred prior to hybridisation from the Domestic&other services sector to the Government & public services sector, which has become part of the HSS sector.

⁸⁵ Statistics South Africa used per household income to categorize households according to SAM 2005 documentation (StatsSA, 2010a).

⁸⁶ This concerns for instance the questions of social security, taxes and income distribution (from wage, interests, and mixed income).

physical I-O matrices. Two basic principles need to be respected: Firstly, both physical and monetary accounts must respect the conservation principle (Eqs. 3 and 4), meaning that each use of a good requires its availability on the resource side of the I-O table, and vice versa, each resource must be used. Secondly, physical and monetary flows are linked by a system of prices. More precisely, total economic value associated with production, trade or consumption of any good equals the aggregate volume of its use multiplied by the (average) price for this use (Eq.5). After Combet (2013) these principles can be formalized mathematically as, for $i = j$:

$$\text{Supply \& Use balance in quantities:} \quad \sum_{s/ag} Q_{i,sector/agent} = \sum_j Q_j \quad (3)$$

$$\text{Supply \& Use balance in values:} \quad \sum_{s/ag} V_{i,s/ag} = \sum_j V_j \quad (4)$$

$$\text{Consistency between values and quantities:} \quad V_{i,s/ag} = Q_{i,s/ag} * p_{i,s/ag} \quad (5)$$

, with:

i index of product (or usable good) of sector i ;

j index of output (product or total resource) of sector j ;

Q quantity in physical units, e.g., PetaJoules (PJ) for energy;

V values (in monetary units);

s/ag index for sector (s) or agent (ag), which consumes a product in respectively intermediate consumption or final consumption or exports;

p price of a certain exchange between output sector j , and consuming sector s or agent ag .

The first ingredient for hybridisation is data on quantities of product use. Energy flows in an economy is particularly suitable for the calculation of the mentioned energy bills and thus for hybridisation, because data is generally available in the form of energy balances, and energy can often be measured in homogenous units, e.g. PetaJoules (PJ) or tonnes-of-oil-equivalents (toe) (see [Box 4](#) below).⁸⁷

The second ingredient to build a hybrid I-O table is the supply and use table in monetary values, which can be found in national accounts. It is build-up as follows: Columns indicate “resources”, and distinguish between intermediate consumption (IC) in monetary value (V_{ij}), value added (VA) and imports (M). Rows indicate “uses” and distinguish between intermediate consumption (IC), final consumption (FC , of households and government, and for investment, I , and exports, X).

The third and last ingredient is a vector of prices, which can often be differentiated between actors for energy sector products on the basis of energy statistics. The result of the hybridisation procedure is a modified I-O table in which the size of consumption and the VA of energy products (in our case) are correctly represented, with the level of product detail as desired for the foreseen analysis of energy or climate policies. A correct picture of energy consumption leads, when using the right greenhouse gas

⁸⁷ However, provided quantity and price data is available, the methodology can be applied to other material flows too (calories, tons of cement, etc.) (see for instance Le Treut, 2017).

emission coefficients, to a proper estimate of greenhouse gas emission intensity of economic activity.

Depending on the targeted degree of sectoral disaggregation, before (or after) hybridisation, the non-hybridised (in our case, the non-energy part) of production and consumption is aggregated into either one large composite sector or into several sectors. The latter is the case in this thesis.

Box 4 Energy balances

Energy flow data is available in standardized energy balances that detail the processes of energy production, transformation and consumption measured according to their energy content (here expressed in petajoules, PJ). This type of statistical system makes it possible to reorganize datasets in a supply-use format similar to the one adopted for national accounts. Energy balances are typically organised as follows (see IEA/OECD energy balances):

1. The top part reports the supply of all energy carriers,⁸⁸ through imports minus exports, domestic production and stock changes. It also signals aggregated statistical discrepancies. Domestic production mainly matches mining and extraction industries in economic Input-Output tables as far as fossil fuels are concerned.
2. The middle part reports energy uses and transformations in the energy industry. It relates to some of the industries of economic Input-Output tables, like refineries and electricity production and distribution. This is also the place in energy statistics where own use or ‘auto-production’ by industries can be found.
3. The bottom part consists of energy use or final consumption of energy. It is split in three: (i) the industrial and (non-energy) mining energy use, (ii) other uses, i.e., agriculture, services, residential and transport uses, with transport encompassing both freight and passenger transport in its public as well as private varieties; (iii) non-energy uses.

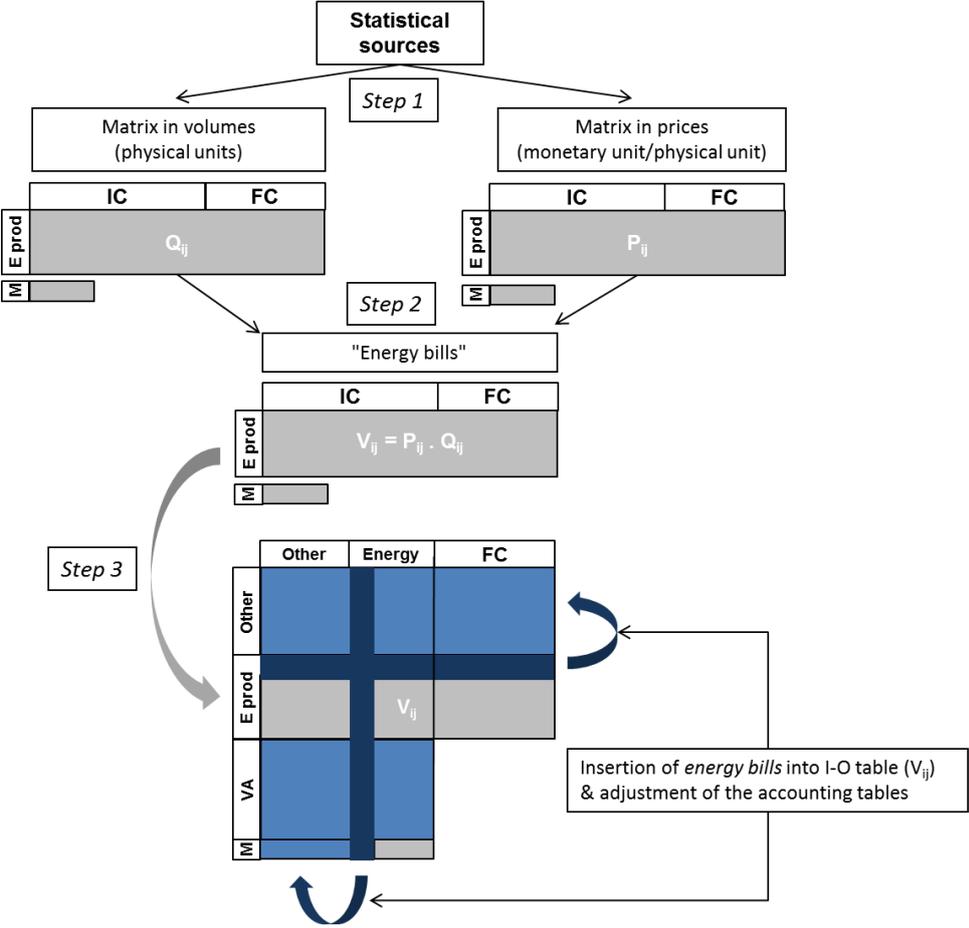
From this description it is clear that all elements are present to link energy balances to I-O elements like the intermediate energy consumptions of productive sectors (CI), the final consumption by households and exports (CF), whereas supply in the energy balance concerns volumes produced (P) and imported (M).

With the above three ingredients plus the choice for the number of non-hybrid (non-energy) sectors, the hybridisation procedure continues as follows (Figure 3.2): From the energy balances and the price vectors, purchase bills V_{ij} can be derived by multiplying observed quantities Q_{ij} and prices p_{ij} . These bills are then substituted for the monetary value in the I-O table, and the rest of the table (rows and columns) is adjusted to conserve the total physical and monetary balances while respecting the original total values for IC, FC, VA and M. In particular, differences in value between national accounts data

⁸⁸ Energy carriers typically included in an energy balance are coal (in different varieties), oil (in different varieties), natural gas, biomass (in different varieties), different transformed solid, liquid and gaseous “fuels” and other refined products, heat (mostly energy content of steam) and electricity.

and the purchase bill data, as obtained for energy from energy statistics, are attributed to one of the large non-hybrid sectors. Plenty of explanations for these differences are possible, but in case of high inconsistency between different economic statistics a reason could be that it represents value attached to goods and services from a sector other than the core physical product. For example, in the case of energy products certain services attached to energy sales, real estate or business consulting activities.

Figure 3.2 Schematic representation of the hybridisation procedure (source: Combet, 2013)



Besides allowing for more accurate estimates of prices and quantities of energy, an important advantage of hybridisation is that it enables to model changes in energy technology more realistically. Furthermore – depending on the objectives of a study and choices made in the construction of energy bills –, hybridisation can render issues such as own use and transformation of energy by non-energy sectors measurable. As these are often excluded as economic transactions, they do not tend to be registered in national accounts whereas they are included in BU models. Of course, primary energy that is consumed by a sector is purchased in a commercial transaction and therefore present in national accounts, independent of how a sector uses this energy resource.

Application of the hybridisation procedure to South Africa

Next, I present data sources and assumptions used to create the hybrid I-O table for IMACLIM-ZA’s calibration. The final hybrid I-O table is shown in Appendix B.3.

Prior to applying the hybridisation procedure to South Africa a complication was that adjustment of SAM data and other economic data (from integrated accounts) was necessary to establish a balanced monetary I-O table and secondary income distribution at the level of detail required for IMACLIM-ZA. This meant, amongst other things, eliminating statistical discrepancies, and combining economic supply and use tables from the SAM into one I-O table in which each sector produces only one product. The latter has been added as step 3a to the hybridisation procedure (see below). Furthermore, South Africa's social accounting matrix (SAM) lacks some detail, e.g. on energy sectors, which also required additional assumptions prior to hybridisation. Also, the SAM contained no detailed information on income distribution, as available in the Integrated Economic Accounts, for the main economic agents (firms, public administrations, households and the rest of the world). Assumptions were therefore made to match sources on income distribution with SAM data. Details on data preparation steps are described in Appendix B.1. Finally, to the three steps common to the hybridisation procedure for all IMACLIM models a step has been added in which the I-O table for 34 sectors and 3 (energy) to 10 (SAM data) household classes is aggregated into one I-O table for 10 sectors and 5 household classes. The resulting four steps of the hybridisation procedure are:

Step 1a: Obtaining an I-O table in energy volume units

Constructing an I-O table of energy volumes (quantities) starts with determining the required level of aggregation and sectoral break-down. For IMACLIM-ZA, with its limited technological detail and a focus on the labour market, the choice has been made to limit the amount of energy carriers to the five mentioned above. In contrast, the non-energy part of the economy needs a more detailed representation than in most IMACLIM-S models to capture the characteristics of different sectors (see section 3.1.1). To allow for further sectoral disaggregation in the future, the I-O table has been developed for 5 energy sectors and 30 non-energy sectors (see Appendix B.1).

Energy volumes produced and imported are estimated on the basis of the Department of Energy's energy balance (DoE, 2009a) and the International Energy Agency's energy balance for South Africa (IEA, 2012). For the year 2005 the IEA's and DOE's energy balances contain some differences. By principle DoE numbers have been used, but outliers were corrected on a case-by-case basis with IEA statistics. Furthermore, for transformation of energy in refineries (oil, Coal-To-Liquids (CTL), and Gas-To-Liquids (GTL)) and for power generation additional data and estimates coming from the SATIM model (ERC, 2013) or other data provided by the ERC were used.⁸⁹ SATIM calibration data is also the basis for estimation of private transport and residential energy use disaggregated by household class (see Appendix B.3).

Step 1b: Obtaining a corresponding table of energy prices by user

Energy prices have been obtained from multiple sources (DoE, 2009b; ESKOM, 2005; NERSA, 2009;

⁸⁹ The ERC obtains a precise picture of South African energy production, transformation and use by combining official energy statistics, industry data, and engineering-based estimation of industrial, transport and household energy consumption. I thus partly use 2006 calibration data of ERC's South Africa TIMES model (ERC, 2013), thanks to support from the ERC's energy modelling team.

SAPIA, 2013). Two assumptions deserve to be mentioned here: The gas price by type of user estimates are derived from gas prices by contract size (NERSA, 2009), and the average crude oil import price is based on 2005 prices for Dubai and Brent crude oil (DoE, 2009b). See Appendix B.3 for more detail.

Step 2: Obtaining an “energy bills” I-O table

The final energy bills I-O table is obtained by a multiplication of the I-O table for energy volumes by the energy prices by user. See Appendix B.3 for the final energy bills I-O table.

Step 3a: Obtaining a SAM based I-O table with sufficient sectoral detail

In the South African Supply and Use tables (StatsSA, 2010b), and in the Goods & services and Production accounts of the SAM 2005 (StatsSA, 2010a) supply and use of products are separated and one sector can generate multiple products, and one product can be generated by multiple sectors. For CGE modelling, the I-O table and the simplicity of a “one sector-one good” approach is more common and probably more practical. Similarly, the IMACLIM framework is also set up around the use of one integrated I-O table. Matrix multiplication between supply or Output tables and use or Input tables creates an I-O table. The multiplication causes a shift in inputs of sectors by ratio of their outputs to the sectors that are assumed to be the main producer of a certain good or service. In reality, inputs to a sector might not have the same composition or structure for each of their products, but the majority of sectors in South African data are the dominant producer of its characteristic good. Deviations in economic structure are thus assumed to be negligible.

The main source for Input table and Output table data is the “Final Social Accounting Matrix, 2005 (Updated Version)” (the SAM 2005: StatsSA, 2010a). The “Final Supply and Use Table 2005” (SU tables: StatsSA, 2010b) are used to add detail on product taxes and other Value Added data, and to add sectoral detail. Notably, the electricity and gas distribution sector of the SAM 2005 has been split; extraction of gas resources has been separated from the SAM 2005’s mining sector in which it was hidden; and refineries and petrochemical industry (clubbed together in the SAM 2005) were split as well. Appendix B.1 shows the monetary I-O table based on SAM data used for hybridisation.

Step 3b: Insertion of energy bills into SAM based I-O table and balancing

This actual hybridisation step starts with replacing monetary energy sector data with “energy bill” data. To maintain the monetary balance between total uses and resources in the I-O table, the differences created in this way need to be corrected. To do so, the first sub-step is to move differences between the old and the new uses (consumption) of energy products to the uses/consumption of non-energy goods of affiliated sectors (e.g. Iron & Steel production and other heavy industry). For imports, a similar change is made. Important adjustments are also made between the refineries sector and the petro-chemistry sector, and for the creation of a transport sector which includes postal services (coming from the communication sector in SAM data) and which includes own internal transport in non-transport sectors. This adjustment could be performed on the basis of energy balances data, which gathers all transport energy use in one category, separated from other productive energy use.

These operations do not affect the overall value of uses, but change sectoral totals. Therefore, without adjustment of the components of Value-Added (VA), margins, and/or taxes on products, the totals of uses and resources (cost structure) by sector (or good or service) would no longer be balanced. In a second sub-step, balances are restored by adjusting the cost structure of production (columns in the I-O table): Values of imports and intermediate consumption (IC) of energy are fixed, because they follow from the energy bills. Other cost components – non-energy IC, VA, margins, and taxes on products - are not fixed and are adjusted, in most cases, by the ratio of change in energy inputs to a sector.

Step 4: Aggregation into a 10-sector I-O table

Finally, the obtained 34 by 34 sector hybrid I-O table is aggregated into a 10 by 10 sector I-O table to fit production and consumption trade-off structures presented in section 3.2.1. This is a simple procedure of summing the values in rows and columns of sectors that will be aggregated. See Appendix B.3 for the outcomes.

3.1.3. Calibration of the electricity sector on SATIM

Section 2.1.4 introduced how hybridisation generates the technological coefficients for energy use – i.e., the consumption of energy in physical-quantity terms per unit produced (which also exist for other intermediate inputs, for capital and labour). The present section treats the procedure by which technological coefficients of the electricity sector (ELC) have been estimated based on the South Africa TIMES energy system model (SATIM) and its results. SATIM has been developed by the Energy Research Centre (ERC) of the University of Cape Town (UCT) (ERC, 2013).

As mentioned, SATIM is used here to account for the constraints on the development of supply and demand of energy use. This is especially important for the South African electricity sector. With only a limited number of power plants, largely controlled by public authorities, and the paramount role of public investment in the development of new power generation capacity, the development of the electricity sector's technology can be assumed to depend more on political choices than on the evolution of relative prices of factors and inputs. Also, the price of electricity is regulated, which further reduces free-market behaviour for this sector. IMACLIM-ZA's electricity sector's (ELC) technological coefficients are obtained from SATIM model runs with different levels of a carbon tax and applied exogenously, meaning without iteration with SATIM and without endogenous feedbacks on these coefficients within the IMACLIM-ZA model. To this end the Full-sector version of the South Africa TIMES model (SATIM-F) (Altieri et al., 2015; ERC, 2013) is used.

The methodology for the TIMES models has been developed by the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA). It is a bottom-up (BU) partial equilibrium model that matches demand and supply for energy carriers or energy services, taking into account often detailed descriptions for costs of energy production and preferences in energy use. The

model is based on linear optimisation. The objective function of the model is to minimize costs over the model projection period (including cost of lost demand) on the condition of meeting the equilibrium value of demand and supply for each commodity at each point in time as well as other constraints defined by the modeller, e.g. fixed investments or greenhouse gas emission budgets.

To allow for the adoption of technological coefficients from SATIM, important assumptions and parameters between the two models, such as the development of energy prices, have been harmonised. As a result, IMACLIM-ZA's reference projection for 2035 incorporates the consequences of the Updated Integrated Resources Plan 2010-030 (IRP-2010) for the electricity sector (DoE, 2013), which SATIM explicitly describes. Similarly, in all IMACLIM-ZA runs with a carbon tax, the vector of primary and secondary factor intensities for the electricity sector is obtained from SATIM runs with a similar carbon tax rate. This way, IMACLIM-ZA captures BU information on the way electricity supply reacts to the introduction of a carbon tax. An *ex post* evaluation of the compatibility of SATIM runs and IMACLIM-ZA scenarios is presented in section 6.1.5.

Estimation procedure

The three scenario runs of SATIM-F that are used in thesis have been generated with the version of SATIM of November 2014, which is similar to the versions used by Durbach et al. (2017), Merven et al. (2015) and Altieri et al. (2015). One run assumes no carbon tax and implementation of the updated IRP-2010 for power generation (RSA, 2013b).⁹⁰ Additionally, runs were performed with the IRP and a carbon tax of respectively 100, 300 and 500 ZAR₁₀/tCO₂. The carbon tax in SATIM is modelled as if it was introduced with a zero value in 2014, increasing linearly towards 2020 and remaining constant beyond. The period modelled is 2007 to 2050, with five year intervals from 2010 onwards. Only results up to year 2035 have been used for IMACLIM-ZA. After 2035, the optimisation procedure starts to underestimate investment needs for new capacity due to the limited time horizon. Though SATIM-F is a full energy system model, only its results for the power generation sector have been used. The advantage of having the full energy system model is that it captures feedbacks from other sectors to power generation concerning electricity demand, the load curve and peak power generation capacity.

Due to differences in calibration, some difference in the absolute price of energy between IMACLIM-ZA and SATIM could not be avoided (see Appendix C.8). This was deemed acceptable because IMACLIM-ZA models economic trade-offs and markets as being price-elastic to relative price changes, which are less affected by small differences in absolute prices. Priority was therefore given to harmonise the relative evolution of prices between the two models, and to the calculation of IMACLIM-ZA's technological coefficients on the basis of input or factor intensities derived from SATIM runs. Compared to Schers *et al.* (2015), who used the same approach to derive technological coefficients for ELC from SATIM runs, a correction has been made to improve the evolution of the

⁹⁰ Three additional assumptions were that there would be no domestic shale gas production, and no availability of discovered but not yet developed gas resources in Northern Mozambique, and that technological learning was estimated conservative.

price of coal, whose very likely future increase was underestimated in Schers *et al.* (2015), resulting in coal prices in 2035 to be much lower than in SATIM. To do so, transport margins have been exogenously increased in IMACLIM-ZA. This should reflect the increase in costs due to depletion of existing coal exploitations and due to added transport costs from moving production from the Central Bassin around Gauteng to the Waterberg coalfield. The future price of electricity was, by consequence, also underestimated in Schers *et al.* (2015), which led to an overestimation of the relative impact of the carbon tax. For electricity also additional assumptions were made to obtain a more realistic evolution of *physical* capital intensity, one that is closer to SATIM capital cost data. These and other assumptions are explained in Appendix C.8.⁹¹

Outcomes: Lower intensity in coal use against higher capital intensity

The consulted SATIM runs show that the capital intensity of electricity production increases with an increasing carbon tax, while coal intensity of electricity production – already set to decline due to increased efficiency of new coal power plants in the updated IRP-2010 – declines even further under carbon taxation (Table 3.3). (For other inputs results are presented in Appendix C.8.) In brief, the use of diesel oil and natural gas in electricity production remains small and negligible in all scenarios in comparison to coal, renewables and nuclear, whereas O&M, and thus the intensity of ELC production in terms of materials & services inputs and labour are assumed to increase moderately (43% in the most extreme case, see Appendix C.8). An evaluation presented in section 6.1.5 shows that the trajectories between the two models are close.

Some explanations for the obtained evolutions of technological coefficients can be given: The main reason for increasing capital intensity and decreasing coal use in electricity production is a shift to more renewable and more nuclear energy in parallel to increasing carbon taxation: Power generation capacity for renewables is 12 GW in 2035 in the updated IRP run of SATIM without carbon taxation, whereas it increases to respectively 37.5 GW and 39 GW for the scenarios with a R100 and a R300 Ctax (see Appendix C.8). New nuclear power generation amounts to 15 GW by 2035 under a R300 Ctax. In the R300 Ctax run, electricity production from coal-fired thermal power plants decreases even more than can be explained from substitution by renewables and nuclear power. The reason is a reduction in electricity consumption of about 10 TWh (or 35 PJ) relative to the no carbon tax case.

A critique on these results is that these SATIM outcomes have been outdated to some extent by recent decreases in costs of solar PV power generation in public procurement procedures in South Africa and by more recent insights into cost of nuclear energy (ERC, 2015; Wright *et al.*, 2017). Under slightly less optimistic assumptions for the costs of nuclear energy, power generation from renewables and natural gas quickly take over the in the updated IRP foreseen role of nuclear power as a substitute for coal-fired thermal power plants in an optimal future electricity supply for South Africa (ERC, 2015).

⁹¹ As an example for “other assumptions”, a lack of detail on labour costs and costs of materials and services inputs in SATIM, required additional assumptions for their evolution within the total costs of electricity production coming from SATIM. Also, assumptions were made to estimate the capital costs of historically already existing power generation capacity in SATIM

Table 3.3 Technological coefficients for capital intensity (kappa) and coal use in ELC production IMACLIM-ZA

	kappa (CFC/Y)**				Intermediate Cons. of COA / Y of ELC			
	2005*	2015	2025	2035	2005*	2015	2025	2035
Upd. IRP without Ctax	1.0	3.2	3.3	3.5	1.0	0.9	0.9	0.85
Upd. IRP + R100 Ctax	1.0	3.2	3.5	4.0	1.0	0.9	0.8	0.65
Upd. IRP + R300 Ctax	1.0	3.2	4.2	5.0	1.0	0.9	0.7	0.4

* By assumption intensities derived from SATIM's base year 2006 are equal to those of IMACLIM-ZA for 2005.

** Capital intensity is underestimated in IMACLIM's hybridisation, due to low capital write-offs in the hybrid I/O matrix for 2005, likely due to a period of underinvestment in new power generation and low capital write-offs costs due to an old electricity stock. The 2005 index value is 3 times lower than in SATIM for this reason. By 2015, after electricity price increases, this is corrected.

Capital intensity obtained from SATIM is in terms of average write-offs per year, and is defined to be equal to volume index-units of capital (CFC/Y); a volume-index-unit of capital from SATIM is assumed to have a constant price, with capital costs per GW capacity reflecting the capital intensity of a technology (the discount rate is constant in the SATIM runs).

3.1.4. Other calibration data

This sub-section discusses first what the primary and secondary distribution of income by economic agent have been based on, and then treats the question of the demography and distribution of population and labour force by skill and household class.

Calibration of secondary distribution of income by agent and household class

The calibration of the distribution of primary and secondary income by economic agent also stems from multiple data sources. For instance, a breakdown of product taxes and subsidies by different types (fuel levy, VAT and other) was missing in the SAM and found in governmental financial statistics (StatsSA, 2012). Furthermore, the SAM 2005 only has one category of transfers between economic agents (accounts 4.4 and 5.5, table 2.1; StatsSA, 2010a). As a consequence, it is unclear what the size of transfers for social and pension contributions and benefits are, or how much income taxes are paid. The Quarterly Bulletin March 2007 and an “Integrated Economic Accounts” presentation of the South African Reserve Bank (SARB, 2007, 2012) were consulted to estimate these aspects of income transfers.

Also, multiple sources have been used to estimate net financial asset positions by economic agent (net debts and savings or other assets), including a SARB working paper reviewing balance sheets of assets and liabilities of households (Aron et al., 2007). Partial information about financial assets and liabilities of companies is found in the SARB's Annual Report 2012 (SARB, 2013a). The latter also serves to estimate South Africa's net asset position relative to the rest of the world. Finally, I assume the Government account to balance other accounts of financial assets and liabilities, thus arriving at an estimate of net public debt of ZAR 678 billion for 2004.⁹² Final estimates of the integrated economic accounts of economic agents can be found in Appendix B.4.

Demography, labour force and household classes

For IMACLIM-ZA an important aspect of demography is its implication for the labour market. The

⁹² Unfortunately only after calibration had been completed a better estimate of public debt was found: R 500 billion in 2005 (SARB, 2013b).

SAM gives the number of employed people disaggregated by job type and educational attainment, but does not report similar data for the unemployed. Disaggregated data about the unemployed can be found in the Quarterly Labour Force Survey reports (StatsSA, 2008b, 2008a, 2014b). The total number of unemployed reported in the latter publications does not exactly match those of the SAM 2005, but the differences are small. I use the number of people employed from the SAM 2005 and use labour force survey unemployment rates for 2005 (26.7% for official unemployment), plus the number of discouraged workseekers reported in the QLFS of September 2005 (3.3 million): This leads to a broad unemployment rate of 38.8%.⁹³ Discouraged workseekers are a category normally considered inactive, but in IMACLIM-ZA the assumption is that they return to the labour market when the employment situation allows for it.

Calibration of employed and unemployed by level of skill follows the categories for skills of labour of StatsSA (StatsSA, 2005: Annex 1). Data on the number of jobs and total wage by job type and by sector is also available in the SAM 2005. The link between job types and skill levels of labour for IMACLIM-ZA is provided in Table 2.1 above. Alternatively, employment by level of education could have been used for the identification of skill levels, but several statistical errors were found in SAM 2005 data about pay and employment by level of education, thereby casting doubt on the usefulness of this data. Besides, job types have the advantage to represent particular roles in production, and thereby correspond to a view on skills of labour as a specific role in production (see section 3.3).

Admittedly, StatsSA's assumed link between job type and educational attainment, used to disaggregate labour categories in IMACLIM-ZA, is not without its problems either: A comparison of the number of people at working age by level of educational attainment with the number of people at working age by job type shows that much more people indicate to work in high or respectively medium skill job types than that there are people with a corresponding level of education (Table 3.4).

The South African level of educational attainment is too low for at least all jobs of high skill job type to be occupied with correspondingly educated people. Whether this is a problem of definition of job types, a question of survey bias on job types in the QLFS, or whether it reflects a real mismatch between job types and educational requirements is unknown. Given South Africa's history of Apartheid, which left the majority of South Africa's population without access to proper education, it is very likely that many people who gained their skills outside formal education now have high skill jobs. To simplify matters, IMACLIM-ZA – using a positional definition of skills in labour supply (see section 3.3) – assumes that the high skill labour category corresponds to the 25% (= 5,036 / 20,113) highest educated part of the active population, that the medium skill labour category corresponds to the 52% (= 10,386 / 20,113) next highest educated active population, and the low skill labour force to the 23% least educated workers and work-seekers.

⁹³ The definition of the broad unemployment rate is: (Officially unemployed + Discouraged workseekers) / (Officially employed and unemployed + Discouraged workseekers). Discouraged workseekers is a standard definition used by Statistics South Africa.

Table 3.4 Population by educational attainment and corresponding job type skill level, 2005*

Age group	Level of educational attainment	Pop. by educational attainment	Broad active population by job type**	Broad inactive population by job type**	Difference educ. – job type by skill
0-14	-	15,4 million	-	-	-
15-64	No education	1.9 million	4.7 million low skilled	3.0 million low skilled	-0.9 million
	Primary education	6.7 million			
	Lower secondary education	12.1 million	10.4 million medium skilled	5.7 million medium skilled	-4.3 million
	Upper secondary education	8.4 million			
	Post-secondary education	0.9	5.0 million high skilled	1.1 million high skilled	5.3 million
15-64 subtotal		30.1 million	20.1 million	10.0 million	-
65+		2.1 million	-	-	-
Total		47.6 million	20.1 million	10.0 million	-

Comments: * Sources Authors' calculation and assumptions, combining SAM 2005 (StatsSA, 2010a) and QLFS Sept 2004 data (StatsSA, 2005); ** Estimates of actives and inactives by skill are based on active population by job type and are shown for the corresponding levels of educational attainment according to CSLF definitions given in Schers et al. (2015). The total and working age population numbers (47.6 and 30.1 million respectively) are mid-year estimates by Statistics South Africa (StatsSA, 2013). To arrive at active and inactive population by skill level, employed people by skill have been compared with employed people by educational degree. The corresponding number of unemployed and inactives of that level of educational attainment were calculated next: From the inactive population with the official (or narrow) definition of unemployment I deducted the number of discouraged workseekers at equal share for all levels of education, and added these to the active unemployed number of people, to calculate the active population by skill according to the "broad" definition of unemployment.

A last question of Base Year calibration data is the distribution of active population by level of skill and inactive population over the household classes. Lacking data on this issue I assume a certain distribution maintaining three basic principles:

1. The number of people working at a certain skill level increases with the richness of (expenditure-based) household classes;
2. Unemployment of the different skills decreases with the richness of household classes, while the average wage of the employed increases;
3. Within each household class the average wage increases with the skill level.

An additional assumption is that within each household class the percentage of inactive workers decreases as the level of skill of workers increases. This results in base year 2005 distribution of wage, employment, unemployment, and inactivity by Hh-class given in Appendix B.4.2.

3.2. Supply & demand for goods, prices and CO₂ emission accounting

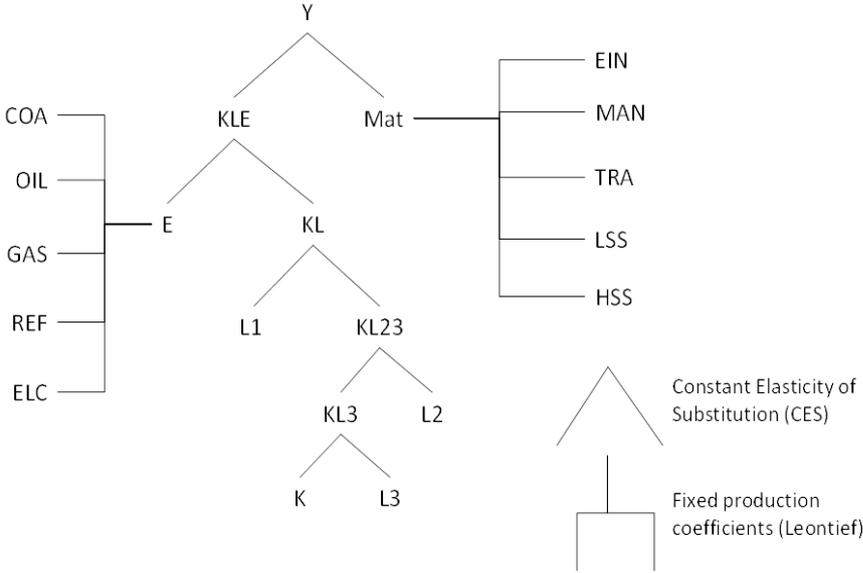
This section presents the behavioural specifications for the supply and demand for goods. It starts with a treatment of trade-offs in production (sub-section 3.2.1), followed by a discussion of the modelling of trade-offs in international trade (3.2.2), and in household final consumption (3.2.3). The related issue of calculation of CO₂ emissions is discussed (3.2.4), before finally presenting how prices are set

in markets for goods and services (3.2.5).

3.2.1. Trade-offs in Production

All sectors except the electricity sector (ELC) have KLEM⁹⁴ production functions that determine the relation between the use of factors of production, namely capital (K) and the three labour-skill factors (L_{sk}), and the inputs of energy (E) and “materials & services” (Mat) in response to changes in relative prices. Following Van der Werf (2008), IMACLIM-ZA has a nested structure that combines capital and labour to form a value added (VA) composite KL ; One level higher KL and energy form the KLE aggregate, which itself is a substitute for the aggregate of non-energy goods and services (Mat) in the production of domestic output Y (Figure 3.3). Fixed, or Leontief, coefficients are used to model the composition of the energy aggregate (E) in terms of individual energy goods, and for the composition of the materials and services aggregate. All other substitution possibilities follow a constant elasticity of substitution (CES) assumption. IMACLIM-ZA perceives changes in relative prices of effective or “productive” units of goods. The CES production function thus takes into account changes in productivity, for which the functional forms follow below.

Figure 3.3 Nested production function structure (for all sectors except ELC)



Labour is modelled as 3 separate skill segments, which enter production functions as follows: On the lowest level (bottom of Figure 3.3) capital (K) and high skill labour ($L3$) are complementary. Support for this hypothesis, though restricted to equipment-capital, can be found in Krusell et al. (2000), who demonstrate a skill premium for equipment-capital on the basis of historic data for the US. Next, we assume that the capital – high skill labour aggregate ($KL3$) is a substitute for medium skill labour ($L2$), and that the $KL23$ aggregate substitutes for low skill labour ($L1$) (Figure 3.3). The final relation between capital and the 3 skill levels depends on the choice of price elasticities (see section 3.6).

⁹⁴ KLEM stands for: Capital, K , Labour, L , Energy, E , and Materials and services, M .

It is important to note that, as in Ghersi and Hourcade (2006) (see section 2.1.4), the capital coefficient of the production tree is calibrated on the fixed capital consumption share of the gross operating surplus, while net operating surplus (profits in the accounting sense) is modelled as a constant mark-up rate (see the discussion about price setting next). This will be elaborated on in section 3.4.2 with the discussion of investment and the capital market.

The CES trade-offs between factors or inputs of Figure 3.3 can be expressed, in a general form, as an intensity of an input or factor A_j over output Y_j of productive sector j , in a trade-off with factor B_j and with the overarching composite factor or input AB_j (Eq.6).

$$A_j/Y_j = APF_j^{-1} * \left(\overline{a_{AB_j}} * \left(\frac{pA_j}{APF_j} \right)^{-1} \right)^{\sigma_{AB_j}} * \left(\overline{a_{AB_j}}^{\sigma_{AB_j}} * \left(\frac{pA_j}{APF_j} \right)^{(1-\sigma_{AB_j})} + \overline{b_{AB_j}}^{\sigma_{AB_j}} * \left(\frac{pB_j}{BPF_j} \right)^{(1-\sigma_{AB_j})} \right)^{-\rho_{AB_j}^{-1}} * \frac{AB_j}{Y_j} \quad (6)$$

, with:

- APF_j and BPF_j productivity growth multipliers of inputs or factors A_j , B_j ;
 $\overline{a_{AB_j}}$ and $\overline{b_{AB_j}}$ CES coefficients calibrated on BY data;
 pA_j and pB_j prices of input or factor A_j and B_j ;
 σ_{AB_j} elasticity of substitution between A_j and B_j (see section 3.6 for values);
 $\frac{AB_j}{Y_j}$ ratio of the aggregate of A_j and B_j , AB_j , over Y_j ;
and ρ_{AB_j} (Eq.7):

$$\rho_{AB_j} = \frac{(\sigma_{AB_j}-1)}{\sigma_{AB_j}} \quad (7)$$

As an example, Eq.8 and Eq.9 give respectively the equations for the intensity of capital over Y , κ_j , and of low skill labour $L_{sk1,j}$ over Y , $\lambda_{sk1,j}$:

$$\kappa_j = K_j/Y_j = \frac{1}{KPF_j} * \left(\frac{\overline{b_{KL3,j}}}{\overline{pK_j}/KPF_j} \right)^{\sigma_{KL3,j}} * \left(\overline{b_{KL3,j}}^{\sigma_{KL3,j}} * \left(\frac{pK}{KPF_j} \right)^{(1-\sigma_{KL3,j})} + \overline{a_{KL3,j}}^{\sigma_{KL3,j}} * \left(\frac{pL_{sk3,j}}{LPF_{sk3,j}} \right)^{(1-\sigma_{KL3,j})} \right)^{(-1/\rho_{KL3,j})} * \frac{KL3_j}{Y_j} \quad (8)$$

$$\lambda_{sk1,j} = L_{sk1,j}/Y_j = \frac{1}{LPF_{sk1,j}} * \left(\frac{\overline{b_{KL,j}}}{\overline{pL_{sk1,j}}/LPF_{sk1,j}} \right)^{\sigma_{KL,j}} * \left(\overline{b_{KL,j}}^{\sigma_{KL,j}} * \left(\frac{pL_{sk1,j}}{LPF_{sk1,j}} \right)^{(1-\sigma_{KL,j})} + \overline{a_{KL,j}}^{\sigma_{KL,j}} * \left(\frac{pK}{KPF_j} \right)^{(1-\sigma_{KL,j})} \right)^{(-1/\rho_{KL,j})} * \frac{KL_j}{Y_j} \quad (9)$$

with:

$LPF_{skl,j}$, and KPF_j Respectively the labour and capital productivity factors, which give relative growth in productivity (their values are defined in section 3.6).

The Leontief parts of the production function, for intermediate consumption (IC) of energy products and materials & services products, are calculated as the BY calibrated ratio of each good over its aggregate good E (Eq.10) or Mat (Eq.11). The prices pE and $pMat$, relevant for the CES trade offs in the production function, are calculated as the weighted average of the prices of the goods out of which they are composed (Eq.12 to 13). The prices of the individual products for IC, in turn, are determined on the basis of pY and pM as it will be explained in section 3.2.5 below.

$$\alpha_{ij} \equiv \frac{IC_{ij}}{Y_j} = \frac{\overline{IC_{ij,0}}}{\overline{E_{j,0}}} * \frac{E_j}{Y_j}, \text{ for } i = COA, OIL, GAS, REF, ELC \quad (10)$$

$$\alpha_{ij} \equiv \frac{IC_{ij}}{Y_j} = \frac{\overline{IC_{ij,0}}}{\overline{Mat_{j,0}}} * \frac{Mat_j}{Y_j}, \text{ for } i = EIN, MAN, LSS, HSS, TRA \quad (11)$$

$$pE_j = \frac{\sum_i (IC_{ij} pIC_{ij})}{E_j}, \text{ for } i = COA, OIL, GAS, REF, ELC \quad (12)$$

$$pMat_j = \frac{\sum_i (IC_{ij} pIC_{ij})}{Mat_j}, \text{ for } i = EIN, MAN, LSS, HSS, TRA \quad (13)$$

For the model to achieve equilibrium at all levels of the nested CES tree with the help of only a few variables: Each sector's Y_j (for OIL its imports M) and producer's price pY_j ; plus the prices of the non-aggregate labour inputs $pL1$, $pL2$, $pL3$ (constrained by wage curves, see section 3.3.2); and the price of capital (which follows from the solution of the capital market, see section 3.4). Intensities of non-aggregated variables: $\lambda_{skl,i}$ to $\lambda_{sk3,i}$ and κ_i are also model variables. The prices of intermediate inputs are endogenous, their calculation is the topic of section 3.2.5. Prices of CES aggregates (KLE to KL3 down the nested CES tree of Figure 3.3) are calculated according to CES specifications, for which the general description is given by Eq.14, similar to Eq.6 before, describes the quantity of primary factors or intermediate inputs:

$$pAB_j = \left(\overline{a_{AB_j}}^{\sigma_{AB_j}} * pA_j^{(1-\sigma_{AB_j})} + \overline{b_{AB_j}} * pB_j^{(1-\sigma_{AB_j})} \right)^{(1-\rho_{AB_j}^{-1})} \quad (14)$$

As an example, which is also one of the model's closure rules (see section 3.5), Eq.15 gives the calculation of pY_j :

$$pY_j = \left(\overline{a_{KLEM_j}}^{\sigma_{KLEM_j}} * pKLE_j^{(1-\sigma_{KLEM_j})} + \overline{b_{KLEM_j}} * (pMat_j AMEI)^{(1-\sigma_{KLEM_j})} \right)^{(1-\rho_{KLEM_j}^{-1})} \quad (15)$$

, with:

$\overline{a_{AB_j}}$ and $\overline{b_{AB_j}}$ CES coefficients for the substitution in production of sector j between the KLE aggregate and the Mat aggregate calibrated on BY data;

$pKLE_j$ and $pMat_j$ prices of inputs KLE_j and Mat_j for IC by sector j ;

AMEI	exogenous material efficiency improvement which reduces the perceived cost of Mat relative to BY – equivalent to APF_j in Eq.6 on p.81; ⁹⁵
σ_{KLEM_j}	elasticity of substitution between KLE_j and Mat_j (see section 3.6);
ρ_{KLEM_j}	calculated on the basis of σ_{KLEM_j} as in Eq.7 above.

3.2.2. International trade

Imports are elastic to the relative price of the domestic over the international good and proportional to the change in domestic output (Eq.16). For the OIL sector no domestic production is assumed and imports follow (price elastic) demand:

$$\frac{M_j}{Y_j} = \frac{\overline{M_{j,0}}}{\overline{Y_{j,0}}} \left(\frac{\overline{pM_{j,0}}}{\overline{pY_{j,0}}} \frac{pY_j}{pM_j} \right)^{\sigma_{pM_j}} \quad (16)$$

, with:

$\frac{M_j}{Y_j}, \frac{\overline{M_{j,0}}}{\overline{Y_{j,0}}}$ ratio of imports over domestic output in sector j (the index 0 indicates a BY value);

pM_j, pY_j resp. the import price and the domestic producer's price for goods of sector j;

σ_{pM_j} Armington price-elasticity for imports (see section 3.6).

Foreign demand relative to its BY quantity is modelled (Eq.17) as a mirror image of imports with an Armington-style price-elasticity (see section 3.6). This elasticity determines foreign demand relative to an exogenous trend δ_X , representing autonomous growth in the volume of international trade:

$$\frac{X_i}{\overline{X_{i,0}}} = \left(\frac{\overline{pX_{i,0}}}{\overline{pM_{i,0}}} \frac{pM_i}{pX_i} \right)^{\sigma_{pX_i}} (1 + \delta_X) \quad (17)$$

, with:

X_i and $\overline{X_{i,0}}$ exports of goods of sector i (the index 0 indicates a BY value);

σ_{pM_j}, pX_i resp. the international price (for j=i) and the domestic export price of good i;

δ_X autonomous export volume growth trend;

σ_{pX_i} export price elasticity (see section 3.6).

To simplify matters, the same international prices are used for imported goods, and for the foreign goods with which South African export products compete in foreign markets.⁹⁶ This does not mean that domestic and international goods are homogenous. Instead, the price elasticities of international trade, σ_{pM_j} and σ_{pX_i} (see section 3.6), incorporate a certain view on the substitutability of domestic and foreign goods. With these price elasticities being different from 1 South African and foreign goods can be said to be non-perfect substitutes, and thus non-homogenous.

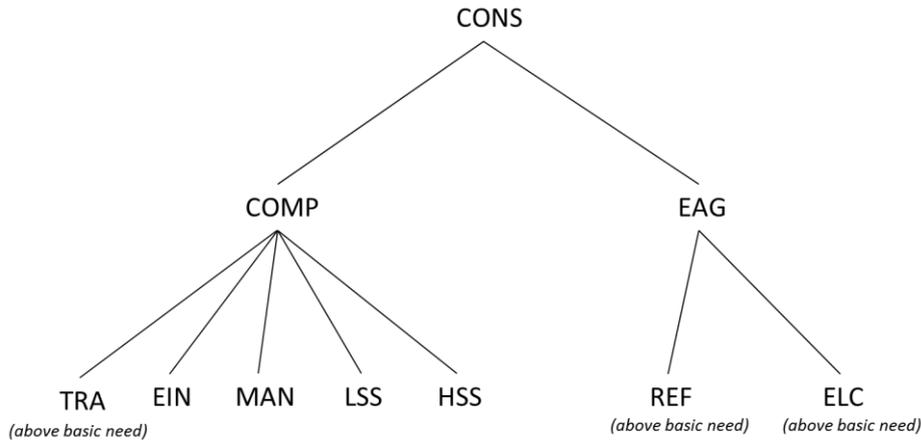
⁹⁵ Note that "efficiency" of usage is the inverse of productivity of an input or factor, and that $pMat_j$ is therefore multiplied with AMEI, unlike pK and pL in Eq. 8 and 9, which are divided by the sector-specific productivity trend to reduce their "perceived" cost.

⁹⁶ A verification of the comparability of domestic and international products was out of scope for this thesis.

3.2.3. Trade-offs in Consumption

Trade-offs in consumption are defined per household class and at the level of *per capita* volumes of consumption. They are modelled through nested CES specifications (Figure 3.4). However, considering the strong inertia in the consumption of energy and transport by households – e.g. rigid housing location choices determining households’ demand for energy for private transport –, CES flexibility is allowed only beyond basic needs, i.e., exogenously set floors of volume of consumption for ELC, REF and COA. Floors of consumption and price elasticities of substitution are given along with the model’s parameterisation in section 3.6.

Figure 3.4 Household classes’ decision tree for volumes of consumption (*per capita*)



Above the exogenously set floors of quantities of volume of consumption mathematical expression of the consumption functions for *per capita* consumption by household class is similar to that of production function by sector and is as follows:

Per capita volume of consumption of aggregate non-constrained consumption CONS for household class Hh is a model solution variable, constrained by households consumption budget constraint (see the discussion of household income and expenditure in section 3.3 below). *Per capita* volume of the energy aggregate good EAG and of the composite good COMP for household class Hh are given by similar CES specifications (Eqs.18 and 19):

$$EAGpc_{Hh} = \left(\frac{\bar{a}_{CONS_{Hh}}}{pEAG_H} \right)^{\sigma_{CONS_{Hh}}} * \left(\bar{a}_{CONS_{Hh}}^{-\sigma_{CONS_{Hh}}} * pEAG_H^{(1-\sigma_{CONS_{Hh}})} + \bar{b}_{CONS_{Hh}} * pCONS_H^{(1-\sigma_{CONS_{Hh}})} \right)^{-1/\rho_{CONS_{Hh}}} * CONSpc_{Hh} \quad (18)$$

$$COMPpc_{Hh} = \left(\frac{\bar{b}_{CONS_{Hh}}}{pCOMP_H} \right)^{\sigma_{CONS_{Hh}}} * \left(\bar{a}_{CONS_{Hh}}^{-\sigma_{CONS_{Hh}}} * pEAG_H^{(1-\sigma_{CONS_{Hh}})} + \bar{b}_{CONS_{Hh}} * pCONS_H^{(1-\sigma_{CONS_{Hh}})} \right)^{-1/\rho_{CONS_{Hh}}} * CONSpc_{Hh} \quad (19)$$

, with:

$EAGpc_{Hh}$ and $COMPpc_{Hh}$ household class Hh 's *per capita* volume of consumption of the EAG and COMP aggregates;

$\overline{a_{CONS_{Hh}}}$ and $\overline{b_{CONS_{Hh}}}$ CES coefficients for the substitution between EAG and COMP for household class Hh calibrated on BY data;

$\sigma_{CONS_{Hh}}$ elasticity of substitution between EAG and COMP;

$pEAG_H$ and $pCONS_H$ prices of the consumption aggregates EAG and COMP for household final consumption (Eq.24-25 below);

and $\rho_{CONS_{Hh}}$ (Eq.20):

$$\rho_{CONS_{Hh}} = \frac{(\sigma_{CONS_{Hh}} - 1)}{\sigma_{CONS_{Hh}}} \quad (20)$$

On the basis per capita volume of final consumption of the EAG and COMP aggregates by household class the model calculates the per capita volume of final consumption of the individual goods. Eqs.21 and 22 illustrate this for EIN and MAN.

$$FC_EINpc_{Hh} = \left(\frac{\overline{a_{COMP_{Hh}}}}{pEIN_H} \right)^{\sigma_{COMP_{Hh}}} * \left(\overline{a_{COMP_{Hh}}}^{\sigma_{COMP_{Hh}}} * pEIN_H^{(1-\sigma_{COMP_{Hh}})} + \overline{b_{COMP_{Hh}}} * pMAN_H^{(1-\sigma_{COMP_{Hh}})} + \overline{c_{COMP_{Hh}}} * pLSS_H^{(1-\sigma_{COMP_{Hh}})} + \overline{d_{COMP_{Hh}}} * pHSS_H^{(1-\sigma_{COMP_{Hh}})} + \overline{e_{COMP_{Hh}}} * pTRA_H^{(1-\sigma_{COMP_{Hh}})} \right)^{-1/\rho_{COMP_{Hh}}} * COMPpc_{Hh} \quad (21)$$

$$FC_MANpc_{Hh} = \left(\frac{\overline{b_{COMP_{Hh}}}}{pMAN_H} \right)^{\sigma_{COMP_{Hh}}} * \left(\overline{a_{COMP_{Hh}}}^{\sigma_{COMP_{Hh}}} * pEIN_H^{(1-\sigma_{COMP_{Hh}})} + \overline{b_{COMP_{Hh}}} * pMAN_H^{(1-\sigma_{COMP_{Hh}})} + \overline{c_{COMP_{Hh}}} * pLSS_H^{(1-\sigma_{COMP_{Hh}})} + \overline{d_{COMP_{Hh}}} * pHSS_H^{(1-\sigma_{COMP_{Hh}})} + \overline{e_{COMP_{Hh}}} * pTRA_H^{(1-\sigma_{COMP_{Hh}})} \right)^{-1/\rho_{COMP_{Hh}}} * COMPpc_{Hh} \quad (22)$$

, with:

FC_EINpc_{Hh} and FC_MANpc_{Hh} household class Hh 's *per capita* volume of FC of EIN and MAN;

$\overline{a_{COMP_{Hh}}}$ to $\overline{e_{COMP_{Hh}}}$ CES coefficients for the substitution between non-energy goods for household class Hh calibrated on BY data;

$\sigma_{COMP_{Hh}}$ elasticity of substitution between the elements of COMP (EIN, MAN, LSS, HSS, TRA) for household class Hh ;

$pEIN_H$, $pMAN_H$, etc. prices of household final consumption of EIN, MAN, LSS, HSS, and TRA (see section 3.2.5);

and $\rho_{COMP_{Hh}}$ (Eq.23):

$$\rho_{COMP_{Hh}} = \frac{(\sigma_{COMP_{Hh}} - 1)}{\sigma_{COMP_{Hh}}} \quad (23)$$

The equations for LSS, HSS and TRA are similar, but of course with the first term of the equation

referring to their CES coefficients (respectively: $c_{COMP_Hh}/pLSS_H$, $d_{COMP_Hh}/pHSS_H$ and $e_{COMP_Hh}/pHSS_H$) and these products prices for household final consumption. For REF and ELC, as sub-items of the EAG aggregate good the price-elastic substitution is defined in a similar manner as that between EIN and MAN in Eqs.21 and 22, but with only two goods in the CES function.

The price of the aggregate goods for household final consumption is calculated in a for a nested CES framework standard way, as the weighted average of its components, which is (Eq.24-26):

$$pCOMP_H = \left(\overline{a_{COMP_{Hh}}}^{\sigma_{COMP_{Hh}}} * pEIN_H^{(1-\sigma_{COMP_{Hh}})} + \overline{b_{COMP_{Hh}}} * pMAN_H^{(1-\sigma_{COMP_{Hh}})} + \overline{c_{COMP_{Hh}}} * pLSS_H^{(1-\sigma_{COMP_{Hh}})} + \overline{d_{COMP_{Hh}}} * pHSS_H^{(1-\sigma_{COMP_{Hh}})} + \overline{e_{COMP_{Hh}}} * pTRA_H^{(1-\sigma_{COMP_{Hh}})} \right)^{(1-\rho_{COMP_{Hh}}^{-1})} \quad (24)$$

$$pEAG_H = \left(\overline{a_{EAG_{Hh}}}^{\sigma_{EAG_{Hh}}} * pREF_H^{(1-\sigma_{EAG_{Hh}})} + \overline{b_{EAG_{Hh}}} * pELC_H^{(1-\sigma_{EAG_{Hh}})} \right)^{(1-\rho_{EAG_{Hh}}^{-1})} \quad (25)$$

$$pCONS_{Hh} = \left(\overline{a_{CONS_{Hh}}}^{\sigma_{CONS_{Hh}}} * pEAG_{Hh}^{(1-\sigma_{CONS_{Hh}})} + \overline{b_{CONS_{Hh}}} * pCOMP_{Hh}^{(1-\sigma_{CONS_{Hh}})} \right)^{(1-\rho_{CONS_{Hh}}^{-1})} \quad (26)$$

3.2.4. Accounting for CO₂ emissions

The hybridisation procedure described in section 3.1.2 leads to an account of quantities of energy use per sector and per household class. It is therefore possible to account for CO₂ emissions from the burning of fossil fuels. On the basis of the quantities of IC of fossil fuels (COA, OIL, GAS, REF) direct CO₂ emissions of consumption of products i (COA, OIL, GAS, REF) by (productive) sector j , $eCO2_{ij}$, can be calculated, in the following manner (Eq.27):

$$eCO2_{iC} = \sum_i \sum_j (\gamma_{ij} \alpha_{ij} Y_j), \text{ for } i = COA, OIL, GAS, REF \quad (27)$$

, with:

γ_{ij} emission coefficient of fossil fuel use of product i in IC by sector j ;

α_{ij} technological coefficients of inputs IC_{ij} over output Y_j (see Eq.21);

Similarly, on the basis of quantities of total household (H) final consumption (FC) of fossil fuels the total direct CO₂ emissions of final consumption, $eCO2_H$, can be calculated (Eq.28). These direct emissions are restricted to the consumption of REF products due to the assumption that final consumption of COA will have disappeared by 2035:⁹⁷

$$eCO2_H = \sum_{Hh} FC_REF p_{c_{Hh}} * pop_{Hh} * \gamma_{REF,H} \quad (28)$$

⁹⁷ A modelling assumption is that household consumption of COA will have disappeared for reason of clean cooking fuel policies (IEA and WB, 2017), already in BY data there is no Household consumption of crude oil (OIL), whereas consumption of natural gas (GAS) is not significant. Government final consumption only consists of HSS, and investment also only uses non-energy goods (EIN, MAN, LSS, HSS, TRA). Direct CO₂ emissions from the consumption of exported fossil fuels do not count as South African CO₂ emissions and are therefore excluded from the analysis, whereas direct CO₂ emissions from domestic use of imported fossil fuels of course are included in South Africa's direct CO₂ emissions.

, with:

$FC_REF p c_{Hh}$ per capital volume of final consumption of REF in household class Hh;

pop_{Hh} the population of household class Hh;

$\gamma_{REF,H}$ emission coefficient of household final consumption of REF;

CO₂ emission factors for fossil fuel burning processes are based on Garg et al. (2006).

3.2.5. Price setting

The price of a good is built up differently for different users/consumers. The basis is the price of the resource of (productive or supplying) of sector j , $pRES_j$. This is the weighted average (according to total volume produced or imported) of the (domestic) producer price of sector j and the price of the international, imported, good j (Eq.29).

$$pRES_j = \frac{Y_j pY_j + M_j pM_j}{Y_j + M_j} \quad (29)$$

Assumptions about prospective international prices, pM_j , for imported goods follow in section 3.6. The producer price of sector j , pY_j , is endogenous and covers total costs of production (Eq.30), including: unit costs of a sector's intermediate consumption ($\alpha_{ij} * pIC_{ij}$), unit labour costs $\sum_{sk} (\lambda_{sk,j} pL_{sk,j})$, the unit value of CFC ($\kappa_j pK$) with pK being the price of the homogenous capital good, Net Operating Surplus (NOS_j) calculated with fixed mark-up rate $\overline{\tau NOS_{j,0}}$, and fixed rate-taxes (minus subsidies) on production ($\overline{\tau Y_{j,0}} pY_j$), the latter two calibrated as the BY data ratios over production costs. Intensities for inputs and factors follow from trade-offs in production (see below). Price-setting for labour and capital are described in sections 3.3 and 3.4.

$$pY_j = \frac{(\sum_i (\alpha_{ij} pIC_{ij}) + \kappa_j pK + \sum_{sk} (\lambda_{sk,j} pL_{sk,j}))}{(1 - \overline{\tau Y_{j,0}} - \overline{\tau NOS_{j,0}})} \quad (30)$$

To set prices per (intermediate) consuming sector or type of final demand an additional fixed mark-up rate is applied for energy products calibrated agent-specific margins, τMS_i , to differentiate prices by consumer. The generalized functional form for the sales price p_{ij} of a product coming from sector i to a sector or agent j is (Eq.31):

$$p_{ij} = (pRES_i (1 + \tau MC_i + \tau MT_i + \overline{\tau MS_{ij,0}}) + tFUEL_{ij} + \overline{tRES_{l,0}} + tCO2 * \epsilon CO2_i) * (1 + \overline{\tau SALE_{i,0}}) \quad (31)$$

, with:

$pRES_i$ the average resource price of good i ;

τMC_i commercial (trade) margins on sales of good i ;

τMT_i transport margins on sales of good i ;

$\overline{\tau MS_{ij,0}}$ specific margins on sales of good i to sector/agent j , fixed at BY calibration values;

$tFUEL_{ij}$	a volume-based fuel levy on consumption of refinery (REF) products by sector or agent j ;
$\overline{tRES}_{j,0}$	other volume-based product-taxes or subsidies on good i , calibrated on BY data;
$tCO2$	a CO ₂ tax per tonne of CO ₂ emitted in consumption of a fossil fuel;
$\varepsilon CO2_i$	sector i 's average CO ₂ emissions per unit of output, calculated as $\sum_j (\gamma_{ji} \alpha_{ji})$, for $j =$ COA, OIL, GAS, REF – see also Eq.27 on p.86;
$\overline{\tau SALE}_{i,0}$	the BY data calibrated sales tax (rate), applied only to FC (by G, H and for I) of non-energy goods and ELC.

Exports (foreign consumers) are exempted from $tFUEL$, $\overline{tRES}_{j,0}$, $tCO2$ and $\tau SALE_i$.

Commercial (τMC_i) and transport (τMT_i) margins are fixed for all sectors except for the TRA and LSS sectors. These sectors have negative margins, which represent the services they render for the (after factory gate) sales and transport of other sectors' products, domestic production and imports alike. Their negative margins are adjusted in such a way that total cross-sectoral transport and commercial margins sum up to zero. For trade (or commercial) margins going to LSS, τMC_{LSS} , this translates into closure rule (Eq.32):

$$\tau MC_{LSS} * pRES_{LSS} \left(\sum_j (\alpha_{LSS,j} Y_j) + FC_{LSS} + G_{LSS} + I_{LSS} + X_{LSS} \right) + \sum_{i \neq LSS} \left(\overline{\tau MC}_{i,0} pRES_i \left(\sum_j (\alpha_{ij} Y_j) + H_{FC_i} + G_i + I_i + X_i \right) \right) = 0 \quad (32)$$

For transport margins going to TRA, τMT_{TRA} , this gives closure rule (Eq.33):

$$\tau MT_{TRA} pRES_{TRA} \left(\sum_j (\alpha_{TRA,j} Y_j) + FC_{TRA} + G_{TRA} + I_{TRA} + X_{TRA} \right) + \sum_{i \neq TRA} \left(\overline{\tau MT}_{j,0} pRES_i \left(\sum_j (\alpha_{ij} Y_j) + H_{FC_i} + G_i + I_i + X_i \right) \right) = 0 \quad (33)$$

3.3. Labour market model

The labour market model is defined as 3 strictly separated (segmented) markets. IMACLIM-ZA in this way has a similar approach to labour market modelling as IMACLIM-Brazil (Lefevre, 2016), with three skill levels whose supply is defined exogenously. The differences are that skills have been defined as constant shares of the labour force (CSLF) and that explicit views on the future demand for skills have been incorporated in the structure and the values of elasticities of substitution of the nested CES production functions. The first part of this section motivates the choices for these two differences with other currently existing labour market models. The second part of this sub-section (3.3.2) treats how wages are set through a wage curve.

3.3.1. Modelling supply and demand for skills

Capital-high skill labour complementarity

First of all, modelling demand for labour by level of skill endogenously, like Acemoglu (2002) does, is not considered a suitable approach for South Africa, because (as mentioned in Chapter 2) technological change in South Africa likely does not depend very strongly on the amount of domestic R&D. The question is rather how fast South African firms adopt globally best available technology. Possibly, an endogenous model similar to that of Acemoglu could be developed to explain the process of technology adoption, but defining and calibrating such a model is out of scope here.

Instead, the choice has been made for a nested CES structure in which high skill labour is complementary to capital. The chosen structure is inspired by a complementary relationship found between equipment-capital and high skill labour by Krusell *et al.* (2000), who demonstrate a skill premium for equipment-capital on the basis of historic data for the US.⁹⁸ It is unknown whether their analysis holds for South Africa as well. And a further issue which limits the applicability of Krusell *et al.*'s study to IMACLIM-ZA is that their study only finds a correlation between equipment capital and high skill labour, and not between infrastructure capital and high skill labour. IMACLIM-ZA does not distinguish between these two types of capital. Still, copying the principle of Krusell's study is considered a practical way to represent recent findings showing that the demand for high skill labour seems to have increased with technological progress (ILO and OECD, 2015). In fact, an elaborate analysis of the South African labour market finds evidence that many sectors have been shedding low skill jobs while increasing demand for high skill jobs in the recent past (Banerjee *et al.*, 2007). Though the latter analysis shows that there are specific reasons for this to be happening in South Africa, Los *et al.* (2014) show that, in recent years, technological change has been a major explanation for decreasing demand for low skill labour and increasing demand for high skill labour, globally and for all sectors.⁹⁹

Though these studies seem to show convincingly that in recent decades technology has given an advantage to high skill labour over low skill labour, some caution is still required: The trend could be temporal and Los *et al.*'s study seems not to correct for exogenous increases in the level of educational attainment of the labour force, which is the definition of skill of labour in the WIOD database which Los *et al.* use for their analysis (Timmer (ed.), 2012). Nevertheless, the assumption of technological change leading to substitution of low skill labour by capital and high skill labour is a likely scenario for the future and deserves to be explored.

Conceptual issues with modelling a skill-segmented labour market

The idea to model the labour market as three separated (segmented) labour markets by level of skill assumes that there is no possibility for high-skill individuals to get jobs requiring lower skills. This

⁹⁸ Krusell *et al.* (2000) have only two types of labour for their estimation model whereas IMACLIM-ZA has three. Medium-skill labour in IMACLIM-ZA roughly corresponds to Krusell *et al.*'s unskilled labour category in terms of level of educational attainment, which can therefore be assumed to be higher for the US in the period studied by Krusell *et al.* than in South Africa in 2005.

⁹⁹ A disadvantage of the approach by Los *et al.* (2014) was that they did not account for outsourcing of service activities by industries, which is a well-known phenomenon (see also Chang, 2014). Considering that the same trend in skill demanding technological change takes place in all sectors, outsourcing of services does not explain the technological change towards more high skill labour in the entire economy.

assumption limits the complexity of the model and makes model resolution easier. Besides, representation of a job market in which jobseekers can move between skill levels raises conceptual issues (what does a ‘skill’ mean in this case?) and practical issues (how does one calibrate inter-skill mobility?). A skill-segmented labour market model for South Africa was tested in Schers *et al.* (2015). They showed that a conventional definitions of skills – being equivalent to the level of education of workers – in the case of South Africa and with above mentioned CES production function structure¹⁰⁰ led to a counter-intuitive result: more high than low skill unemployment. They identified a need to change some elements of the standard approach of supply and demand for skills to allow their projection to obtain a more plausible comparative development of skill-specific unemployment rates. Schers et al. (2015) then identified three axes for improvement of their model for supply and demand of labour by level of skill:

(i) Skills defined positional, as constant shares of the labour force

(ii) Differentiating income elasticities of consumption

(iii) Differentiating labour productivity trends by skills

The first solution can be explained as follows: The common approach in models with skill differentiation would be to define skills as constant levels of educational attainment (CEA). The CEA approach can be summarised to represent a view of the labour market in which firms look for sets of skills with worker’s educational degree being the indicator of the set of skills acquired. For ease of calibration, and for interpretability these skill thresholds would need to be maintained at a calibrated level of educational attainment, e.g. unfinished primary school for low or unskilled labour, and finished primary school plus unfinished high school for medium skill labour, completed high school and beyond for high skill labour. The unexpected result which Schers et al found in their trials with this CEA-approach was that unemployment ended up higher for high than for low skill labour. These results were explained from the fact that the projected increase in the level of educational attainment of the South African labour force (the amount of people having obtained a high school degree or higher) outgrows any possible increase in demand for high skill labour in sectoral production functions assuming reasonable labour productivity growth and elasticities of substitution.

Changing the way in which skills of labour are defined led to a more intuitive result. This alternative definition is to consider education as a positional good. In this view, what matters for firms are the relative, and not the absolute level of educational attainment of individuals. There is indeed some evidence that education has become increasingly “positional” over time (Bol, 2015). A simple way to model this second approach is then to define skills as a constant share of the labour force (CSLF). The shares are still calibrated on the level of educational attainment of the calibration year, but are then kept constant in projection, irrespective of how nominal educational attainment evolves. For South

¹⁰⁰ The nested CES production function structure used in IMACLIM-ZA is advantageous for high skill labour in the case of increasing capital productivity – which is one of the assumptions in model parameterisation. See the discussion in section 3.6.

Africa such an approach might make it possible to model the gap between low quality education for the majority of South Africa's population, and high quality education for a minority (Spaull, 2013).

The second proposal which could increase future demand for high skill labour in a CGE model with a segmented labour market is to differentiate income elasticities by product. This means that a higher demand for high skilled labour could be encouraged through the introduction of income elasticities of consumption differentiated by (sectoral) good. The rationale is that, as people get richer, they tend to spend a higher share of their income on goods and services other than basic needs, and that these (non-basic-needs) goods and services are high-skill intensive. However, the limited disaggregation in terms of goods of our model does not allow to properly exploit this option. Indirectly, Schers *et al.* (2015) in their CEA trials mechanically already incorporated such a high skill product bias in final consumption with increasing household income, because a higher skilled population led (in the CEA approach) to a relatively bigger population in their richest and highest skilled household income-skill (4 and 5). This led to a relatively bigger share in consumption of products being intensive in high skill labour too (HSS, see Appendix C.5 showing demand by household class in base year calibration data).¹⁰¹ But, as their "CEA" outcomes showed, this effect was insufficient to absorb all expected future high skill labour.

The third proposal, differentiating labour productivity trends by level of skill, is a way to introduce pressure on the high skill labour market into the model. Schers *et al.* (2015) postulate a uniform 1%-a-year labour productivity improvement across skills and sectors. In a CEA approach this would mean that not only more high skill labour with high (value added) labour productivity enters the labour market, but also that the increased high skill labour force obtains higher labour productivity on average. This might be double counting the benefits of educational improvement, unless technological progress indeed increases productivity for a given level of education. Calibration data to distinguish these two effects was not available. In a CSLF approach productivity gains can be considered to reflect the combined impact of the increase in educational attainment and technological change.

Besides these motivations for (physical) labour productivity gains, other phenomena, which Schers *et al.* (2015) do not take into account, also lead to (in IMACLIM-ZA exogenous) changes in labour intensity. Notably, Schers *et al.* (2015) propose that one could consider composition or quality effects translating into an exogenous increase of high skill labour-intensity (decreasing physical productivity) for some sectors. For example, shifting from producing basic equipment to producing technically complex equipment could require higher engineering costs in manufacturing industries (composition effect). Similarly, better enforcement of building regulations could require more consultancy work in building companies (quality effect). On average, physical labour productivity could (or should) still increase, but growth in high skill labour productivity would be below average in these cases.

¹⁰¹ A discussion of the distribution of the active population among household classes in regard to the level of skill of the class' labour force can be found in section 3.1.4 and Appendix C.6.

Conclusion: Acknowledging the heterogeneity of 2005 vs. 2035 skills and products

Taking a step back, it appears that the issue faced in modelling South Africa's future labour market composition stems from the fundamental heterogeneity of skills and products modelled in 2005 versus their counterparts a distant 30 years ahead. In the abstract framework of CGE modelling, both heterogeneities are hidden behind identical naming conventions in 2005 and 2035 (definitions of skills or of products). From this perspective, all suggested alternatives allow a similar acknowledgment of the hidden heterogeneities through a changed definition of either the skills themselves, their use in production or the complex nature of systems (or technologies) of production that use them. It is thus probable that either of these alternate approaches to skill segmentation could lead to similar, if not identical projections, if properly calibrated. As a result of identified limitations though, this thesis, like Schers *et al.* (2015), focuses on the most straightforward treatment of skill segmentation dynamics, fitting South Africa's situation, being a definition of skills as constant shares of the labour force (CSLF approach).

Adding investment in skills to the model

One of the constraints for the South African economy identified in Chapter 1 has been a shortage of high skill labour, pushing up salaries for this category, and thereby labour costs for industries (Banerjee *et al.*, 2007; Daniels, 2007). One could therefore consider investment in skills a potential channel to divert growth from a fossil-energy based trajectory towards a more environmentally friendly path of economic growth.

A way to incorporate such a pathway in a macro-economic model would be to assume a link between an investment in education and the skills of labour. However, no sound basis for assumptions about the link between investment in education and the output of education in terms of degrees could be found. For instance, Grigoli (2014) points at "education spending inefficiency", to explain that no straight-forward relationship can be found between enrolment in secondary education and spending on education. According to Grigoli, different factors seem to influence inefficiency in enrolment in secondary education – he finds adult literacy, income inequality, the proportion of the government wage bill as a share in total government spending, population density, government effectiveness, and GDP per capita correlating to education spending efficiency – and he arrives at the conclusion that many developing and emerging countries could increase net enrolment levels in secondary education without increasing spending. This conclusion might be a bit far-fetched though, as Grigoli also admits that he has no information about quality of education for developing and emerging countries, because most countries do not measure comparable indicators for quality of education such as PISA scores. His finding, for instance, that South Africa could increase net secondary school enrolment without additional costs by about 25 over 100 pupils neglects the signals about problems with low educational quality as signalled in Altieri *et al.* (2015). Intuitively, quality of education seems to be relevant for education's impact on (labour) productivity, but there seem to be no means available to measure it. Considering Grigoli's findings, presently there seems to be little ground to assume a link between

quality of education and investment in education.

The modelling approach for a scenario on investment in education in this thesis therefore looks at two alternative ways to capture economic impacts of investments in skills. Firstly, this thesis explores what happens if in a positional labour market suddenly more people obtain a place in the high skill labour category.¹⁰² Secondly, one could imagine that investment does not change the positionality of skill segments in labour supply of the CSLF approach, but that it does have an impact on productivity. The approach then becomes to evaluate what minimum productivity gains would be required to make an investment economically and environmentally more beneficial than other channels of recycling of carbon tax revenue. The details of both these “*what if*” approaches to model an investment in skills of labour are given in section 4.5.

3.3.2. Wage setting and the price of labour

For labour, at each level of skill, the monetary market balance implies that the total of net wages paid equals the total of net wages earned. At the sectoral level, the ratio of each skill-related net wage is fixed to the economy wide average net wage at that level of skill. The “volumes” market balance means that the total labour endowment by skill (L_{sk}) – for respectively low, medium and high skill labour – minus the number of unemployed (by skill level, u_{sk}) equals the sum of labour by skill level of all sectors ($\lambda_{sk,i}Y_i$, see eq.34).

$$(1 - u_{sk})\overline{L}_{sk} = \sum_{j=1}^n \lambda_{sk,j}Y_j \quad (34)$$

Within the above definition of labour-skill segments, wage curves are used to model the relation between wage and unemployment. The corresponding unemployment rate is linked to the average net wage for each level of skill through a wage curve (Eq.35) in which wages are indexed on the Consumer Price Index (CPI), and increase with the increase in physical labour output productivity (ϕ_{sk}). Change in wage with unemployment is determined by the elasticity of the wage curve (σ_{wu}).

$$\frac{w_{sk}}{\phi_{sk}CPI} = \overline{w}_{sk,0} \left(\frac{u_{sk,0}}{u_{sk}} \right)^{\sigma_{wu}} \quad (35)$$

Average wage of skill sk in sector j , $w_{sk,j}$, varies with average wage of skill sk across sectors, w_{sk} . For the new inter-sectoral average wage for a level of skill to fit to the constraint of the wage curve of Eq.35 all sectoral wage rates are multiplied by a model variable, $VAR_{wage,sk}$ (Eq.36):

$$w_{sk,j} = \frac{w_{sk,j,0}}{w_{sk,0}} VAR_{wage,sk} \quad (36)$$

Labour costs of skill sk in sector j , $pL_{sk,j}$, are equal to the prevailing net wage $w_{sk,j}$ plus payroll taxes (both employers’ and employees’ social contributions), which are levied according to a skill-specific rate $\tau CS_{sk,j}$, and pension contributions (both public and employees’ private pension contributions)

¹⁰² One could imagine for instance an increase in the number of places (pupils or students) in schools which are considered to be the best by employers, or by sharply increasing educational quality and bridging social gaps for a lot of pupils or students in other schools.

$\tau OCS_{sk,j}$ by skill level sk (Eq.37): the former is calibrated on the hybrid I-O table (harmonised with current and financial accounts data) for 2005, while the latter is a model variable (see section 3.5).

$$pL_{sk,j} = (1 + \overline{\tau CS_{sk,j,0}} + \tau OCS_{sk,j,0})w_{sk,j} \quad (37)$$

3.4. Income distribution and the capital market

The first part of this section (3.4.1) discusses how all primary income (capital income and labour income plus taxes minus subsidies on production and products) is re-distributed to obtain the secondary distribution of income of the economic agents of IMACLIM-ZA: firms, households, government, and the rest of the world (ROW). The second part (3.4.2) makes the step from gross fixed capital formation to how the markets for physical and financial capital are defined.

3.4.1. Distribution and use of income

Primary distribution of income

Production and sales of goods and services (including imported ones) generate the following types of primary income:

1. Net wages;
2. Social (security) and pension fund contributions (over wages);
3. Gross operating surplus (GOS) including specific margins;
4. Taxes (minus subsidies) on production;
5. Taxes (minus subsidies) on products (e.g. a sales tax, fuel levy, and carbon tax).

Primary income is not equally distributed among the economies four economic agents (or eight, if one counts households as 5 agents): : firms, households, government, and the rest of the world (ROW). Net wages are household income. Social (security) contributions count as income to government. Pension contributions are counted at the same time as an income for firms, and as an accumulation of debts or an obligation of (financial) firms to households. Taxes (minus subsidies) on production and on products count as government income. GOS is calculated as the sum of total capital amortisation costs ($CFC_j = \kappa_j Y_j pK$); net operating surplus ($NOS_j = \frac{\overline{\tau NOS_{j,0}}}{(1 + \overline{\tau NOS_{j,0}})}$) and specific margins ($MS_j = \sum_i (pRES_j \tau MS_{ji})$) (Eq.38):

$$\sum_j GOS = \sum_j \left(\kappa_j Y_j pK + pY_j \frac{\overline{\tau NOS_{j,0}}}{(1 + \overline{\tau NOS_{j,0}})} + \sum_i (pRES_j \tau MS_{ji}) \right) \quad (38)$$

Gross Operating Surplus (GOS) in South African national accounts includes profits and mixed income. Profits and mixed income is partly attributed to firms' and government balance sheets as retained profits. Another part of GOS represents profits accruing to household owned companies. A third part of GOS consists of "imputed rents" for housing and goes to households as well.

Secondary distribution and use of income

Primary income is re-distributed through different kinds of transfers: interest payments or receipts,

taxes/contributions and subsidies/benefits, and other transfers, which for instance include insurance reimbursements, or development assistance (by or to South Africa). This is called the secondary distribution of income between agents. It results in agents' Gross Disposable Incomes (GDI), which is used by different economic agents in different ways:

Firms' (F) gross disposable income (after taxes), GDI_F , is defined (Eq.39) as firms' on BY data calibrated fixed share in GOS minus a 'debt service' for paying interests and dividends (RK_F), a fixed share in other types of transfers between agents (OT), and corporate income and property tax payments (T_{IF}). Additionally, firms are assumed to manage pension funds of households: Following the SAM 2005 pension contributions (PC) are added to firms' income, while pension benefits (PB , going to households) are subtracted, both after taxation. The difference between PC and PB is assumed equal to pension equity accumulation (PEQ) and is subtracted from firms' GDI and transferred to households, because it is a fund of household assets which (financial) firms only manage, not own.

$$GDI_F = \overline{\omega_{GOS,F,0}}GOS - RK_F + \overline{\omega_{OT,F,0}}OT - T_{IF} + PC - PB - PEQ \quad (39)$$

, with:

$RK_F = \tau i_F D_F$	interests and dividends at rate of returns τi_F over firms' net debt, D_F ;
$\overline{\omega_{GOS,F,0}}$	BY data calibrated share of firms in GOS income;
$\overline{\omega_{OT,F,0}}$	BY data calibrated share of firms in other transfers (OT);
$T_{IF} = \tau IF * GOS_F$	corporate income or profit taxes, calculated with average tax rate τIF times firm's GOS: τIF is a model solution variable in the Reference Projection (RP) and fixed at RP value in carbon tax scenarios;

For the calculation of PC, PB and PEQ, see Appendix A.1.3.

The only use of GDI_F is re-investing it, for firm's Gross Fixed Capital Formation ($GFCCF_F$). Firms' self-financing capacity (SFC_F) is calculated as the difference between GDI_F and $GFCCF_F$ (Eq.40). In BY data $GFCCF_F$ is 104.5% of GDI_F , this means firms are net borrowers (a negative SFC_F). The prospective rate of $GFCCF_F$ over GDI_F is assumed exogenously (see section 3.6). Firm's SFC_F is accumulated over the projection period and adds to BY $D_{F,0}$ to obtain new net debt (D_F). Debt accumulation is explained below.

$$SFC_F = GDI_F - GFCCF_F \quad (40)$$

Household class' (Hh) before tax Gross Domestic Income, $GDIBT_{Hh}$, is defined as (Eq.41):

$$GDIBT_{Hh} = \sum_{sk} (\omega_{W,sk,Hh} \sum_j (\lambda_{sk,j} Y_j W_{sk,j})) + \overline{\omega_{GOS,Hh,0}}GOS - RK_{Hh} + PB_{Hh} + \overline{\omega_{OT,Hh,0}}OT + SB_{Hh} \quad (41)$$

, with:

$\omega_{W,sk,Hh}$	household class Hh's share in net wage of skill sk (see Appendix A.1.3);
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$\lambda_{sk,j} Y_j w_{sk,j}$	net wages of skill sk in sector j , with labour intensity λ_j of Y_j ;
$\overline{\omega_{GOS,Hh,0}}$	household class' BY data calibrated fixed share in GOS;
RK_{Hh}	interests and dividends calculated as: $-\tau i_H D_{Hh}$, with households' interest rate τi_H over household class Hh 's net debt D_{Hh} ;
PB_{Hh}	pension benefits (see the description of Firm GDI above);
$\overline{\omega_{OT,Hh,0}}$	household class BY calibrated share Hh 's share in other transfers;
SB_{Hh}	social benefits, consisting of unemployment benefits and other social benefits, calculated as (Eq.42):

$$SB_{Hh} = rU_{Hh} * NU_{Hh} + \overline{rOSB_{Hh,0}} * N_{Hh} \quad (42)$$

, with:

rU_{Hh}	household class Hh 's average unemployment benefits per unemployed person, which equal CPI indexed Base Year (BY, 2005) household class Hh 's average unemployment benefits per unemployed person;
NU_{Hh}	household class Hh 's number of unemployed persons (see section 3.6), which equal a household class' BY share in unemployed by level of skill times the new total number of unemployed per level of skill of labour;
$\overline{rOSB_{Hh,0}}$	household class Hh 's average fixed on BY data calibrated average <i>per capita</i> other social benefits, which equal nil, as all BY social security has been allocated to unemployment benefits or other transfers (see Appendix B.4) , however it is used to model the per capita lump sum transfer to households in the RSUM scenario;
N_{Hh}	household class Hh 's population (see section 3.6);

A household class' *after tax* gross disposable income, GDI_{Hh} (Eq.43), is obtained from $GDIBT_{Hh}$ by deducting income taxes and adding the net growth in pension equity (PEQ, see Appendix A.1.3):

$$GDI_{Hh} = GDIBT_{Hh} * (1 - \tau IHh) + PEQ \quad (43)$$

, with:

τIHh	household class Hh 's income and property (revenue) tax rate, a model solution variable in the Reference Projection (RP) and fixed at RP value in carbon tax scenarios.
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As a closure rule, GDI_{Hh} plus net borrowing or lending, or a household class' self-financing capacity, SFC_{Hh} , is used for consumption, FC_{Hh} , and for gross fixed capital formation, $GFCF_{Hh}$ (Eq.44). SFC_{Hh} also equals the difference between a household class' gross savings (including growth in pension

equity) and $GFCF_{Hh}$ (Eq.45). Households' gross savings rates and households' investment rate ($GFCF_{Hh}$ over their GDI_{Hh}) are assumed exogenously (see section 3.6.4).

$$GDI_{Hh} - SFC_{Hh} = FC_{Hh} + GFCF_{Hh} \quad (44)$$

$$SFC_{Hh} = \tau S_{Hh} * GDI_{Hh} - GFCF_{Hh} \quad (45)$$

, with:

τS_{Hh} household class Hh's gross saving rate (section 3.6.4).

Governmental (G, Gov) Gross Disposable Income (GDI_G) is the sum of government's BY calibrated share $\overline{\omega_{GOS,G,0}}$ of GOS , its income from taxes ($T_Y + T_{Prod} + T_I$), and social contributions SC_{Hh} , plus its share $\overline{\omega_{OT,G,0}}$ in other transfers (OT) (Eq.46). Transfers for social security benefits, SB_{Hh} , consist (as explained above) of unemployment benefits and other social security benefits to households and are deducted from government income, just as the debt service RK_G – paid over public debt, D_G , at interest rate τi_G :

$$GDI_G = \overline{\omega_{GOS,G,0}}GOS + SC_{Hh} + T_Y + T_{Prod} + T_I - SB_{Hh} - RK_G + \overline{\omega_{OT,G,0}}OT \quad (46)$$

, with:

$T_Y = \sum_j (\overline{\tau Y_{j,0}} * pY_j * Y_j)$, the total of taxes (minus subsidies) on production;

$T_I = T_{IF} + \sum_{Hh}(GDIBT_{Hh} * \tau IHh)$, the total of firms' and household's income, profit and property (revenue) taxes;

$T_{Prod} = T_{Vol} + T_{Sales}$, product taxes consisting of volume based product taxes, T_{Vol} (Eq.47), and a sales tax, T_{Sales} (Eq.48), being respectively:

$$T_{Vol} = T_{Fuel} + T_{PrOth} + T_{CO2} \quad (47)$$

, with:

$T_{Fuel} = IC_{REF} * \overline{tFUEL_{IC,0}} + FC_{REF} * \overline{tFUEL_{FC,0}}$, the BY calibration value volume based fuel tax for respectively IC and FC of REF products;

$T_{PrOth} = \sum_i \left((Y_i + M_i - X_i) * \overline{tPrOth_{i,0}} \right)$, sector-specific other product taxes paid over IC, FC, G and I of volumes of products of sector i ;

$T_{CO2} = (eCO2_{IC} + eCO2_H) * tCO2$, the total quantity of CO₂ tax revenue calculated as the emissions from IC and FC (see resp. Eq.27 and 28 on p.86) times the carbon tax rate;

And:

$$T_{Sales} = \sum_i \left(\frac{\tau SALE_i}{(1+\tau SALE_i)} * (FC_i pFC_i + G_i pG_i + I_i pI_i) \right) \quad (48)$$

, with the assumption that $\tau SALE_i = \overline{\tau SALE_{i,0}}$ (it's BY calibration data value) for $i = \text{ELC, EIN, MAN, LSS, HSS, and TRA}$; and assumed zero for $i = \text{COA, OIL, GAS, REF}$.

Government uses its GDI_G minus the government's self-financing capacity (SFC_G), which is the public budget surplus (assumed negative, or a deficit) for: a. public expenditure, G^*pG – defined as an exogenously assumed share of South Africa's GDP (see section 3.6.4) –, and b. public investment $GFCF_G$, which is assumed to be a BY data calibrated constant share of GDP (Eq.49):

$$GDI_G - SFC_G = G^*pG + GFCF_G \quad (49)$$

, with G^*pG consisting only of consumption of HSS at price $p_{HSS,G}$, of Government FC of HSS.

SFC_G is also the annual change in the public debt (D_G), which accumulates according to the specification which follows below. The relative size of SFC_G over South Africa's GDP is assumed exogenously and functions as a model constraint (for more details see section 3.5 below). Private and corporate income and property (revenue) tax rates are the variables which adjust (at equal rates) to make SFC_G match the exogenously set budget constraint while respecting the constraints for public expenditure and investment ($GFCF_G$).

The rest of the world (ROW) is relevant for income distribution between domestic agents in a few instances: Firstly, the trade balance causes a monetary flow between South Africa and ROW, as will be shown in the presentation of the Balance of Payments (BoP) below. Secondly, we assume ROW to balance SA's surplus for "other transfers income" (Eq.50). Thirdly, ROW balances the sum of debt services of other agents, being a net receiver of interests or dividends from South Africa (Eq.51).

$$OT_{ROW} = \sum_{ag=H,F,G} (\overline{\omega_{OT,ag,0}} OT) \quad (50)$$

$$RK_{ROW} = - \sum_{ag=H,F,G} RK_{ag} \quad (51)$$

Below it will be shown that the total of final consumption and gross fixed capital formation for domestic agents is bigger than their Gross Disposable Income after taxation ($GDI_{AT,ag}$). Altogether with other budget constraints defined above, this means agents have net borrowing or lending (Self-Financing Capacity, SFC_{ag}), for which any shortage or surplus is automatically compensated by the Rest of the World, ROW (Eq.52).¹⁰³ (In BY calibration data households and ROW are net lenders, whereas Firms and Government are net borrowers.)

$$SFC_{ROW} = - \sum_{ag=H,F,G} SFC_{ag} \quad (52)$$

The total of domestic agents' net debt is automatically compensated by the Rest of the World, ROW (Eq.53). The interest rate of ROW, τi_{ROW} (Eq.54), is endogenous and is the counterpart of total of net domestic interest and dividend receipts, $\sum_{ag=H,F,G} RK_{ag}$, over the total net debt position of ROW, D_{ROW} .

¹⁰³ Might the exogenously assumed household savings rate become high enough, ROW becomes a net borrower of South Africa.

$$D_{ROW} = -\sum_{ag=H,F,G} D_{ag} \quad (53)$$

$$\tau_{i_{ROW}} = -RK_{ROW}/D_{ROW} \quad (54)$$

The requirement for equilibrium on the balance of payments (BoP) leads to another closure rule and shows how transfers of income, net borrowing and lending (SFC), and the trade balance are connected (Eq.55):

$$SFC_{ROW} = \sum_{i=1}^n M_i pM_i - \sum_{i=1}^n X_i pX_i + RK_{ROW} + OT_{ROW} \quad (55)$$

, with:

$\sum_{i=1}^n M_i pM_i$ the value of imports by South Africa;

$\sum_{i=1}^n X_i pX_i$ the value of South African exports.

The two principal variables through which the model can reach equilibrium on the BoP, given all behavioural rules discussed in this Chapter so far (e.g. on price setting and on trade-offs in international trade) are the domestic interest rates and the relative value of the vector of domestic prices (p_{ij}) compared to the vector of international prices (pM_i), in other words: the Real Effective Exchange Rate – whose role will be discussed in more detail in the next sub-section (see Box 5 in Chapter 4).

Accumulation of financial assets

As in Schers et al. (2015), the calculation of accumulated net debt for all agents, $D_{ag=H,F,G}$, assumes that an agent's gross self-financing capacity $GSFC_{ag}$, i.e. SFC_{ag} net of interest payments, evolves linearly over time between BY (2005) and the projection year (2035), allowing to express the accumulation of net debt as follows (Eq.56, see Appendix A.1.8 for its derivation):

$$D_{n,ag=H,F,G} = (1 + \langle \tau_{i_{ag}} \rangle)^n \overline{D_{ag,0}} - \sum_{k=0}^{n-1} (1 + \langle \tau_{i_{ag}} \rangle)^k \overline{GSFC_{ag,0}} - \sum_{k=0}^{n-1} (1 + \langle \tau_{i_{ag}} \rangle)^k (n-1) dGSFC_{ag} + \sum_{k=0}^{n-1} k (1 + \langle \tau_{i_{ag}} \rangle)^k dGSFC_{ag} \quad (56)$$

, with:

$\overline{D_{ag,0}}$ agent's BY calibration data net debt;

$\overline{GSFC_{ag,0}}$ and $GSFC_{ag,n}$ agent's Gross SFC, resp. from BY data, and in year n ;

n years projected into the future (in this thesis $n=30$);

$dGSFC_{ag} = \frac{(GSFC_{ag,n} - \overline{GSFC_{ag,0}})}{n}$, the average annual change in $GSFC_{ag}$;

$\langle \tau_{i_{ag}} \rangle = \frac{(\overline{\tau_{i_{ag,0}}} + \tau_{i_{ag,n}})}{2}$, the approximated average projection period interest rate.

The summations $\sum_{k=0}^{n-1} (1 + \langle \tau_{i_{ag}} \rangle)^k (n-1) dGSFC_{ag}$ and $\sum_{k=0}^{n-1} k (1 + \langle \tau_{i_{ag}} \rangle)^k dGSFC_{ag}$ can be approximated by geometric series to ease model solving: details follow in Appendix A.1.8.

3.4.2. Capital and investment

Characterisation of capital in IMACLIM-ZA

IMACLIM-ZA has three types of capital. These can all be derived from capital as a part of primary income, represent by GOS. This can be split into two types of capital: amortisation costs, also called consumption of fixed capital (CFC), and net profits *or* net operating surplus (NOS) (see sections 2.1.4 and 3.1.1). The third type of capital is financial capital, which is the value of financial assets or net debts and which grows through borrowing or lending. Putting it in a simplified manner, GOS provides the profits with which firms can pay returns to capital (RK, or interests and dividends) to their (financial) asset holders.¹⁰⁴

As discussed previously, the split in physical capital use and net profits is made to represent the technological dynamics of capital intensity of production hidden in the non-labour remainder of value-added (Gherzi and Hourcade, 2006). Isolated from the physical consumption of capital, profits in the accounting sense require their own specific dynamics. On the one hand, from a microeconomic perspective, assuming for instance competitive pressures and thus marginal cost pricing, profits could be interpreted as following the rule of aggregate decreasing returns to scale. On the other hand, the introduction of new products and technologies and the requirements by investors might be seen as a reason for profits to remain high. In theory, other behavioural “rules” than profit maximisation in perfect markets could be defined to determine future profit rates. To simplify matters IMACLIM-ZA models profits as fixed mark-up rates over the entire costs of production, assumed constant at their calibration value.

Another simplification is that the physical capital good in IMACLIM-ZA is modelled as a homogenous good across sectors: Investment is constrained by the assumption of a constant ratio (calibrated at BY value), of each of its components I_i to total consumption of fixed capital (CFC, $\sum_{i=1}^n \kappa_i Y_i$) (Eq.57) – with κ_i being the (physical) capital intensity of production (see Eq.8 above). The vector of all components I_i over CFC is called the β (beta) vector in IMACLIM-ZA (Eq.58):

$$\frac{I_i}{\sum_{j=1}^n \kappa_j Y_j} = \frac{\bar{I}_{i,0}}{\sum_{j=1}^n (\bar{\kappa}_{j,0} \bar{Y}_{j,0})} \quad (57)$$

$$\beta = \left\{ \frac{I_i}{\sum_{j=1}^n (\kappa_j Y_j)} \right\}_i \quad (58)$$

In contrast to IMACLIM-R (Hourcade et al., 2010), or for some sectors in soft-coupled IMACLIM models like IMACLIM-Brazil (Lefevre, 2016), physical capital is not immobilised in IMACLIM-ZA, because the model does not track accumulation of capital stocks by sector. Instead, the assumption is that the 30 year projection period creates sufficient time to gradually build up the capital stocks that are implicitly represented by CFC.

¹⁰⁴ In turn asset holders can provide funding if firms (and government) lack resources for investment, though nothing prevents borrowed money to be used for consumption.

Matching supply and demand for capital formation

The previous does not mean that physical capital intensity is unconstrained. It is constrained via its connection to the value of capital income in the sense of National Accounts (as GOS) and by the requirement for returns (interests and dividends) over accumulated financial assets of firms (net debts, D_F , discussed above).¹⁰⁵ This can be understood from the set of closure rules which constrain the capital market.

First of all, economic equilibrium requires that total investment in goods of sectors i equals total Gross Fixed Capital Formation (GFCF) by the agents (ag): Households (H), Firms (F), and Government (G) (Eq.59) – with pI_i calculated as the prices for FC according to Eq.31 above:

$$\sum_{ag=H,F,G} GFCF_{ag} = \sum_i (I_i p I_i) \quad (59)$$

As written in section 3.4.1, agent's GFCF is a fixed ratio over Gross Disposable Income after income and property taxation (GDI_{ag}) for Households and Firms, and a fixed ratio over GDP for Government. GOS_{ag} and RK_{ag} are part of agent's GDI. Technically, the implication of these behavioural rules for investment mean that a scenario will generate higher investment when agent's GDI is higher, especially of firms. This is either the case when profits are higher, if interest rates are low, or if profit taxes are low.

But, another requirement is that demand for investment (and thus domestic production) is sufficient. This means that IC, FC(incl. investment itself) and exports should be sufficiently high, and that substitution by imports should be low. The latter implies that there should be sufficient growth in income, through productivity gains and cost reductions. In this sense, one could argue that investment is endogenous – though severely constrained, or “semi-endogenous”.

Furthermore, a situation could turn up in which profits are high, profit taxes are low, but demand for capital (domestic output) is low as well – e.g. because taxes make other products expensive. In this case the domestic interest rates adjust at the same rate through a model variable (VAR_{τ_i} , Eq.60) to clear the capital market, moving redundant funds from firms, who are net indebted, to the two agents with negative net debts (net asset holders): Households and ROW.¹⁰⁶ (The interest rate of ROW adjusts according to Eq. 54 above.)

$$\tau_{iS/G/H} = \overline{\tau_{iS/G/H,0}} VAR_{\tau_i} \quad (60)$$

Another variable, the REER (discussed in section 3.4.1) *or* the relative height of the vector of domestic prices, p_{ij} , compared to the vector of international prices, pM_i , is also important, as it influences the trade balance, and therefore interacts with RK_{ROW} and SFC_{ROW} through the BoP (see Eq.55). All producer prices are model variables and can therefore adjust. In case of a devaluation of the real effective exchange rate of the Rand this means that the interest rate of ROW will be lower. For this

¹⁰⁵ Net debts also implicitly represent the history of past investment, at an aggregate level.

¹⁰⁶ Government is the other net indebted agent, and also produces net returns to financial capital going to H and ROW.

and other reasons, a prospective parameterisation is sought which warrants a “sufficient” rate of returns to financial capital (τi_{ag}) in this thesis’ Reference Projection (see section 3.6).

3.5. Overview of model variables and constraints

This section presents an overview of model solution variables and constraints that can be associated to them (Table 3.5, see also Appendix A.2). Most of the model’s constraints have been discussed above. Some concern elements necessary to guarantee market balances in the model, while some other constraints are merely technical in nature, and introduced to avoid loops in the calculation of variables, for instance as is the case for the commercial margins, τMC_{LSS} , and transport margins, τMT_{TRA} .

Indexing all absolute values from BY calibration used in the projection by the Consumer Price index (CPI) – e.g. past debts, or volume-based product taxes – allows the model to respect the standard general equilibrium rule of long-run money neutrality. The only exception to this rule is the set of net debts (D_{ag}) at BY calibration value: Their CPI-indexed values are additionally deflated by an exogenous factor meant to represent monetary inflation and to reduce the relative weight of historic debts on the future economy.

Lastly, the model is price homogeneous and units of real GDP are chosen to be its *numéraire*. The GDP price index (GDP PI) is therefore assumed constant. All reported price changes are therefore relative to the GDP price index, except when mentioned otherwise: e.g., for wages the adjective “real” is used to express their evolution relative to the Consumer Price Index (CPI).

Table 3.5 Overview of IMACLIM-ZA's constraints and variables

Variable	Closure rule	Comment
ρY_j	For ELC: Eq.30 on p.87 For other sectors: Eq.15 on p.82	Consists of a vector of 10 values: one for each sector. Together with the next closure rule (for Y_j) this constraint is the key element for balance of value flows in goods markets.
Y_j	Eq.4 on p.62	Consists of a vector of 10 values, one for each sector ; for OIL, M_{OIL} is the variable because there is no domestic production. This guarantees balance in quantities in goods markets.
FC_i	$FC_i = \sum_{Hh} FC_{i,Hh}$	Consists of a vector of 10 values: one for each sector: Total household final consumption of sector i's products should equal that of individual household classes.
κ_i	Eq.8 on p.81	Consists of a vector of 10 values: one for each sector.
$\lambda_{sk,i}$	Eq.9 on p.81 and its generalized form Eq.6	Consists of a matrix of 30 values: one for each sector and each of the three skill levels of labour.
τMT_{TRA}	Eq.32 on p.88	The rate of transport margins for the TRA sector adjusts in order for the total of transport margins to be zero.
τMC_{LSS}	Eq.31 on p.88	The rate of trade margins for the LSS sector adjusts in order for the total of trade margins to be zero.
VAR_{MSFC}	$VAR_{MSFC} = \sum_{Hh} \sum_i (\overline{pRES}_i \overline{\tau MS}_{i,FC,0} FC_{i,Hh})$	As a constraint on the structure of Hh consumption and to guarantee balance between the I-O table part of the model and agents' balance sheets, the total of specific margins paid over household FC of energy products (see Eq.31 on p.87) – at the rigid BY calibrated margins $\overline{\tau MS}_{i,FC,0}$ – is a separate value, which is used in the calculation of GOS and GDP, see resp. Eq.38 and 5 on p.94 and p.62.
VAR_{Tsales}	$VAR_{Tsales} = \sum_{Hh} \sum_i \left(FC_{i,Hh} p FC_i \frac{\overline{\tau SALE}_{i,0}}{(1 + \overline{\tau SALE}_{i,0})} \right)$	Similarly, the balance between primary income generated in the I-O part of the model and agents' primary income is guaranteed by a constraint on sales tax paid for in FC.
$\tau OCS_{sk,j}$	$\sum_j \sum_{sk} (\tau OCS_{sk,j} w_{sk,j} \lambda_{sk,j} Y_j) = PB$	Pension contributions are assumed equal to pension benefits (PB) in 2035: The rate of pension contributions over net wage of all skills and sectors, $\tau OCS_{sk,j}$, adjusts relative to its BY calibration values for all skills and sectors with the same rate.
VAR_{wage}	Eq.36 on p.93	Average net wage for all three skill levels are adjusts to clear the three labour markets at equilibrium unemployment.
$CONSp_{cHh}$	$GDI_{Hh} (1 - \tau_{SHh}) = \sum_i (FC_{i,Hh} p FC_i)$	Consists of a vector of 5 values of <i>per capita</i> volume of CONS (one per household class). This variable interacts with the budget constraint via the nested CES structure (section 3.2.3).
VAR_G	$\frac{\sum_i (G_i p G_i) GDP_0}{GDP \sum_i (G_{i,0} p G_{i,0})} = exp_target$	A multiplier of government final consumption (G, of HSS) to achieve an exogenously assumed growth in gov. expenditure.
D_{Hh}	Eq.55 on p.99	Consists of a vector of 5 values: one for each household class.
CPI	$= \sqrt{\frac{\sum_i (FC_i p FC_i) \sum_i (FC_{i,0} p FC_i)}{\sum_i (FC_i p FC_{i,0}) \sum_i (FC_{i,0} p FC_{i,0})}}$	The CPI is used for wage indexation and to deflate historic debts and other values or unit prices copied from BY data, like the volume-based product taxes (see section 3.4.1).
D_G, D_F	Eq.55 on p.99	Calculated in the same way as for households, with agent-specific endogenous variables and parameters.
$\tau IF, \tau HH$	$\frac{SFC_G}{GDP} = deficit_target$	Corporate profit taxes and private income taxes adjust at the same rate to achieve the budget deficit target (section 3.4.1).
$VAR_{\tau i}$	Eq.60 on p.101	See also Eq.59.

3.6. Prospective parametrisation

3.6.1. Evaluation of results of prospective energy-economic modelling

Applying a model for policy analysis

Regarding what economic analysis can contribute to our understanding of a societal issue, particularly that of climate change mitigation, I like to refer to a statement by De Bruyn (2013) who, in referring to Van Ierland and Hennipman, writes that economics should act as a teleological science. Economics should not discuss the objective of obtaining a certain mitigation objective, as it is surrounded by uncertainties about consequences which the discipline of economics cannot assess as quantifiable costs and benefits. De Bruyn states:

“Far more than assessing whether the costs of climate policy outweigh the benefits, economists should therefore devote their efforts to reducing the costs of such policy. What institutions can we design to remove the social obstacles faced at present and achieve a better balance between equity and efficiency? Fortunately this kind of comparative institutional analysis has a rich tradition in economic studies.” (De Bruyn, 2013)

Of course, no model predicts the future, and one needs to interpret model outcomes in the light of modelling assumptions. Still, a model helps in making expectations explicit, and in seeing the combined impact of multiple assumptions about the functioning of our world. Or, as Krugman puts it:

“I do not mean to say that formal economic analysis is worthless, and that anybody's opinion on economic matters is as good as anyone else's. On the contrary! I am a strong believer in the importance of models, which are to our minds what spear-throwers were to stone age arms: they greatly extend the power and range of our insight. In particular, I have no sympathy for those people who criticize the unrealistic simplifications of model-builders, and imagine that they achieve greater sophistication by avoiding stating their assumptions clearly. The point is to realize that economic models are metaphors, not truth. By all means express your thoughts in models, as pretty as possible (more on that below). But always remember that you may have gotten the metaphor wrong, and that someone else with a different metaphor may be seeing something that you are missing.” (Krugman, 1993)¹⁰⁷

In line with these two views, I think that it is important to make it explicit how policies are assessed. This is not an obvious, since prospective modelling cannot rely on observations to verify its outcomes.

Defining a reference projection

Reference and scenario projections are not predictions of South Africa's economic future, because multiple reference projections are possible, each with different assumptions about future values of the

¹⁰⁷ With thanks to a MAPS seminar participant for pointing me to Paul Krugman's reflections on the use of models.

models parameters. The Reference Projection only serves as a point of departure for the scenario analysis. It offers a reference in comparison to which one can estimate the relative impacts of different policy options. The difference between policy scenarios and the reference projection should not be considered as *the* expected impact of a policy, because, as mentioned above the reference projection is incomplete. Particularly, it lacks a damage functions that takes into account the economic impacts of climate change.

In this thesis, several scenario and reference projection parameters could not be based on bottom-up modelling insights, or other expertise. Also, often, only “reasonable” ranges of values were available for parameters. In those cases, values of parameters have been chosen in such a way that the combined set of parameters leads to a “coherent and reasonable” projection for a reference economic future of South Africa. This is an economic future that meets certain requirements, and which is in line with common understanding of future economic growth in South Africa. The underlying idea is that certain macro-economic variables do not change easily, or only tend to change within a certain, commonly observed, range. For instance, this seems to be the case for the labour and capital shares in value added, for the real exchange rate, and for interest rates and debt to GDP ratios. As such, the approach bears resemblance to Kaldor’s stylized facts (Kaldor, 1957), with the remark that (as discussed in Chapter 2) such stylized facts might not be a good guidance for economic modelling over the course of a few decades, because the technological future is uncertain and for developing countries maybe even more. I therefore stress once more that what is important is to be explicit about one’s assumptions.

This section presents a list of macro-economic indicators (in section 3.6.2) against which the reference projection has been evaluated in the process of its construction with the help of the prospective parameters, leading to their definition as given in sections 3.6.3 and 3.6.4.

Analysis of the robustness of findings

Of course, being explicit about one’s assumptions might not be sufficient to get a feeling for the robustness of one’s findings. For instance, Rozenberg *et al.* (2014) show that the preferable policy option or mitigation measure resulting from a modelling exercise depends on the definition of such a reference projection, and especially the choice (for values) of different drivers or dynamics in the projection. A few options exist to make the evaluation of modelling results more quantifiable or at least qualitatively insightful.

To increase the robustness of the analysis on what likely is the best policy for carbon tax revenue recycling in South Africa this thesis includes an analysis of carbon tax revenue recycling scenarios under alternative assumptions, and through sensitivity analyses on several model parameters. These are presented in Chapter 5. Sensitivity analysis helps understand what effect different modelling choices and different parameter values have on the evolution of economic activity in the reference projection and the different policy scenarios.

3.6.2. Criteria for establishing a Reference Projection parametrisation

Indicators to evaluate whether a Reference Projection (RP) responds to the criterion of representing a reasonable or “common sense” macro-economic future are listed here. Below follows a motivation for their choice and for “reasonable ranges of values”, if applicable.

Macro-economic, and trade related indicators:

1. GDP growth rate, and *per capita* GDP growth rate;
2. The Real Effective Exchange Rate;
3. Trade balance surplus or deficit and the Balance of Payments (BoP);

Public finance and government budget related indicators:

4. Public debt over GDP;
5. Government expenditure;

Investment and profitability related indicators:

6. Share of Gross Fixed Capital Formation (GFCF, or investment) in GDP;
7. Profitability of, or rate of returns on capital;

Labour and labour income related indicators:

8. Labour share of value added;
9. Unemployment rate by level of skill.

GDP growth rate, and per capita GDP growth

The combination of objectives for a “common sense” reference projection defined above is intended to lead to a “reasonable” rate of GDP growth. For reason of weak South African GDP growth numbers in recent years, and in the light of criticisms of the National Development Plan’s aspiration of a 5% average annual GDP growth (National Planning Commission, 2011; Natrass and Seekings, 2015) this thesis does not subscribe to establishing similarly high growth figures in its reference projection. Moreover, the policy changes analysed in this thesis do not concern the major structural reforms in economic policies that are generally considered as necessary for robust GDP growth (see for instance Hausmann, 2008). The objective is therefore to obtain average GDP growth around 3% per year.

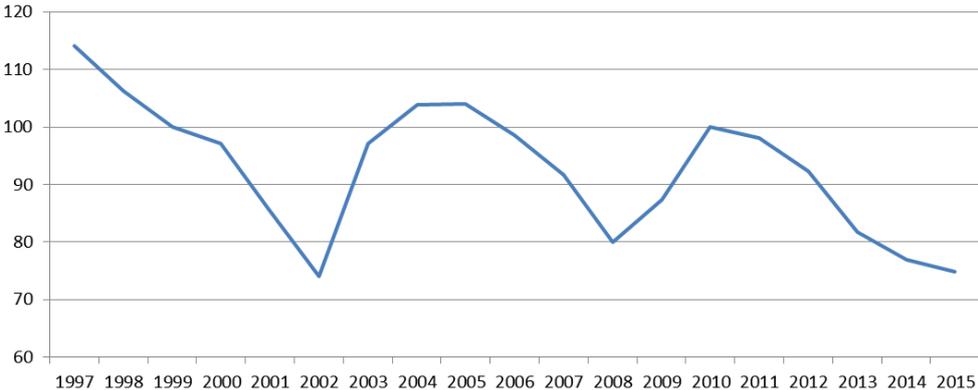
To achieve this GDP growth figure, many economic models rely on an increase in Total Factor Productivity (TFP) in combination with capital accumulation, which is often driven by an exogenous saving rate or exogenous foreign investment. In IMACLIM-ZA (as discussed in section 3.4.2) investment is constrained indirectly via the Balance of Payments and the need to generate income (profits and returns), given this constraint, inter-periodical investment is assumed to have followed demand for capital under resulting GDP growth numbers. Growth can thus been identified to be the result increases in the labour supply, of output productivity growth and of real cost reductions (see

section 2.1.4). Trends in output productivity growth are assumed exogenous (see the next sub-section) and consists of growth in capital and labour output productivity and of gains in efficiency in materials and services use in production. Due to productivity growth being defined by sector, and due to the endogenous trade-offs in production functions and due to endogenous structural change which influences average productivity growth and cost reductions, GDP growth can be considered a semi-endogenous outcome of multiple aspects of model parameterisation.

A “reasonable” real effective exchange rate

The REER is the Real Effective Exchange Rate, it represents the value of a basket of goods in domestic prices relative to prices of a country’s trading partners. The REER is an expression of purchasing power in domestic goods vs that in foreign goods. It can therefore, amongst other options, be represented by Relative Consumer Price Index (RCPI).¹⁰⁸ Historic data for the relative Consumer Price Index (RCPI) of South Africa show that in recent decades it varied up to 20 points around a value of 95 (with the 2010 index being 100), with 2005 finding itself in the upper range with an index of about 105 (Figure 3.5) (OECD, 2018).

Figure 3.5 Historic Relative consumer price index for South Africa (2010 = 100), source: OECD (2018)



For the movements in the REER different explanations could be imagined, some are related to the Market Exchange Rate (MER) of the Rand rather than relative changes in the prices of goods due to changes in production costs: One of these potential explanations for changes in the REER are changes in prices and demand for (mineral) resources such as coal, gold, platinum and diamonds. But, changes could also be caused by changes in the capital account, e.g. through flows of foreign direct investment (FDI). These have an impact on the MER, and if nominal prices do not adjust equally fast as the MER changes, this causes a change in the REER.

¹⁰⁸ The Real Effective Exchange Rate (REER) is officially defined as the average of the bilateral Real Exchange Rates (RERs) between the country and each of its trading partners, weighted by the respective trade shares of each partner (Catao, 2007). Catao says: “The RER between two currencies is the product of the nominal exchange rate (the dollar cost of a euro, for example) and the ratio of prices between the two countries.” And Catao also says: “economists usually measure the real exchange rate in terms of a broad basket of goods. Because the price of such a basket normally takes the form of an index number—such as the consumer price index (CPI), which includes both goods and services—the RER is also typically expressed as an index that can be bench-marked to any chosen time period.” (Catao, 2007) The OECD uses Relative Consumer Price Indexes and adds that they are a measure for international competitiveness (OECD, 2016). In this thesis, lacking the possibility to calculate RERs between South Africa and it’s trading partners, the rate of the GDP in domestic prices over the South African GDP in foreign prices is used as a proxy for the REER.

Explaining these movements of the REER is out of scope for this thesis, which therefore settles at the simple assumption that the RCPI or the REER should, in the long-run should remain between the historically observed values of 0.7 and 1.1 (2005 having a REER of 1.05 on this scale). Without information about the change in price of a basket of goods in South Africa's trading partners, alternatively one can compare South Africa's GDP in domestic prices with GDP calculated in foreign prices: by calculating the ratio of GDP expressed in domestic prices over GDP in import prices. This is what I use in this thesis to approximate the evolution of the REER relative to BY.

Trade balance and the Balance of Payments (BoP)

The height of the trade balance as a percentage of GDP, is for a large part fixed exogenously in IMACLIM-ZA. It can be related to several assumptions (see section 3.5). The equilibrium trade balance ($\sum_{i=1}^n M_i pM_i - \sum_{i=1}^n X_i pX_i$) depends on the entire Balance of Payments (BoP, see Eq.55 on p.99). The only component that could change the relative size of the trade balance over GDP is the sum of returns to capital ($RK_{ROW} = -\sum_{ag=H,F,G} RK_{ag}$). As discussed above, its size depends on the accumulation of debt (or assets/equity) and on agent-specific interest rates, $\tau_{i_{ag}}$, for domestic agents. With interest rates kept close to or above BY calibration values, assumptions about saving and investment relative to agent's GDI_{ag} (see sections 3.4.1 and 3.6.4) cause the trade balance to end up at a surplus of a few percentage points of GDP. This would be a reasonable perspective, because it would resemble the situation for South Africa from 1999 to 2003, even though it would mean a break in the trend compared to the period 2004 to 2016 in which South Africa ran a trade balance deficit in most years (World Bank, 2018).

Public debt over GDP

Another common indicator for the "health" of an economy is the level of public debt. With the national government and the central bank of a country often being the last resort in times of economic crisis, a high public debt could imply a limitation of their capacity to intervene. The objective is therefore that South Africa's public debt does not increase more than a few dozen percentage points between 2005 and 2035 and that it will maximally be around 70% of GDP.

Government expenditure

Section 3.4 discussed how capital intensity of production steers demand for investment, and therefore Gross Fixed Capital Formation (GFCF), and it mentioned that if demand for investment is low, while profits are high (e.g. due to capital productivity gains) – firms in IMACLIM-ZA will be inclined to increase returns (interests and dividends) to asset-holders (thus increasing their interest rate, τ_{i_F}). A likely response, in a country with high inequality and a need for improvement of public services, would be an increase in taxes and government expenditure. As an exogenous parameter, the share of government expenditure over GDP (through VAR_G , see Table 3.5) is used to keep the interest rate in check and to increase public services in pace with private profits.

Gross Fixed Capital Formation (GFCF) as percentage of GDP

Chapter 2 explained how capital accumulation is considered as one of the elements to explain economic growth, though the limitations of older economic hypothesis which considered capital accumulation to be a mono-directional driver of economic growth have been revised to take into account the need for technological change and economies of scale to avoid diminishing returns to capital. Despite these criticisms a certain rate of gross fixed capital formation over GDP is considered necessary (assuming the necessary technological change will also take place) for economic growth or to maintain a certain level of *per capita* GDP. South Africa's rate of GFCF over GDP has, since the end of the 1980's, been on the low end in international comparison with rates between 15 and 20 percent. South Africa's GFCF over GDP ratio is significantly lower than of some developed and emerging Asian economies, such as the Republic of Korea, Indonesia, and India, which in the same period registered GFCF over GDP rates between 20 and 35 percent of GDP, but it did not differ much from the ratios of Turkey, Brazil and Mexico since 2005, and is still above Nigeria's GFCF over GDP ratio which is estimated at 15% by World Bank.¹⁰⁹ By assumption, the reference objective for South African GFCF is that it should remain at least at the same rate over GDP as in recent decades, meaning around 18% of GDP, but ideally should increase.

Profitability of, or returns on capital

The profitability of, or the returns to capital can be defined in different ways. Common measures for returns focus on profitability over assets, but in IMACLIM-ZA the returns to investors (in the form of interests or dividends) is of importance too. Three definitions seem relevant to define the profitability of capital or returns on investment in IMACLIM-ZA: First of all it could be represented by a "return on assets" measure, which could be calculated by dividing IMACLIM-ZA's $RK_F (= \tau i_F * D_F$, see Eq.50 on p.95) by a fictive capital stock – which could be calculated by combining the value of CFC with an assumed depreciation rate; Secondly, it could be calculated as interests and dividends over assets or (financial) equity – represented by τi_F ; Thirdly, one could consider what part of firms' gross operating surplus, GOS_F , translates into interests or dividends to asset holders: This can be calculated by dividing RK_F by GOS_F after taxes – the rest of GOS either goes to government in the form of taxes or is "retained" for firm's own investment ($GFCF_F$) or saved (a positive SFC_F).

The first of the three definitions seems too theoretical, because it requires an unknown depreciation rate. It is therefore left out of consideration. For the other two definitions some initial tests with IMACLIM-ZA showed that they do not necessarily need to evolve in the same direction, e.g. when growth is capital intensive, GOS can be relatively high, but interests and dividends can be relatively low. Findings about a decreasing labour share (see next) suggest that profitability of capital must have risen in recent decades, but this is no reason to assume changes in the future evolution of returns to either capital, equity or investment can be made. The aim is therefore to parametrise RP in such a way

¹⁰⁹ World Bank, OECD data: <http://data.worldbank.org/indicator/NE.GDI.FTOT.ZS?locations=ZA-ID-KR-IN-NG-BR-TR-MX> (04/04/2017)

that both indicators discussed here do not witness strong deviations from BY values.

Labour share in value added

Without drastic changes in the negotiation positions of workers and of firm owners (e.g. through changes in labour laws), and without expectations of big changes in economic structure, the labour share of value added should not change dramatically. Data for the past decades does show that the labour share in national income or gross domestic production has decreased between 1995 and 2012 for many G20 economies, including South Africa (ILO and OECD, 2015). For a number of OECD countries¹¹⁰ it has been found that wages have increased at lower rates than labour productivity since 2000 (ILO and OECD, 2015).

The ILO and OECD G20 report discusses several explanations for this decline in labour share: technological change has been found to be *capital augmenting* and even labour *replacing* in recent decades; globalization seems to have had some impact by undermining labour's negotiation position; changing regulation of financial and capital markets has been found to disadvantage labour's negotiation position to some extent as well; institutional changes seem to undermine labour's negotiation position too, but ILO and OECD conclude that more studies are needed to better understand the role of institutional changes for labour's share of income (ILO and OECD, 2015).

It is unclear how these factors will continue to evolve in the coming decades for South Africa. The objective has therefore been defined that the share of gross labour income over GDP should stay within a range of a few percentage points (typically below 5 pct. points) from the calibrated Base Year (BY) value of 45% of GDP (see calibration I-O data in Appendix B.4). Of course, as stated before (see section 3.3.1), the vision on technological progress incorporated in the reference projection in this thesis is that technological progress continues to develop in a capital intensive direction, advantageous for high skill labour, and disadvantageous to low skill labour. Due to the assumption of fixed profit mark-ups, this does not necessarily affect the labour share in value added negatively.

Unemployment rate by level of skill

Foreseen demographic changes, the before-mentioned GDP growth objective, and exogenous productivity growth should lead to decreasing unemployment. This also implies that some changes take place to in South Africa's unemployment rate. This could be due to policy changes or due to other factors, such as demographic change which leads to a decreasing dependency ratio towards 2035 (National Planning Commission, 2011), or due to increasing educational attainment (see below), which could justify a part of assumed productivity increases. The expectation, and objective, for the reference projection is therefore a mildly optimistic decrease in the unemployment rate.

¹¹⁰ Australia, Canada, France, Germany, Italy, Japan, Republic of Korea, the United Kingdom and United States (ILO and OECD, 2015).

3.6.3. Production and trade-related drivers of growth

Identification of drivers of growth and related parametrisation

Several parameters in IMACLIM-ZA are important for the modelling of macro-economic along the lines of the indicators discussed above. The discussion of the question of modelling growth the context of development and environmental constraints in Chapter 2 led to the conclusion that within the scope of this thesis exogenous technological change would be the best possibility to model GDP growth. Another element identified relevant for growth was capital formation. As mentioned above, capital formation (or investment), is semi-endogenous in IMACLIM-ZA. The height of investment follows the capital intensity of domestic output. Investment and output can be said to be interdependent. Output therefore must have another determinant. This determinant is demand, in other words: growth in *real* income. Demand will grow if there is growth in factor productivity, and if there are other types of gains in purchasing power – meaning *GDP deflated* price decreases. Factor productivity growth and input efficiency gains (or factor or input intensity decrease of production) are therefore important drivers of growth.

Other parameters of importance are the set of price elasticities of production and for international trade: Higher price elasticities imply more flexibility to substitute products or factors that have become expensive for one or another reason by inputs or factors that stayed cheaper. This is especially important for the trade-off between imports and domestic products. Also in domestic production, higher price elasticity implies a greater flexibility to “substitute away” from more expensive factors or inputs to production. The discussion of exogenous assumptions about productivity growth and about price elasticities for trade-offs in production and trade continues in this sub-section.¹¹¹ Section 3.6.4 treats further prospective parametrisation, notably demography and the composition of future labour supply, but also parameterisation of economic agent’s expenditure behaviour.

Productivity trends

The assumptions about productivity growth are chosen in such a way that the RP achieves the above mentioned “reasonable” projection for GDP growth and other macro-economic indicators. On the other hand, those indicators cannot be the only criteria, and the assumed rates of productivity growth themselves should also reflect “common sense” values for productivity growth.¹¹² IMACLIM-ZA’s reference projection (RP) and all its “main” carbon tax revenue recycling scenarios (see section 4.3.1) are run with the following exogenous cross-sectoral median trends in productivity gains – for capital and labour they are differentiated at the sectoral level (see Appendix C.1):¹¹³

¹¹¹ The technological coefficients for electricity production (ELC sector) have already been discussed in section 3.1.2.

¹¹² To define these values, the standard definition of productivity growth needs to be translated to IMACLIM’s engineering-based definition of productivity growth: Often, productivity is defined as total value added (including taxes) over the amount of factor or input used (OECD, 2001a). At constant prices IMACLIM’s engineering, or physical output-based definition of productivity – physical volume of output over physical quantity of inputs or factor use (e.g. a worker or an hour worked for labour) – should have the same productivity growth rates. If on the other hand, for some reason, GDP deflated prices of products decrease, then physical output productivity will be lower than productivity measured using a value added-based definition. The expectation is that GDP deflated changes in unit prices will be limited, and that reference values for VA definitions of productivity are valid for IMACLIM-ZA as well.

¹¹³ Due to price-elastic trade-offs the finally resulting productivity growth can be different from these trends.

- Labour productivity (for all skill levels): +1.00% a year
- Capital productivity: +0.25% a year
- “Materials & services” (Mat) efficiency: +0.25% a year¹¹⁴

As a reference for labour productivity growth, recent numbers for G20 economies function as a benchmark: ILO and OECD find that labour productivity rose by about 17% between 1999 and 2013, which comes down to an average annual increase in labour productivity of 1.13% (ILO and OECD, 2015). It is unclear whether South Africa’s labour productivity increase should be expected to be higher, due to South Africa’s status as emerging country, or whether it should be expected to be lower due to South Africa’s economic woes discussed in Chapter 1. Klein (2012) finds a higher increase for labour productivity in South Africa, namely by 2.8% on average between 2007 and 2010, but this is a very short time period to estimate a long-term trend. Sensitivity analysis (see Chapter 5) is meant to overcome the lack of data or expertise by means of assessing the impact on the modelling outcomes of this assumption.

For capital productivity and for efficiency growth in use of materials and services’ inputs, lower growth rates have been chosen than for labour productivity: In the case of capital productivity this reflects a general impression that technology of production has become more capital-intensive (more machines and infrastructure) per worker, while for material and services productivity the assumption reflects a general impression that technology is moving slowly towards lighter materials and more efficient services. But, considering that no historic time series have been found for these factors, and that no expertise about their future development was consulted, a moderate growth rate of +0.25% per year has been chosen.

Energy efficiency improvements could have been added, as autonomous energy efficiency improvement (AEEI), but due to assumed strong increases in international energy prices, progress for a “balanced” reference projection in terms of energy efficiency is achieved without an AEEI. The role of energy efficiency improvements is furthermore the topic of an alternative scenario analysis which will be discussed in Chapter 5. The productivity assumptions therefore exclude autonomous energy efficiency improvement (AEEI).

Another question is the extent to which factors’ productivity improvements translate into factor income gains. These income gains do not necessarily correspond to a factor’s “effort” to improve its productivity – such as economic models which use marginal cost pricing suggest. For instance, the improvement of machinery or other types of capital by improved skills of workers who operate the machinery does not necessarily lead to wage increases if workers fear unemployment. Also, a producer’s influence on price setting could play a role in profit- and wage-setting in this particular industry or sector.¹¹⁵ Another view is that price-setting reflects negotiation power, though a variety of

¹¹⁴ Materials “productivity” is the inverse of the intensity or efficiency of production in non-energy goods & services.

¹¹⁵ Schers et al. (2015) saw this as a justification to explain why not all productivity growth automatically translates into wage growth. But,

reasons can be given for the lag of wage growth on labour productivity growth in recent decades (Cotis, 2009; ILO and OECD, 2015). Without adhering to the marginal cost pricing idea, but for reason of simplicity I stick to the idea that long-run labour productivity and real wage growth are generally correlated (as found for South Africa by Tsoku and Matarise, 2014). National skill-specific wages are indexed on labour output productivity growth (φ_{sk} in Eq.35 on p.93), which I choose to be represented by median cross-sectoral labour output productivity growth. This approach also reflects that sector-specific wages, for each skill level, change at the same rate for all sectors (see Eq.36 on p.94). Finally, concerning capital income IMACLIM-ZA (as previously discussed) assumes that profits are fixed mark-up rates over production costs, while returns to capital (represented by the interest rate) are endogenous.

Related parametrisation of production: Elasticities of KLEM production functions

In the same way as price elasticities of international trade determine the extent to which IMACLIM-ZA allows the modelled South African economy to adjust to new prices, elasticities of production and consumption functions determine how responsive the economy is to changes in relative prices of inputs and factors, or of consumer products. For reason of comparability the present study sticks to elasticities for the KLEM-part of the production functions as used in earlier work with IMACLIM-ZA (Table 3.6). These elasticities have been based on estimates by Van der Werf (2008) and Okagawa and Ban (2008), who provide international estimations of production function elasticities for KLEM-type nested-CES production functions.

The large set of sectoral values reported by both authors provides a range in which one may reasonably confidently place the values chosen for each IMACLIM-ZA sector. Appendix C.3 motivates the choice for the elasticities in IMACLIM-ZA and compares them with those by Van der Werf and from Okagawa and Ban.

Table 3.6 Reference projection and main Ctax scenario of nested-CES KLEM production function price elasticities*

	COA	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
KLE to Mat	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
KL to E	0.25	0.25	0.20	0.20	0.25	0.64	0.64	0.99	0.18
KL23 to L1**	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
KL3 to L2**	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
K to L3**	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10

* No estimates for the OIL sector are provided, as no domestic output is assumed between 2005 and 2035.

** L1 is low skill labour, L2 is medium skill labour, and L3 is high skill labour.

For the KL-part of the production function, the structure has been based on Krusell *et al.* (2000). As discussed in section 3.3.1, definitions of skills of labour and of capital differ between IMACLIM-ZA

retrospectively their assumption that labour productivity gains are only translated into wage gains to a limited extent seems to have been a necessary response to a devaluation of the REER of the South African Rand, while imports (e.g. of manufacturing products and of refinery products (fuels)) remained an imported component of household final consumption.

and Krusell *et al.*'s model for capital-labour (KL) substitution in the United States between 1963 and 1992. The chosen elasticities are therefore only loosely based on Krusell *et al.*'s estimates (see Appendix C.3 for a motivation).

Elasticities of the wage curve

For South Africa, differences have been found in wage setting behaviour for different parts of the labour market (Kingdon and Knight, 2006). Elasticities of wages to broad unemployment rates range from -0.02 (for high educated Africans) to -0.21 (for non-homeland Africans). They find higher elasticities for people working in the private sector, and below average elasticities for younger people, low-experienced persons and for men. In a similar fashion in Colombia, informal labour was found to have a wage curve elasticity of -0.18, whereas formal sector jobs were found to have a wage curve elasticity of -0.06 and public sector jobs to have no significant wage curve elasticity (Montuenga-Gomez and Ramos-Parreño, 2005).¹¹⁶ Also, Kingdon and Knight (2006) find that the broad definition of unemployment leads to more significant wage curve elasticities in South Africa than the more narrowly defined official unemployment rate. IMACLIM-ZA therefore uses a wage-unemployment elasticity of -0.10 for high and medium skill labour, and of -0.15 for low skill labour, assuming that it represents a labour market with more flexible characteristics.

International trade: trend in export volume

Having signalled the importance of the growth in demand for GDP growth, it should be evident that growth in international demand needs to develop in parallel to growth in domestic demand in order for international demand not to slow-down South African GDP growth. A trend-increase is modelled around which the price-elastic export volume evolves (δX in Eq.28 on p.83). It reflects the growth of South African export markets (Europe, China, Other Asia, Other Africa, the US) independent of terms-of-trade variations. This trend in export market growth is set at +2.0% a year, which is lower than the average 3.6% annual growth in volume of world trade from 2000 to 2016 (CPB, 2017) – though it is close to average growth in volume of world trade from 2005 to 2016 (of 2.6% per year), and about equal to the growth rate in the most recent years, being 1.3%-2.7% (CPB, 2017). Assuming export growth to equal the lower range of 2.0% might be considered a conservative estimate. But, whether global growth in trade should be estimated higher for the years to come is unknown, nor is it known whether the volume in global growth reflects growth in the volume of South African exports. These are factors of importance for the future of South African exports, just like investment in South Africa's physical infrastructure and the global evolution of transport costs.

International prices

Another factor that determines the South African perspective for growth related to international trade

¹¹⁶ The period of their analysis might be too short to qualify for Blanchflower and Oswald's (1995) observation that the wage curve is rather a long term mechanism, which can have short term deviations. Still, there might be a logic for a higher elasticity for informal work in a highly unequal country with significant poverty: Colombia had about 8.2% of its population below the poverty line and 1.1% living in severe poverty (UNDP, 2013). And Colombia had a Gini index of 53.5 in 2013 according to the World Bank, putting it, like South Africa, among the top 20 of most unequal countries.

is the future evolution of international prices of goods and services. Sections 3.4 and 3.5 discuss how the height of the vector of international prices relative to the vector of domestic producer prices is endogenous in IMACLIM-ZA (while the model is price-homogenic), with the GDP Price Index being its numéraire. As a consequence, it is not possible to define future international prices in an absolute sense (deflated by the GDP PI) in IMACLIM-ZA. However, international prices can change relative to each other. As a reference price I use the international price for high skill services, pM_{HSS} , for the reason that its price is likely the most constant due to the nature of the services sector (e.g. real estate, R&D, education and health care) to be labour intensive and to offer less possibilities for productivity gains than other sectors.

The assumed relative evolution of international prices follows those of the import prices in consulted SATIM runs for reasons of consistency (see section 3.1.2), being: For imports of COA the assumption is that the import price, pM_{COA} , evolves like the domestic price of coal for electricity production in SATIM's updated IRP run without a Ctax (+50%); For imports of GAS I use SATIM's average import price for natural gas and LNG relative to its value in 2010 (no data available for 2005/2006), being about +120%; For OIL, no data was available from the electricity module of SATIM and a value in-between that of COA and GAS was chosen (+80%), while for REF the electricity module of SATIM gives domestic diesel prices to increase by about 40%, but a higher value is chosen to reflect the increase in international oil price, thus arriving at an assumed +60% price increase. For ELC, no increase in its (GDP PI deflated) import price is foreseen in SATIM's electricity module in the Updated IRP run.

For other prices the assumption is that international prices change in a similar manner as domestic resource prices, relative to $pRES_{HSS}$: Manufacturing and other industrial prices might decrease in real (GDP deflated) terms relative to those of high skill services thanks to higher productivity gains, thus for pM_{MAN} I assume a decrease of 10% relative to pM_{HSS} , and the same for the LSS sector (e.g. for agriculture, construction, trade & retail, hotels & restaurants). TRA and EIN are assumed not to benefit as much from productivity-driven price decreases, because they face increased energy prices, thus their prices are assumed constant relative to pM_{HSS} .

The assumptions about international prices for RP and Ctax scenarios are summarized in Table 3.7.

Table 3.7 Evolution of international prices (pM_j) in 2035 for RP and Ctax scenario relative to pM_{HSS}

	COA	OIL	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
Assumed prices foreign goods relative to pM_{HSS} in 2035, as pct of BY relative price	150%	180%	200%	160%	100%	100%	90%	90%	100%	100%

Price elasticities of international trade

Price elasticities for substitution between domestic and imported goods have been based on estimations for the GTAP5 database (Dimaran et al., 2002). Due to differences in sector aggregation

and categorisation, GTAP values for price elasticities of imports could not be used in a straightforward manner. Also, elasticities of substitution for international trade turned out to be important for model resolution. To facilitate obtaining a “coherent and reasonable” reference projection for South Africa’s economic future, values a bit above those estimated by Dimaran *et al.* have been chosen (Table 3.8). For ELC a very low elasticity has been assumed, because imports are severely restricted by technological potential. For OIL there is no domestic production. A more detailed discussion of the chosen elasticities of substitution is given in Appendix C.2.

To model exports one option often used in CGE modelling is to represent exports as a matter of choice for domestic producers to produce for the domestic or for the international market. In IMACLIM-ZA another approach is used, in which Armington-style price elasticities determine ROW’s choices for substitution between South African and international goods. Using the approach of Cabral and Manteu (2013) (see Appendix C.2) price elasticities of international demand are estimated in three steps: First I calculate the shares of the main export-markets for South Africa’s main export products on the basis of data from OEC (2017). Secondly, price elasticities for imports per category of goods and country or region were consulted (Zhang and Verikios, 2006). Thirdly, using the shares of export markets by product and the import price elasticities of these export markets, the South African export price elasticities were estimated (Table 3.9). Additionally, for ELC a very low elasticity is assumed, because exports are severely restricted by technological potential. The OIL sector has no domestic production.

Table 3.8 Reference projection and main Ctax scenario Armington price elasticities of imports

	COA	OIL	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
Assumed Armington elasticities imports	0.75	-	0.75	2.00	0.25	3.00	4.00	1.50	1.90	1.50

Table 3.9 Reference projection and main Ctax scenario Armington price elasticities of exports

	COA	OIL	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
Assumed price-elasticities exports	2.00	-	1.00	1.50	0.25	2.00	2.00	1.50	1.90	1.50

3.6.4. Prospective demography and parameterisation of household behaviour

Prospective population and labour force by educational attainment

To have an idea of future educational attainment, similar to Schers et al. (Schers et al., 2015), estimations by De Franclieu (De Franclieu, 2015) are used.¹¹⁷ IMACLIM-ZA uses a conservative adjustment (the Low Educational Progress scenario: LEP) of projections for future levels of educational attainment for South Africa by the New Wittgenstein Centre for Demography and Global Human Capital (K.C. et al., 2013) with middle UN population prospects (UN DESA, 2013). K.C. *et*

¹¹⁷ For scenarios of total population by age group and working age population by educational attainment level, as well as for estimations of expenditure by student I am grateful to Louis de Franclieu for the work he did during his internship at CIRED.

al. estimate future attainment levels on the basis of a historic link between present and future educational enrolment levels by type of education and age group. IMACLIM-ZA's LEP reflects concerns about quality of primary and secondary education, and about high public budget deficits. The scenario assumes enrolment levels by type of education to remain constant from 2010 onwards. The choice to use UN population data has been made in order to have flexibility in demographic scenarios to model IMACLIM-ZA's future demography of South Africa, as the UN presents a variety of demographic scenarios, whereas K.C. *et al.* do not.

The resulting projected population numbers, with work force by educational attainment and their translation into labour skill factors are presented in Table 3.10 both for the case that skills remain constant in terms of educational attainment, and if skills remain constant as shares of the labour force.¹¹⁸ Backgrounds about these projections for population by level of educational attainment and skill are given in Appendix C.6.

Table 3.10 Population by educational attainment and skill in 2035, LEP scenario, with CSLF definition of skills*

Age group	Level of educational attainment	Pop. by educational attainment (thousands)	Change vs BY	Broad active population by job type (thousands)	Broad inactive population by job type (thousands)	Difference educ. – job type pop. by skill level
0-14	-	14 407	-7%	-	-	-
15-64	No education	287	-85%	6 306 low skilled	4 110 low skilled	6 365
	Primary education	3 764	-44%			
	Lower secondary education	16 343	+35%	13 916 medium skilled	7 736 medium skilled	-12 813
	Upper secondary education	18 122	+116%			
	Post-secondary education	1 841	+102%	6 752 high skilled	1 536 high skilled	6 448
15-64 subtotal		40 356	+34%	26 974	13 382	0
65+	-	4 765	+129%	-	-	-
Total		59 528	+25%	26 974	13 382	

* Comments: CSLF = Constant Shares of Labour Force, see section 3.3); Source: Author's calculations on the basis of De Francieu's (2015) projections of educational attainment levels combining UN population prospects (UN DESA, 2013) and projections for future educational attainment by K.C. *et al.*(2013).

Demography and income distribution by household class

The next question is how employed and unemployed labour by skill can be divided over the five household classes. Especially for reason of model resolution, the assumption made is that the distribution of employed, (broadly defined) unemployed, and inactives by skill over the five household classes in 2035 is the same as it was assumed for 2005 (see section 3.1.4).¹¹⁹ Multiplying this

¹¹⁸ The constant shares of labour force numbers show that rising educational attainment induces a slightly better match between the levels of educational attainment and the associated with StatsSA's job type-based skill definition (see section 0).

¹¹⁹ If the model was to correctly re-distribute active population by skill endogenously over the five household classes – which are expenditure classes at the level of households in the SAM 2005 –, it would require an assumption about the shape of the distribution of net

distribution by projected new total amounts of employed, unemployed and inactives gives their new totals by household class. In a next step, the shares of the different household classes in the below-15 and above-65 populations is determined on the basis of the household classes old shares in these population groups and the growth of household classes working age population. The new shares of household classes in these population groups are applied to the projected number of below-15 and above-65 population.

Another questions is the distribution of wage and other income over household classes. For the same reason of ease in model solving (see the previous footnote), a simple approach is used to distribute income over the five household classes: For net wage income first, one calculates the theoretical skill-specific-share in wage revenue for each household class on the basis of the household class' skill-specific BY average wage and its new number of employed people. Multiplying these shares by the projected total net wage per level of skill gives new net wage income by household class (see also Appendix A.1.3 for details).

Household class-specific *per capita* average unemployment benefits are calibrated at BY values and are indexed on the CPI, and then multiplied by the number of unemployed people per household class – calculated as specified above. Household class-specific average *per capita* pension benefits are calculated as their BY calibrated values indexed on the change in national average wage. They are multiplied by a household class' population of persons of 65 and older. Other social benefits are calculated like per capita unemployment benefits, except that they are calculated as *per capita* averages for the entire population of a household class (see Appendix A.1.3).

Property revenue by household class follows from multiplying the negative of household class' net debt by households' average interest rate: $-\tau i_H D_{Hh}$ (see Eq.41 on p.95). Household classes' net debt positions follow from BY calibration data net financial asset positions, the household classes' future self-financing capacity, households' increase in real GDI, and the endogenous interest rate (see the discussion of debt accumulation in section 3.4.1). Household's gross saving rates and $GFCF_{Hh}$ determine their net savings and are discussed next. The evolution of household class GDI_{Hh} is endogenous (see Appendix A.1.3).

Household classes' parts in other transfers (from households to other economic agents or vice versa) are calculated using a reference transfer value that is calculated on the basis of BY household class transfers and growth in a household class' population. This gives the new shares in other transfers of each household class, which when multiplied by the total of households' other transfers give each household class' other transfers (see Appendix A.1.3).

wages over employed by household class, plus assumptions about the distribution of non-wage income over individuals, the grouping of individuals into individual households. Furthermore, a sorting mechanism would be needed to cut-off actives, non-active income gainers, and their family members over the household classes. This sorting mechanism would have to be re-ran with each iteration of the model when solving, or it should be modelled as a separate module which is required to converge with the rest of the model. To simplify matters this option has not been implemented in IMACLIM-ZA.

Total of household revenue and other transfers adds up to become household classes' gross disposable income before revenue and property income taxes, $GDIBT_{Hh}$. Revenue taxes are calculated by multiplying a household class' $GDIBT_{Hh}$ by its class-specific revenue and property income tax rate. This class specific tax rate is endogenous in the Reference Projection (RP), where it is calculated as its BY value multiplied by a model solution variable that applies to all household and firm revenue and property income tax rates: τ_{IF} and τ_{IHh} (see Appendix A.1.6 for details).

Savings, investment and net lending and borrowing

After tax GDI_{Hh} is used by household for consumption or for gross savings. In BY 2005 SAM data, the saving rate of households was very low, according to SAM data, on average 0.1% (StatsSA, 2010b) – and this included household's growth in pension equity. This is an unsustainable situation, as household savings fuel domestic investment (beyond firm's re-investment). The assumption is that households' gross saving rates will increase, with the additional assumption that low-income households save less than high-income households: Table 3.11 gives assumed 2035 gross saving rates.

Table 3.11 Saving rate assumptions by household class for projections for 2035

Household class	Class 1	Class 2	Class 3	Class 4	Class 5
Saving rates (pct of GDI_{Hh})	0.5%	1.0%	1.0%	2.5%	3.5%

To compute households' net savings (their SFC_{Hh}) their $GFCF_{Hh}$ needs to be deducted from their gross savings. Total household GFCF is calculated as a fixed rate over total household gross disposable income (GDI), calibrated on BY data. It is multiplied by BY data calibrated shares of household classes in total household GFCF to obtain class-specific $GFCF_{Hh}$. Another assumption is that SFC_{ROW} in the long-run should go from a surplus of 3.6% in BY calibration data to close-to-zero in RP. The reason is that continued foreign indebtedness seems an economically unhealthy situation as it will lead to future income losses. The increase in household saving rates (Table 3.11) is meant to achieve this objective, bringing domestic lending in equilibrium with domestic borrowing.

The two domestic net borrowers in BY calibration data are firms and government. Government's net borrowing is assumed to increase in share of GDP from 2% in 2005 to 3% in 2035 (as part of the balanced RP, see section 0). While for firms the assumption is that under RP conditions (see Ch.4 for a discussion of the RP projection) increased after tax GOS is partly used to change their status of a net borrower, with their SFC_F at 0.7% of South African GDP in BY calibration data, to become a net saver (or lender) with an SFC_F of 1.0% of South African GDP. To achieve this, the exogenous ratio of firm $GFCF_F$ over firms' GDI_F is reduced by one tenth, from 105% in BY calibration data to 94% in 2035. In this way, firms (in total) also become a net financier of government.

4. Reference Projection and results of scenario analysis

Having discussed the parameterisation and criteria for evaluation of RP in section 3.6, this section first discusses and analyses the results of the Reference Projection (RP) to provide a benchmark for evaluation of CO₂ tax revenue recycling scenarios. Later on in this chapter (section 4.2) a decomposition analysis is presented to understand the pattern of South Africa's economic development in RP. Next, the main carbon tax scenarios and their results are presented (section 4.3), which are also explained and analysed (in section 4.4) with the objective to clarify the mechanisms through which the different carbon tax revenue recycling schemes can successfully promote both GDP growth and decarbonisation of the South African economy. Finally, this chapter considers how recycling of a part of carbon tax revenue into an investment in skills could impact GDP growth, employment and a reduction of CO₂ emissions (section 4.5).

4.1. A reference projection for 2035

This section shows that RP's parameterisation leads IMACLIM-ZA to a projection for 2035 in which a South African economy with moderate *per capita* GDP growth moves towards more industry & manufacturing, and towards more services. There is some decoupling between CO₂ emissions and GDP, due to a combination of decarbonisation of electricity production, energy efficiency efforts in other sectors, and structural change. Still, *per capita* CO₂ emissions increase relative to base year (BY), from an already high level in 2005. A positive development is that RP outcomes show a significant decrease in unemployment and in poverty, but also a slight increase in income inequality. Real *per capita* consumption levels increase for all household classes, but least for the poorest.

Key outcomes of a reference projection for 2035

RP¹²⁰ results in a 55% increase of South African CO₂ emissions compared to Base Year (BY, 2005) to 687 Mt CO₂. This growth in emissions reflects most of all the growth in economic activity: *Real* GDP grows on average by 2.7% per year between 2005 and 2035, leading in total to a 125% growth in economic activity. *Per capita real* GDP grows 80%, and reaches 59.4 kZAR₂₀₀₅ (10.9 kUSD₂₀₁₃). This means that in this scenario South African *per capita* GDP is in the range of present-day *per capita* GDP of Turkey and Argentina (resp. 10.8 and 12.4 kUSD₂₀₁₆ in 2016). CO₂ intensity of South African GDP thus decreases between BY and RP from 0.28 to 0.19 kgCO₂/ZAR₂₀₀₅ (or 1.54 to 1.06 kgCO₂/USD₂₀₁₃). Emissions remain high on a *per capita* basis though: 11.5 tonne CO₂ in 2035.

Broad unemployment decreases in RP from 39% in 2005 to about 24% in 2035. This is accompanied by *real* wage increases of 52% for high skill labour and of 40% and 41.5% for medium and low skill labour respectively. In parallel, labour's share (gross wages) in Value Added (VA, excluding taxes on

¹²⁰ RP could not reach the objective set for at least 0.1% precision in meeting the constraints for economic equilibrium: while all other constraints were met with the required or even higher precision. This lowered precision however did not lead to significant imbalances, as apart of it originated in the way constraints were defined. The biggest disbalance was between total uses and resources resulting in a 4 million ZAR₀₅ disequilibrium compared to a GDP of 3.5 trillion ZAR₀₅. Trying to re-solve RP while freezing income taxes and liberating the Self Financing Capacity turned out to reach the required precision with the same results, except for a 0.003% increase in CO₂ emissions.

production and products) goes from 51% in 2005 to 54% in 2035. However, inequality in gross disposable income, measured as household class 5 (richest) over class 1's (poorest) gross disposable income (GDI_{Hh}), increases 7%.

Changes in macro-economic structure

In RP South Africa moves slowly away from the “Minerals Energy Complex” (MEC) discussed in Chapter 1, as the share of mining (COA and a part of EIN) in South Africa’s GDP decreases. However, the high skill services sector (HSS) is the only sector besides the small ELC which sees it’s share in GDP increase. This could be a sign of the MEC, as the MEC is often accompanied by a big services sector, existing thanks to profits and tax income from minerals and energy sectors (see the discussion in Chapter 1). However, in IMACLIM-ZA it is not the growth of the mining sectors that explains growth of HSS, because EIN, COA and REF together see their share in GDP decrease by 1.2 pt. to 13.2% (Figure 4.1). And while the manufacturing sector (MAN) does not see it’s share in GDP increase, it does observe the biggest growth of physical volume of domestic output (Table 4.1): +129% vs BY. This is bigger than the growth in the volume of domestic output of EIN (+114% vs BY), and HSS and LSS (respectively + 109% and +105% growth vs BY). In this sense, South Africa shows signs of industrialisation and economic diversification in RP.

Figure 4.1 GDP shares of sectors, for BY (2005) and RP (2035)

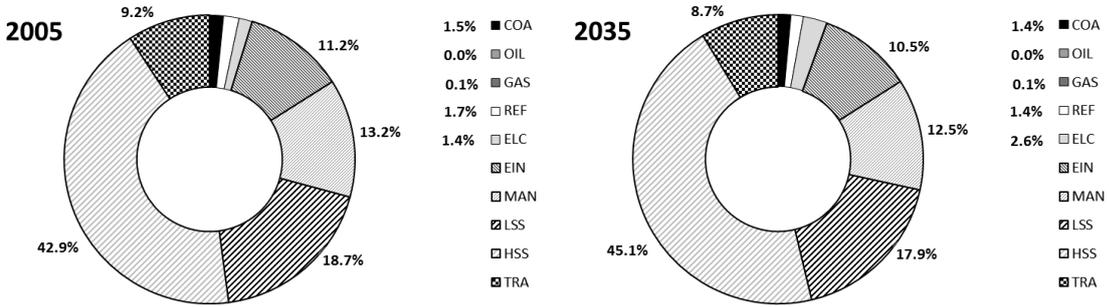


Table 4.1 Growth in domestic output by sector

	COA	OIL	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA	Avg.*
Domestic output (Y) vs BY	+82%	id.	+106%	+81%	+66%	+114%	+129%	+105%	+109%	+95%	+108%

* The average is calculated as the geometric mean of the sectoral growth in volume of domestic output weighed on the basis of BY shares in GDP and on the basis of projected GDP shares in RP.

The composition of the Uses side of GDP changes too: Consistent with assumptions about growth in public expenditure and about the current account and the Balance of Payments (BoP, see below), the shares of government and of the trade balance in GDP increase. Maybe surprisingly, investment’s share in GDP decreases slightly from 18.0% in 2005 to 17.3% in RP. This is a consequence of technological change, which is discussed in section 4.2.2 below.

Results for the trade balance and the real effective exchange rate

In RP South Africa runs a trade balance surplus. This derives from assumptions about net borrowing

and lending of domestic agents (see sections 3.4.1 and 3.6.4). In brief, government's budget deficit becomes 3% in 2035, which is higher than in BY, and it is assumed to gradually move towards this higher deficit in the years between BY and RP (see section 3.4.1 on accumulation of assets and debts). Government's deficit is bigger than what households and companies (the latter start reducing their debts) are assumed to save on a net basis in RP. As a result, South Africa continues to be (as in 2005) a net borrower from ROW: at 0.1% of GDP in 2035. The net foreign debt of South Africa – which can also be seen as net negative ownership of (financial) assets – increases from 27% of GDP in 2005 to 39% in 2035.

The small number for net international borrowing masks what happens on the Balance of Payments, where South Africa has net transfers to ROW (0.7% of GDP in 2035) and also net negative returns on capital (or interests and dividends, RK_{ROW} , 2.8% of GDP in 2035), which the country as a whole pays over its net debts.¹²¹ The total amount of income (primary + secondary transfers) going abroad is 3.5% of GDP. In macro-economic terms these flows enable ROW to finance South Africa's trade balance surplus and South Africa's deficit of 0.1% of GDP on the capital account.

To obtain the trade balance surplus under the assumed current account deficit plus the small net capital account deficit, a slight decrease in South Africa's Real Effective Exchange Rate (REER) is required for economic equilibrium.¹²² Indeed, in RP the REER turns out to be 5.6% lower than in 2005. With 2005's REER being indexed at 105 by the OECD (2018), this means that South Africa's REER in 2035 would approximately be 100.

CO₂ emissions by type of activity

The relative decoupling of CO₂ emissions and GDP despite industrialisation of the South African economy results from a combination of decarbonisation of electricity production, of more energy efficiency in other sectors¹²³, and of structural change towards sectors that on average have less (direct) emissions per unit of primary income (GDP) earned. Total direct CO₂ emissions of electricity increase less than those of most sectors (Table 4.2), and less than the 66% growth in output of electricity production (Table 4.1). Total direct CO₂ emissions from GAS, TRA and EIN increase fastest, but also less than these sector's output volumes.

If one were to allocate CO₂ emissions from energy sectors¹²⁴ and transport to the other sectors intermediate consumption, final consumption, and exports this would not change the general picture that industrial processes plus the transport of their products, together with exports are the main drivers behind the increase in South African CO₂ emissions. The share of household consumption in direct plus indirect CO₂ emissions as calculated above is only 20.5% in RP (Table 4.2). In fact, households

¹²¹ A part of the explanation for South Africa's negative balance of payments are rising rates of return on capital (the interest rate in the model), which is a variable for model resolution and which has resemblance to RP being configured for increasing non-retained company profits after taxes. As the rate of returns for ROW only goes up between BY and RP up from 6.7% to 7.3%.

¹²² This also depends on assumed price elasticities for international trade and assumptions about international prices.

¹²³ All sectors decarbonise per volume unit produced due to higher energy efficiency (see section 4.2.2 later on).

¹²⁴ Energy sectors with domestic production in South Africa are: ELC, electricity production; REF, refineries (oil refineries, CTL and GTL); COA, coal mining; and GAS, gas production (mainly coke ovens and gas works)

and labour intensive sectors decrease their share in South African CO₂ emissions, both directly due to only a moderate increase in energy consumption, as well as indirectly, due to cleaner electricity. For the labour intensive sectors LSS and HSS direct CO₂ emissions increase less than their volume of output due to increased (endogenous) energy efficiency. It will be shown below that households are assumed not to increase their energy consumption much in face of relatively increasing energy prices.

Table 4.2 Change in sources of total CO₂ emissions RP vs BY

Abbr.	Sector	2005 direct CO ₂ emissions		2035 direct CO ₂ emissions			2035 total of non-energy sector direct + indirect energy & transport sector emissions		
		unit: Mt CO ₂	pct. of total	Mt CO ₂	pct. of total	Growth vs 2005	Mt CO ₂	pct. of total	Growth vs 2005
ELC	Electricity	240	54.3%	338	49%	+40%	<i>9.3 Mt or 1.4% unallocated</i>		
REF	Refinery products	56	12.7%	99	14%	+76%			
COA	Coal (from mining)*	0.0	0.0%	0	0.0%	-			
GAS	Gas resources*	19	4.3%	39	5.7%	+104%			
TRA	Transport services	32	7.3%	60	8.8%	+86%			
EIN	Energy int. ind. & other mining	31	7.0%	59	8.6%	+89%	279	41%	+72%
MAN	Manufacturing	26	5.9%	42	6.0%	+60%	91	13%	+57%
HSS	HSS	8.3	1.9%	11	1.6%	+31%	59	8.5%	+32%
LSS	LSS	5.4	1.2%	9	1.2%	+60%	56	8.2%	+54%
HHR	Households - REF and TRA*	21	4.8%	32	4.6%	+49%	72	11%	+49%
HHO	Households - other*	2.7	0.6%	0	0.0%	-100%	66	9.5%	+15%
EXP	Exported Energy sector em.	-	-	-	-	-	55	8.0%	+88%
	Total	443	100%	687	100%	+55%	687	99%	+55%

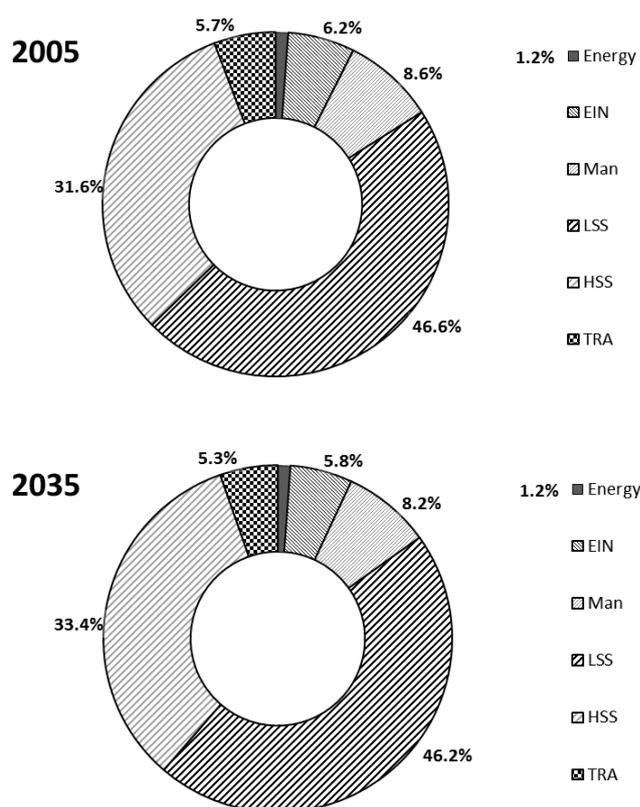
* Comments:

- 1 Due to hybridisation own use electricity generation is now included in the electricity sector, and its emissions therefore do not show up in the coal sector.
- 2 Gas resources consist partly of gas works and coke oven gas which are actually emissions of the iron and steel and other energy intensive industries.
- 3 Household refinery products also include kerosene and LPG for heating purposes, but to simplify refinery products are considered to be mainly used for transport purposes.
- 4 Household other emissions in 2005 include those from coal for heating, I add indirect emissions from electricity which has mainly a domestic purpose, and I ignore electric transport.
- 5 In the totals of direct and indirect emissions I neglect and thus do not re-allocate the indirect emissions coming from refineries and transport of the ELC, REF and TRA sectors.
- 6 Gas resources emissions consist of the CO₂ emissions from producing gas in coke ovens or in gas works, and are thus included in the Energy Intensive and other mining (EIN) sector

Outcomes for employment by sector

In the composition of employment few changes take place between sectors. The HSS and LSS sectors gain most employment in absolute numbers (6.7 out of 8.2 million new jobs), but only the HSS sector sees its share in total employment increase from 31.6% to 33.4%. The percentages of total employment of other sectors decrease a little, but change little relative to each other (Figure 4.2). In view of the larger increase in volume of output of MAN and EIN than for other sectors, this outcome reflects the high increase in labour (output) productivity for MAN and EIN. Below, the change in employment by level of skill will be discussed in connection to observed technological and structural change (in section 4.2.2).

Figure 4.2 Shares of employment by sector, for BY (2005) and RP (2035)



Income inequality, poverty and consumption

The Reference Projection leads to a decrease in poverty, but also to a slight increase in relative income inequality. The decrease in poverty can firstly be seen from an increase in *real per capita* consumption budgets, ranging from +29% for the poorest class (class 1), to +68% for class 4 (Table 4.3). Consumption budgets reflect changes in income, but also in saving and investment behaviour. Income inequality, measured by the of HH class 5 (richest) over HH class 1 (poorest) gross disposable income (*gdi, after taxes and transfers*) still increases by 7%, with average HH class 5's *gdi* equalling 44.6 times that of class 1. Of course, *real per capita* consumption levels increase (Table 4.4).

In terms of (physical) volumes, the picture coming out of RP implies South Africans buying more appliances, vehicles, furniture, clothes, food, leisure, and low skill services (MAN & LSS) – and to a lesser extent more materials (EIN), high skill (HSS) and transport services (TRA) – while South African households almost do not consume more energy (COA, ELC, REF) (Table 4.4). Household consumption of coal is phased out by assumption.¹²⁵ But, further decrease of primary energy demand for household classes 1 and 2 reflects other aspects of how the model parameterises the response to increasing energy prices of these household classes. (More detail on household consumption in RP is presented in Appendix D.1.3.)

¹²⁵: the assumption is that South Africa achieves universal access to clean cooking fuels by 2035.

Table 4.3 Change in real per capita consumption budgets, RP vs BY

Household class	Hh 1	Hh 2	Hh 3	Hh 4	Hh 5	All
Increase of <i>real per capita</i> consumption budget vs BY*	+29%	+41%	+61%	+68%	+33%	+53%

* Consumption budgets equal gross disposable income after taxes and transfers, minus investment and net borrowing or lending.

Table 4.4 Comparison of household class consumption profiles, BY and RP

Class	Item	Unit	Hh1		Hh2		Hh3		Hh4		Hh5		Average	
			2005	2035	2005	2035	2005	2035	2005	2035	2005	2035	2005	2035
Per capita consumption		kZAR₀₅	1.9	2.5	4.1	5.8	5.9	9.4	10.3	17.4	81.2	108	20.8	31.7
COA		GJ/person	0.29	0.0	0.59	0.0	0.82	0.0	0.88	0.0	0.09	0.0	0.6	0.0
ELC		GJ/person	0.86	0.91	1.67	1.88	2.23	2.67	3.8	4.7	23.0	24.4	6.4	7.7
REF		GJ/person	0.35	0.35	0.83	0.85	1.23	1.36	3.4	3.9	13.1	13.5	4.0	4.6
Primary energy		GJ/person	2.8	2.6	5.6	5.6	7.6	8.0	13.7	15.7	70.8	74.6	20.6	23.8
EIN		index of BY (2005)avg	7.9	10	16	22	21	35	46	79	408	550	100	154
MAN		index of BY (2005)avg	12	16	27	41	38	69	60	113	354	522	100	170
LSS		index of BY (2005)avg	16	21	24	35	31	53	54	96	373	523	100	161
HSS		index of BY (2005)avg	2.3	2.7	5.6	7.3	9.0	14	24	38	471	587	100	142
TRA		index of BY (2005)avg	19	23	45	57	70	93	107	153	221	261	100	135

* For total primary energy, based on modern energy efficiency of coal power plants, ELC consumption has been by a factor 2.5.

4.2. Explaining RPs results through decomposition analysis

Chapters 2 explained how growth depends on exogenous assumptions about factor and input output productivity, and on (rigid) profit margins and wages. Chapter 3 explained that IMACLIM-ZA – as used in other models for small open economies – has a closure in which the trade balance is more or less fixed and in which the Real Effective Exchange Rate (REER)¹²⁶ adjusts to find equilibrium between domestic GDP growth and the growth in the volume of exports (section 3.5).

In order to arrive at an explanation of the results found in the difference Ctax scenarios, and continuing on the mentioned discussions in Chapters 2 and 3, this section first discusses this link between GDP growth and the REER as found in results of IMACLIM-ZA (section 4.2.1 and Box 5). (This forms the basis to understand the economic impacts of carbon taxation in combination with revenue recycling in section 4.3.1.) The second part of the present section (4.2.2) shows for RP how results follow from structural and technological change, and how these also determine outcomes for CO₂ intensity of GDP, employment by sector and level of skill of labour, and for income inequality. A

¹²⁶ The REER is the Real Effective Exchange Rate, it represents the value of a basket of goods in domestic prices relative to prices of a country's trading partners (see section 3.6.2 for a discussion of the REER). The REER is an expression of purchasing power in domestic goods vs that in foreign goods. It can therefore, amongst other options, be represented by Relative Consumer Price Index (RCPI). The REER relative to BY as shown in Box 5 is calculated as the ratio of GDP expressed in domestic prices over GDP in import prices.

summary at the end of the section (0) wraps up the description of the Reference Projection.

4.2.1. Explaining GDP growth and unemployment for RP

Complexity of economic interactions is one of the main reasons to use a macro-economic model to support economic decision-making. Macro-economic models necessarily simplify matters, but represent essential economic behaviour in order to show what happens when different economic mechanisms interact. These models obviously depend on what we think to know about the different mechanisms present in an economy. Despite these simplifications, for a model to be useful or applicable, some degree of complexity needs to be maintained. The complexity of multisectoral general equilibrium models like IMACLIM-ZA makes it difficult to explain the results obtained in scenario analysis. However, for economic policy making it might be more useful to understanding *why* a scenario obtained the results it did. Explaining how results for GDP growth follow from assumptions about changes in parameters¹²⁷ is complicated, because it requires presenting a number of *simultaneous* and *looped* general equilibrium changes as a logical *chain* of events. Furthermore, the more complex the model is in terms of interactions between parameters, the less feasible it is to distinguish how results are linked to changes in specific parameters. This sub-section therefore discusses an approach that will be used in the remainder of this chapter to provide insight into why the scenarios presented in this thesis obtained their results for GDP growth and employment. The approach is applied to RP here.

The approach is constructed around an indicator that is an index for the change in domestic income relative to the volume of products supplied to the South African economy. To simplify matters I will call this indicator the *domestic income multiplier* (DIM). The DIM is complementary to another explanatory indicator for GDP growth, namely the REER. Box 5 below shows how a change in the REER is both a formal result of IMACLIM-ZA, parallel to GDP growth, and at the same time an explanation for GDP growth. Compared to the REER, the added value of the DIM in explaining results for GDP growth is that it is applicable to the sectoral level too, and that it can be linked more easily to scenario assumptions through its components (which are specified below).

This sub-section first shows that growth in employment by scenario is a results which is not very intuitive and that to understand this result one has to explain how come GDP grows beyond average productivity growth of primary factors. The discussion in this section then shows how several components of GDP growth are able to explain how growth of GDP relative to primary factor use can be different from average primary factor productivity growth. Sub-section 4.2.2 (next) links each of these components *a posteriori* to the technological and structural change that follow from scenario assumptions. The components concerned are: Change in the (with the GDP price index deflated) value

¹²⁷ E.g. productivity, factor availability, and exogenous changes in import price structure, or in the tax system.

of the volume of goods & services supplied to the South African economy¹²⁸; Cost reductions (see also section 2.1.4 before); and import substitution. They incorporate growth in income both due to domestic drivers of growth and due to changes in international trade, and they can be aggregated into the mentioned domestic income multiplier (DIM). Lastly, this sub-section shows that the DIM, just as the REER, is uncorrelated to GDP *per worker*, but that it can largely explain variation in employment results between scenarios.

A missing explanation for GDP growth and employment results

One of the ways to decompose change in GDP is by decomposing it into the following three components:¹²⁹

1. Change in GDP per worker;
2. Change in the size of the active population;
3. Change in the percentage of active population employed (the employment rate).

For RP it turns out that, once demographic change and change in the employment rate (= 1 – rate of unemployment) have been taken into account, GDP per worker grows 35.3% compared to base year (BY) data (see Table 4.5). However, GDP per worker does not correlate to GDP growth in IMACLIM-ZA results, as shown for RP and 8 R300 Ctax scenarios in Figure 4.5 (a discussion of Ctax scenario results follows in section 4.4). To understand why GDP per worker does not correlate to GDP and explain the results for GDP and employment for RP, I add detail to the decomposition analysis.

Table 4.5 Decomposition of GDP growth in three key components (by multiplication), RP vs BY

	GDP per worker	Active population	Employment rate	GDP
RP (vs BY)	1.353	1.341	1.239	2.249

Further detail can be added on the basis of an insight from section 2.1.4, namely that cost reductions contribute to GDP growth. Cost reductions (as its opposite: cost increases) follow from changes in factor

and input intensities and factor prices. In IMACLIM-ZA changes in factor intensities follow from changes in productivity, resulting from prospective scenario assumptions (see section 3.6) and price elastic trade-offs between intermediate inputs and primary factors (see section 3.2.1).

At the level of the aggregate economy, cost reductions equate to the changes in the total value of resources over GDP. For RP the reduction of costs per unit of GDP is 5.2% (Table 4.6). Its inverse is the ratio of primary income (GDP) over the value of resources, which I also call the *ratio of income over costs*: its value is 1.055 for RP (= 1 / (1-0.052)). It adds growth to the productivity improvement of primary factors.

¹²⁸ By supplied to the South African economy is meant the use or consumption of goods & services in intermediary or final consumption, plus their use for investment and their exportation.

¹²⁹ The decomposition analysis of GDP growth in this section is performed from taking a per worker perspective of GDP growth (or, value added labour productivity). This choice is motivated by the practical consideration that labour is the most constrained factor in IMACLIM-ZA (see a discussion about the modelling of the capital market in section 3.4). However, in principle any factor or input could be used to structure this decomposition analysis.

Box 5 GDP growth, the REER and the trade balance in IMACLIM-ZA

The Real Effective Exchange Rate (REER) is officially defined as the average of the bilateral Real Exchange Rates (RERs) between the country and each of its trading partners, weighted by the respective trade shares of each partner (Catao, 2007): “The RER between two currencies is the product of the nominal exchange rate (the dollar cost of a euro, for example) and the ratio of prices between the two countries.” Catao also says: “economists usually measure the real exchange rate in terms of a broad basket of goods. Because the price of such a basket normally takes the form of an index number—such as the consumer price index (CPI), which includes both goods and services—the RER is also typically expressed as an index that can be bench-marked to any chosen time period.” (Catao, 2007) Similarly, the OECD uses Relative Consumer Price Indexes as an indicator for the REER and adds that they are a measure for international competitiveness (OECD, 2016). In this thesis, lacking the possibility to calculate RERs between South Africa and its trading partners, the rate of the GDP in domestic prices over the South African GDP in foreign prices is used as a proxy for the REER.

The REER can be seen both as an explanation for and as a consequence of GDP growth. To see this, one has to recall that, as argued in section 2.1.4, GDP growth can result both from domestic drivers and from international trade. This box explains how the REER serves as an indicator for both types of origins of GDP growth. Nevertheless, this box first shows that given the conditions of the scenario runs in IMACLIM-ZA the REER adjusts to match the result for GDP growth with the constraint on the trade balance and the current account.

Change in the REER as a development parallel to GDP growth

That the REER is negatively correlated to GDP growth is a formal outcome of the IMACLIM-ZA model and its prospective parameterisation (section 3.6). To see this, recall from Eq.16 on p.83 that for each sector the volume of imports of a sector is positively related to the volume of domestic output, which means that they are roughly proportional to GDP:¹³⁰

$$\frac{M_j}{Y_j} = \frac{\overline{M}_{j,0}}{\overline{Y}_{j,0}} \left(\frac{\overline{pM}_{j,0}}{\overline{pY}_{j,0}} \frac{pY_j}{pM_j} \right)^{\sigma_{pM_j}} \quad (16)$$

At the same time, the volume of exports of all sectors evolves roughly proportional to an exogenously defined trend, δ_x , see Eq.17 on p.83:

$$\frac{X_i}{\overline{X}_{i,0}} = \left(\frac{\overline{pX}_{i,0}}{\overline{pM}_{i,0}} \frac{pM_i}{pX_i} \right)^{\sigma_{pX_i}} (1 + \delta_x) \quad (17)$$

This means that the evolution of the volume M over the volume X of a sector depends on: 1. The evolution of Y over X ; and 2. the evolution of relative prices between on the one hand domestic products (pY , which explains a large part of the change in pX , see section Xx) and on the other hand foreign products (pM).

¹³⁰ A condition is that the average change in relative prices and the price elasticities are not too extreme, but the latter is not the case in RP and the Ctax scenarios presented in this thesis.

A third constraint is that the trade balance surplus is defined by the Balance of Payments, in particular by the Self Financing Capacity of the Rest of the World (SFC_{ROW}) given by Eq.55 in section 3.4:

$$SFC_{ROW} = \sum_{i=1}^n M_i pM_i - \sum_{i=1}^n X_i pX_i + RK_{ROW} + OT_{ROW} \quad (55)$$

This equation says that the SFC_{ROW} equals the negative of the trade balance ($X^*pX - M^*pM$) plus the interests and dividends receipts by ROW (RK_{ROW}) and other transfers which ROW receives (OT_{ROW}). As OT_{ROW} is fixed over GDP, and with SFC_{ROW} and RK_{ROW} almost fixed (see section Xx), this means that the trade balance is approximately fixed to GDP as well (at about 3.5%, see Figure 4.6 later on, while in BY calibration data has a trade balance deficit of 0.1%).

Under these circumstances, at constant prices, the relative growth of imports, and therefore GDP between timesteps 0 and t divided by the trend for growth in exports should approximately correspond to: $(GDP_t/GDP_0) / (1 + \delta_x)^t = (1 - 0.001) / 1.035$.

However if $GDP_t/GDP_0 > 0.965 * (1 + \delta_x)^t$ then the average price of South African goods, $\langle pY_j \rangle$, needs to decrease relative to the average price of foreign goods, $\langle pM_j \rangle$, in order to reduce the rate M_j/Y_j and increase the rate $X_i/\overline{X_{i,0}}$, and respect the constraint for the trade balance: $\sum_{i=1}^n X_i pX_i - \sum_{i=1}^n M_i pM_i \cong 3.5\% * GDP_t$. In case the opposite is true, and GDP growth is much smaller than the trend for growth in volume of exports, the average domestic price needs to increase relative to the average foreign price to respect the constraint on the trade balance. This relative evolution of domestic over foreign prices is expressed by the REER, which can therefore be considered to facilitate the adjustment of GDP to the assumed growth of the volume of international trade, given a certain value for the trade balance relative to GDP.

Change in the REER as an expression of change in a driver of GDP growth

From another perspective, the REER also *explains* GDP growth. Firstly, a decrease of the REER can be a sign of an improvement in international competitiveness, when comparing two scenarios.¹³¹ However this is conditional on: a. the fact that the current account and the trade balance are constant over GDP; and b. on the fact that the average price elasticity of import substitution and exports are constant too.¹³² Secondly, given the conditions just mentioned, a change in the REER is also an expression of change in an underlying phenomenon which is one of the drivers for GDP growth (next to productivity growth): At the assumption of a constant trade balance and current account (relative to GDP, as described above) the REER also expresses the costs of a “productive factor unit” relative to the average price of a certain basket of goods of foreign products.

This last statement is rather abstract, and therefore deserves further explanation: Recall that the REER expresses the relative costs of a specific basket of goods & services in domestic prices relative to the

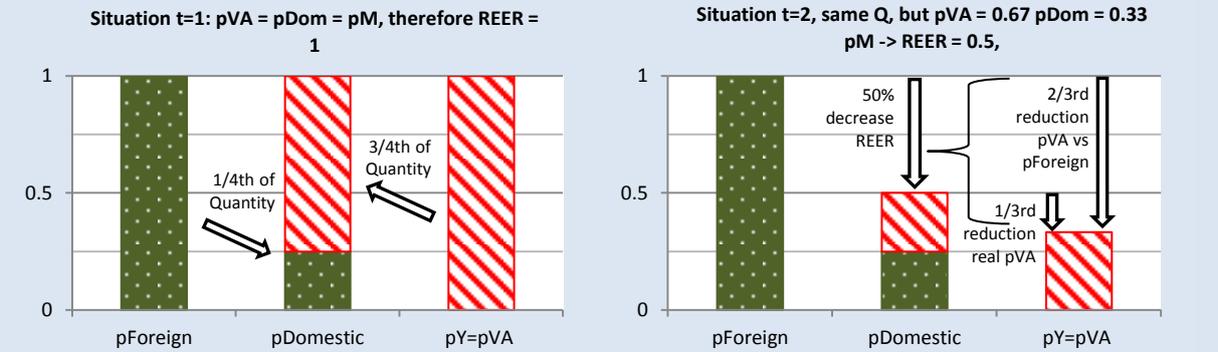
¹³¹ The measurement of the international competitiveness is one of the purposes of the REER according to the OECD (2016).

¹³² At higher elasticities, the change in the volumes of goods & services traded with the change in domestic prices relative to foreign prices will be stronger. A smaller change in the REER will be sufficient in the latter case to obtain a certain trade balance fixed as a percentage over GDP.

same basket of goods in the rest of the world (when converted into the same currency). Furthermore, consider that for an aggregate economy, all costs – i.e. the total value of “resources” in Input-Output terminology – ultimately consist of costs for imports and of primary income (= value added including indirect taxes). All other things equal – notably constant productivity of primary and secondary factors and constant trade-offs between foreign and domestic goods – the average price of products sold in the domestic economy *relative* to that of foreign products depends on the reward (price) in *real*¹³³ terms of domestic primary factors.¹³⁴ Therefore, all other things equal, total *nominal* primary income (value added) per product is proportional to the domestic components of the cost structure (resources) of that product’s sector. However, it does not need to be constant to the foreign components of resources. If “*real*” primary factor prices change, this implies that factor prices change relative to the price of foreign goods (all other things equal).

Figure 4.3 summarizes this logic: Assume that at constant technology the good available to the domestic economy consists for 1/4th of its volume of foreign products and for 3/4th of domestic output (Y). Initially the REER = 1, but let’s assume that for an unknown reason the real price of a domestic primary factor (pVA) is suddenly reduced by 1/3rd. At constant technology, this means that the price of a primary factor (pVA) is reduced by 2/3rd compared to the price of foreign products. As a result the REER becomes half of its initial value.

Figure 4.3 Change in REER expressing change in factor prices relative to foreign prices, all other things equal



The decrease of primary factor prices relative to their productivity could also be called the decrease of the real price of a “productive factor unit”. Section 2.1.4 discussed how under normal circumstances such a decrease leads, all other things equal, to GDP growth in IMACLIM models (and the opposite: an increase of the real price of a productive factor unit to a reduction of GDP). The section also showed that impacts on GDP of this development in primary factor prices operate both through domestic drivers (purchasing power) and international drivers of growth (competitiveness). This is summarized in (the non-shaded elements of) Figure.4.4: One mechanism prevents an infinite reduction

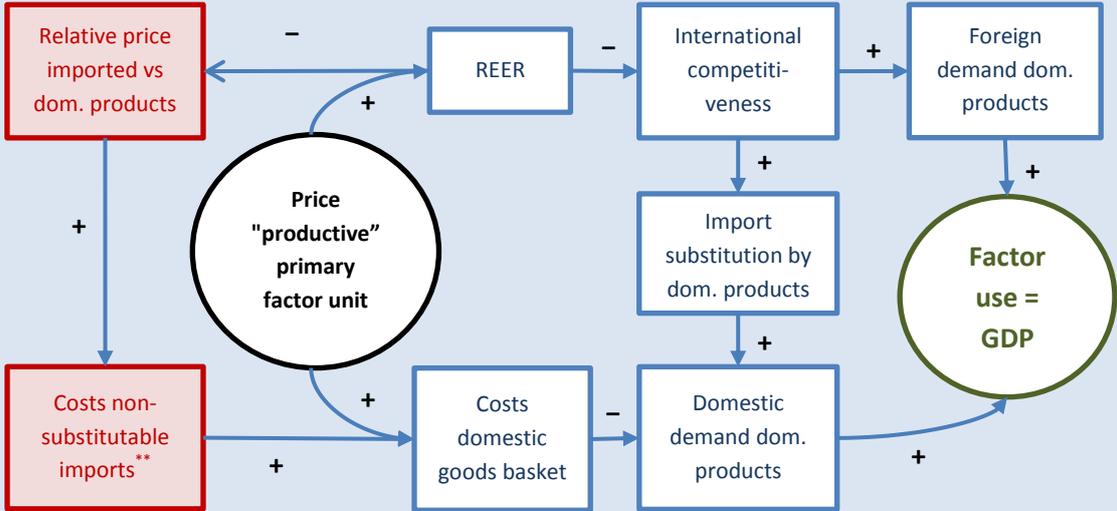
¹³³ The “*real*” factor price says how many baskets of goods & services can be bought with a factor unit’s remuneration (income or reward): see section 2.1.4.

¹³⁴ Consider also that, at constant technology and trade-offs between domestic and foreign goods, the part of resources that is costs for imports (within the resources of production per unit supplied to the local economy) is constant relative to price of imported goods. Therefore only the value added part of resources per unit produced can change relative to foreign prices.

of “real” primary factor prices for stimulating GDP growth, being that some imports are non-substitutable and would become unaffordable if domestic factor prices would become extremely low (in the shaded elements of Figure.4.4).¹³⁵

The conclusion is that under the hypotheses of RP and the Ctax scenarios presented in this thesis – namely an almost constant trade balance and current account – the REER also reflects changes in an important driver of GDP growth, and one that is significantly different between scenarios, namely that of the costs of domestic primary factor’s productivity relative to the price of foreign products.

Figure.4.4 Causal loop diagram of how a change in primary factor prices over factor productivity impacts GDP



Explanation of the figure: A causal loop diagram shows how variables in a model are linked: a “+” sign with a connecting arrow indicates a positive relationship of a change in one variable on the other, a “-” sign a negative relationship; For IMACLIM-ZA this figure is conditional on a constant current account and trade balance (relative to GDP), as well as fixed price elasticities for international trade; One mechanism (in shaded boxes) in the scheme functions as a brake on the relation between GDP and productive primary factor unit costs: Non-substitutable imports would become too expensive if primary factor productivity would become very cheap.

Continuation of the text before the box:

In RP the aggregate cost reduction is the sum of a number of changes in the cost structure of resources (see section 4.2.2 for more detail): Energy costs per unit of GDP increase (1.6%), whereas costs for imports (-1.7%) and for intermediate inputs (-5.1%) decrease. Within the category of (primary) income components, labour income increases, whereas the other types of primary income (net profits, capital amortisation, and indirect taxes) see their share in income diminish. The sum of change in primary income per unit of GDP is (by definition) zero.

When applied to the decomposition of GDP growth, this leads to the result that change in GDP per worker consists of a 1.055 change in income over total resources, times a 1.28 rate of change (= 1.35 / 1.055) in value of supply per worker (Table 4.7). However, to explain GDP growth this is insufficient. As I will show in section 4.4 below, similar aggregate cost reductions between scenarios do not translate into similar GDP growth, and cost reductions prove to be uncorrelated to GDP growth.

¹³⁵ Of course, one can also imagine that foreign investors would not want to invest if they knew that the value of their investment were to disappear quickly because of a constant reduction of the REER.

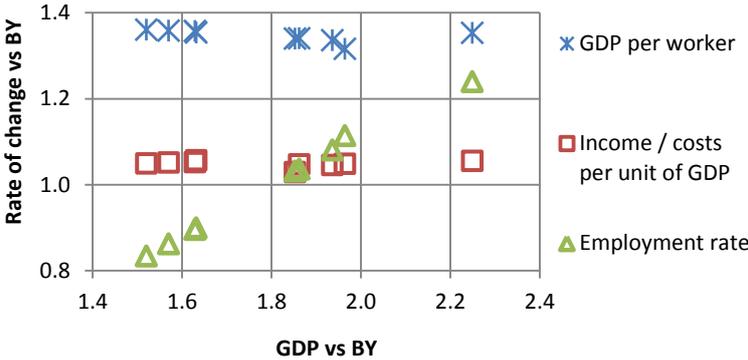
Nevertheless, while there are little differences in cost reductions between RP and the different scenarios, there are significant differences in the nature of the composition of these cost reductions, which can be related to differences in the type of revenue recycling. Section 4.4.1 discusses this for the different Ctax scenarios.

Table 4.6 Change in value of resources per unit of GDP, for RP vs BY

	Aggregate economy ⁽⁵⁾
Energy IC costs ⁽¹⁾	+1.6%
Mat IC costs ⁽²⁾	-5.1%
T&C margins ⁽³⁾	-0.0%
Import costs	-1.7%
Total "non-income"	-5.2%
Labour (gross wages)	+1.2%
Capital write offs	-0.2%
NOS & spec.margins	-0.7%
Total indirect taxes ⁽⁴⁾	-0.3%
Total primary income	+0.0%
Resources per unit	-5.2%

(1) Costs for intermediate consumption (IC) of energy, and energy sectors, encompass COA, OIL, GAS, REF and ELC; (2) Mat is the aggregate of Materials & services, and consists of EIN, MAN, LSS, HSS, and TRA; (3) T&C margins are Transport & Commercial margins, and consist of an after-factory gate transfer or payment of transport and trade (commerce) costs levied over domestic products and imports; (4) Indirect taxes are fuel levies, a sales tax (VAT) and other taxes minus subsidies on products – taxes minus subsidies on production have been included in this category here too. (5) For the aggregate economy the volume of supply is the GDP.

Figure 4.5 Change vs BY of GDP per worker, income/costs per unit of GDP, and employment rate, against GDP growth vs BY, for RP and R300 Ctax scenarios



A posteriori, intuitive explanations can be found to explain why differences in the composition of cost reductions (due to the different revenue recycling mechanisms) lead to differences in GDP growth. However, it is preferable to have a more objective, traceable and quantifiable explanation for the GDP growth result of different scenarios. The puzzle of explaining GDP growth results is therefore not finished, and it is necessary to look for an explanation of both GDP growth and the employment rate.

Table 4.7 Extension of the decomposition of GDP growth of RP vs BY by splitting GDP per worker into two components

	Value of supply per worker*	Income / costs per unit of GDP**	GDP per worker	Active population	Change employment rate	GDP
RP (vs BY)	1.282	1.055	1.353	1.341	1.239	2.249

* The rate of change in value of supply per worker is calculated as the rate of RP's GDP deflated value of supply per worker in RP over it's value in BY data;

** The ratio of income over costs per unit of GDP indicates growth thanks to cost reductions. It is measured as the ratio of primary income relative to the total value of resources, which can be considered the cost per unit of GDP.

Quantifying the combined impact of changes in domestic and foreign markets on GDP

While differences in cost reductions do not explain GDP growth results for the scenarios of IMACLIM-ZA, the logic behind how cost reductions contribute to GDP growth does contain an indication for finding a quantifiable explanation for GDP growth results. Section 2.1.4 discussed that cost reductions partly explain that income and final demand can outgrow (gross) primary factor

productivity. Such growth in demand causes factor use to grow in comparison to the situation in the previously existing economic equilibrium. However, section 2.1.4 also explained that what ultimately matters for GDP growth is the change in primary factors' average (gross) productivity growth *relative to* the total of primary factors payments (primary income, including indirect taxes) per product sold. The latter determines the "real" price of a factor's productivity, by which is meant the volume of goods that can be afforded with a factor's income. When total primary income per volume unit supplied to the South African economy increases, primary factors' "productivity" becomes more expensive. This leads to lower GDP (see section 2.1.4).

Analysis of the results of carbon tax revenue recycling scenarios below (section 4.4.1) confirms the previous predictions: It shows that cost reductions are achieved in different ways in the different scenarios. The average price of primary factors' productivity is the central element to explain these differences. In some cases, a reduction of the average price of labour compensates for the fact that more indirect taxes are levied per product via carbon taxation. Would this compensation not have taken place, then the economy would have been in disequilibrium, because output (at similar productivity) would no longer match demand. The latter would occur for two reasons: Firstly, South African products would become less attractive in international comparison; and secondly, domestic purchasing power would have been reduced. In other cases, carbon tax revenue is recycled in a way in which the amount of "real" primary income per product does not increase. The REER expresses this "real" price of primary factor's productivity (see Box 5).¹³⁶ Nevertheless, it is an aggregate indicator, and the mechanism through which scenario assumptions lead to parallel changes in GDP and the REER remains rather intuitive, and cannot be quantified easily.

To provide more insight into how scenario assumptions for carbon tax revenue recycling lead to different outcomes for GDP growth, this thesis proposes an additional indicator. This additional indicator can be said to measure the *change* in income over demand for products. More precisely, the envisioned indicator measures how domestic income grows relative to the volume of products supplied to the South African economy¹³⁷ compared to a reference, e.g. base year data. To construct this indicator, the change in income over costs per unit of GDP (the inverse of cost reductions) is combined with two other elements which can be obtained in decomposition analysis of GDP growth, starting from the decomposition presented in Table 4.7 above. These two elements are explained here and consist of (their calculation is given below, I stick to the "per worker" approach): *i.* Change in the (weighted) average value per volume unit of supply; *ii.* Change in the (weighted) average volume of supply over volume of domestic output.

¹³⁶ In fact, change in the REER is generally considered an expression of a change in international competitiveness. In IMACLIM-ZA, lacking the possibility to calculate price levels relative to price levels in multiple trade partners, this is conditional on a constant trade balance and current account (relative to GDP): See Box 5 before.

¹³⁷ "Supplied" in the sense of national accounting, meaning total volume of resources, "South African markets" thus includes exports.

Change in the average value of supplied goods and services

The first of the two aspects is calculated as the average value of total supply, deflated by the GDP price-index. To see why it is relevant for GDP growth, recall from the discussion above that the impact on growth of cost reductions is calculated as a change in the *ratio* of income over costs (details follow below). An increase in this ratio does not lead to income growth when simultaneously the average value of all products supplied to the South African economy's uses (not just goods for final consumption) decreases. Technically speaking, a change in the average value of goods and services supplied to the South African economy should measure divergence in the price index of total supply and that of final demand or primary factors.¹³⁸ Such a divergence could be caused by structural change (in demand) moving towards products that have, on average, an increase/decrease in their value, by increasing/decreasing average primary and secondary factor prices at the same rate. E.g., in case of an average increase in the value of goods & services, GDP and income generation get more concentrated in sectors whose prices have risen above average. One possible explanation for this change in average value and price per product could be that primary factor prices change in such a way that secondary factor prices change in the same way, thereby increasing costs and income at the same rate, and without a negative consequence for demand. This could for instance be the case when a change in primary factor prices is accompanied by a change in the REER in the opposite direction.

Calculation of the change in the average value of supply

To calculate the change in the average value of supply on a *per worker* basis – the denominator for the decomposition analysis in this chapter – it is necessary to separate the change in value of supply per worker into growth in (physical) volume of supply (domestic production, *Y*, plus imports, *M*) on the one hand, and value per volume unit of supply on the other hand (see Eq.61). For the aggregate economy, volume is measured as GDP, but this concerns a kind of “net” volume of goods & services supplied (real income), while here, “gross” physical volume of supply is meant, see Eq.61:¹³⁹

$$\left[\frac{\text{Resources Value}}{L} \right]_t \bigg/ \left[\frac{\text{Resources Value}}{L} \right]_0 = \left[\frac{\text{Resources Value}}{\text{Volume } Y+M} \right]_t \bigg/ \left[\frac{\text{Resources Value}}{\text{Volume } Y+M} \right]_0 * \left[\frac{\text{Volume } Y+M}{L} \right]_t \bigg/ \left[\frac{\text{Volume } Y+M}{L} \right]_0 \quad (61)$$

, with:

<i>L</i>	Total employed labour force;
<i>Resources Value</i>	Total (deflated) value of all sectors' resources = IC+VA+M+indirect taxes;
<i>Volume Y + M</i>	For timestep (with subscript) 0: Aggregate volume of Y + M ≡ 1; While for timestep t: Aggregate volume of Y + M is calculated as the geometric mean of

¹³⁸ Keep in mind that this divergence is measured independent of any change in the cost structure itself, which, as discussed above, is measured through a change in the ratio of income over costs.

¹³⁹ Recall that the change in value over volume of supply ($\frac{\text{Resources Value}}{\text{Volume } Y+M}$) is *not* the same as the change in income over costs per unit of GDP, which was treated already separately above

the weighted average of all i sector's growth rates of volume of supply (vs. timestep 0): $((Y+M)_{i,t}/(Y+M)_{i,0})$, respectively weighted by BY $(\overline{\%GDP}_{i,0})$ and projection year $(\%GDP_{i,t})$ sectoral GDP shares (see Eq.62):¹⁴⁰

$$[Volume\ Y + M]_t = \sqrt{\sum_i \left(\frac{\%GDP_{i,0}}{\%GDP_{i,0}} * \frac{(Y+M)_{i,t}}{(Y+M)_{i,0}} \right) * \sum_i \left(\%GDP_{i,t} * \frac{(Y+M)_{i,t}}{(Y+M)_{i,0}} \right)} \quad (62)$$

Multiplying the ratio of change in value per volume unit supplied to the South African economy ($Y+M$) with the ratio of change in income over costs gives the average change in income per product supplied to the South African economy. Note that this has characteristics of a multiplier, considering that an increase of income equals an increase in demand and in turn, supply again: The addition of a little more supply adds a little more (but smaller) growth of income, etcetera.

Change in the rate of volume of supply over volume of domestic output

The second of the two elements additional elements for the income multiplier reinforces this process of income growth. It measures the change in the (weighted average) rate of the volume of total supply over the volume of domestic output, and therefore functions as a measure for import substitution. In case domestic products substitute imported products more than in the initial situation, this rate is <1 ; and when imported products substitute for domestic products compared to an initial situation this rate >1 . In the former case, domestic income grows more than calculated by the growth of income per unit of supply, because a larger share of supply has a domestic origin, which means that domestic value added can grow. In the latter (opposite) case, domestic income grows less than income per unit of supply, because a part of supply does no longer generate (domestic) value added. This rate should therefore be relevant for income growth, and should therefore be integrated into the DIM. Obviously, the previously mentioned two elements (change in the rate of income over costs, and change in the value per average volume unit of supply) should be multiplied by the inverse of the change in the rate of volume of supply over volume of domestic output.

It should be noted that this rate plays a paradoxical role in a decomposition analysis for GDP growth: If one takes the perspective of primary factor productivity (as I do with labour productivity in the decomposition analysis presented here), growth in volume of supply over volume of output should be multiplied by the growth in the volume of output per worker to obtain the growth in the volume of supply per worker. In a next step, growth in volume of supply per worker can be multiplied by the growth in income per volume unit of supply to obtain income growth per worker, in other words: GDP per worker.

An example is a situation in which (suddenly and exogenously) imports that are taxed start to

¹⁴⁰ No official definition of the volume of aggregate gross volume of domestic output or of gross volume of supply per worker exists. To approximate the change in these indicators, the GDP share weighted average sectoral growth in volume of supply, or domestic output per worker is calculated, taking the geometric mean of its calculation on the basis of BY and of projection year sectoral GDP shares.

substitute a part of (non-taxed) domestic output. Tax income replaces labour income in value added generation, so income per unit of supply does not need to change (if the tax is sufficiently high). However, due to the reduction of the number of workers to produce the domestic output for the national economy, GDP per worker increases. But, as domestic output is substituted by foreign products, the number of workers decreases, and therefore also GDP (all other things equal).¹⁴¹

Definition of change in the rate of volume of supply over volume of domestic output

Growth in volume of supply per worker can be split in a change in volume of domestic output per worker (which equals labour's gross output productivity), and change in volume of supply per worker over volume of domestic output per worker (see Eq.63); The latter of the two rates represents import substitution: The more domestic output substitutes for imports, the lower the rate of volume of supply over volume of domestic output becomes.

$$\left[\frac{\text{Volume } Y+M}{L} \right]_t / \left[\frac{\text{Volume } Y+M}{L} \right]_0 = \left[\frac{\text{Volume } Y}{L} \right]_t / \left[\frac{\text{Volume } Y}{L} \right]_0 * \left[\frac{\text{Volume } Y+M}{\text{Volume } Y} \right]_t / \left[\frac{\text{Volume } Y+M}{\text{Volume } Y} \right]_0 \quad (63)$$

$\left[\frac{\text{Volume } Y}{L} \right]_t$ is calculated in the same way as the $[(\text{Volume } Y+M)/L]_t$ in Eq.62;

$\left[\frac{\text{Volume } Y+M}{\text{Volume } Y} \right]_t$ also calculated as the $[(\text{Volume } Y+M)/L]_t$ in Eq.62, except that for consistency in the weighing procedure with the other indicators, changes of per worker rates of these volumes are averaged (Eq.64):

$$\left[\frac{\text{Volume } Y+M}{\text{Volume } Y} \right]_t = \sqrt{\sum_i \left(\%GDP_{i,0} * \left(\frac{L_{i,t}}{L_{i,0}} \right) / \left(\frac{Y_{i,t}}{Y_{i,0}} \right) \right) * \sum_i \left(\%GDP_{i,t} * \left(\frac{L_{i,t}}{L_{i,0}} \right) / \left(\frac{Y_{i,t}}{Y_{i,0}} \right) \right)} \quad (64)$$

Final decomposition of GDP growth in RP

Calculation of all elements for RP compared to BY leads to the values presented in Table 4.8: The volume of output per worker turns out to grow on average by 25.6% (2nd column); the volume of supply over the volume of output per worker decreases by 1.8% (3rd column: a rate of change of 0.982); and the value over volume of supply increases by 4% (4th column).

Table 4.8 Overview of decomposition from GDP growth to change in employment, RP vs BY

(Values are relative to BY)	Output volume (Y) per worker	Supply volume (Y+M) over Y*	Value / volume of supply*	Value of supply per worker	Income / costs per unit of GDP*	GDP per worker	Active population	Change employment rate	GDP
RP (vs BY)	1.256	0.982	1.040	1.282	1.055	1.353	1.341	1.239	2.249

Comment: * The indicators marked with an asterisk (*) are part of the calculation of the Domestic Income Multiplier.

Calculation of the Domestic Income Multiplier (DIM)

For each of the just presented components it can be argued that they have an impact on growth of

¹⁴¹ Of course, reality is more complex, e.g. due to consumer preferences, the role of international financial transfers, and exchange rates.

income relative to (or: beyond) primary factor productivity growth: When the ratio of value over volume of supply increases (at a constant income over costs or resources ratio), income and thus final demand must increase relative to the volume of supply. For the ratio of the volume of supply (Y+M) over the volume of domestic output (Y), the inverse is true. When it increases, imported products provide a larger share of demand in South African markets. When it decreases, the opposite is true. The idea is therefore that an indicator for GDP growth in IMACLIM-ZA scenarios can be found once one combines these two indicators with the other indicator which corresponds to growth of demand over gross output productivity, namely the reduction of costs per unit of GDP (change in income over costs, see the discussion above).

The most simple way to combine these indicators is to multiply the components that have a positive impact on income or demand for domestic output relative to factor output productivity, and to divide this by the indicator which has a negative impact on growth of demand for domestic output. In other words: To multiply growth in value over volume of supply (1.040 for RP) with the increase in income over costs per unit of GDP (1.055 for RP) – which gives growth in income per volume unit of supply (1.097) – and to multiply this with the inverse of the change in the ratio of domestic output (Y) over the volume of supply (Y+M) ($1 / 0.982 = 1.019$).

The combination of these elements thus combines the change in real income over the volume of supply, and the change in the share of the volume of domestic output in the volume of supply. As the volume of supply roughly corresponds to the volume of goods which constitute real income, the change in income over supply volume times the change in domestic share in supply can be considered a multiplier for growth in domestic income. It is an index for the change in domestic income relative to the volume of products supplied to the South African economy. Correspondingly, I call it the domestic income multiplier (DIM), an index for the change in domestic income per volume unit of products supplied to the South African economy, for which the value for RP is 1.118 (Table 4.9).

Table 4.9 Calculation of Domestic Income Multiplier for RP, vs BY

Components to be multiplied	Value RP vs BY
Change in value per unit of supply	1.040
* Change in income / costs per unit of GDP	1.055
= Income over volume of supply	1.097
* Change in average share of Y in Y+M	1.019
= Domestic Income Multiplier	1.118

Some additional context for the use of the DIM

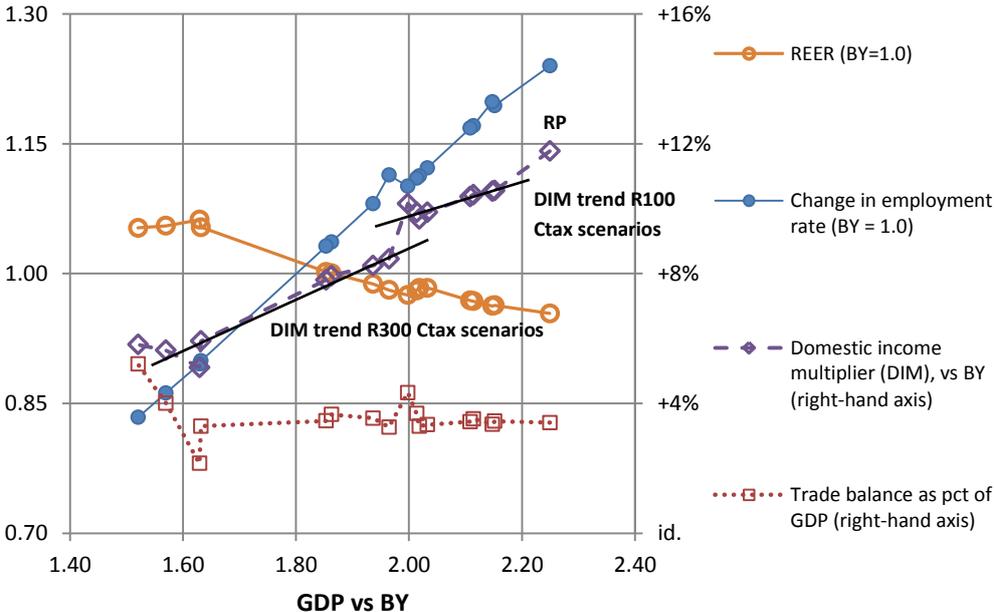
Taking a step ahead of the presentation of the results of Ctax scenarios (in section 4.3) the DIM has been calculated for these scenarios too. Plotting these results and that for RP against GDP growth relative to base year (BY) data shows a strong linear correlation (Figure 4.6). Two different trends can be identified for each set of carbon tax scenarios, which must be related to structural impacts of the

structure of the tax system, e.g. through rigidities in energy demand. Some not qualified multiplier effects, operating through the I-O matrix, should account for the relation found between the DIM and GDP. Deviations from the trend lines largely correspond to variation around the average trade balance surplus (Figure 4.6).

Of course, there is a correlation between GDP growth and the REER too, as explained in Box 5 before. But, in contrast to the REER, which is a rather aggregate scenario result like GDP growth itself, the DIM can be linked to detailed structural and technological changes that are different for each scenario and which therefore help in providing a logical explanation of scenario results. The next sub-section shows how the components of the DIM follow from changes at the sectoral level, especially structural and technological change which can be related to changes in relative prices and the structure of the growth of (the volume of) demand.

A weakness of the DIM lies in the way in which its sub-indicators have been calculated, particularly the slightly arbitrary choice of weighing of sectoral changes. Also, possibly other similar indicators could be constructed that could provide the same link between structural and technological change and GDP growth and employment. Furthermore, the relations found are dependent on the condition that there are no significant differences between scenarios in the trade balance and the current account (and thus also the broad capital account), and in the trend in the volume of exports. The relation that has been found here is therefore specific for the scenario analysis performed in IMACLIM-ZA for this thesis, and not a generalizable result for economic analysis. Nonetheless, these weaknesses do not discard the indicator's added value in showing the logic for aggregate GDP growth and employment results of the different scenarios, which will be further elaborated on in section 4.2.2.

Figure 4.6 Main indicators for GDP growth vs BY plotted against change in GDP; for RP, R300 and R100 Ctax scenarios



From GDP growth to employment

Note that for the construction of the DIM *the inverse* of the change in the share of the volume of supply (Y+M) over the volume of domestic output (Y) is multiplied with the other two components. This is in contrast to the use of this indicator in the decomposition and calculation of GDP per worker, where one multiplies the other components with volume of supply over domestic output and not its inverse value (Table 4.8). Whereas substitution of imports by domestic output leads, *all other things equal*, to a decrease of GDP per worker (or value added productivity of labour), it also leads to an increase of the DIM and therefore to a growth of demand for domestic output relative to factor gross output productivity – i.e. GDP growth.

More generally speaking, when GDP grows relative to GDP per worker, employment must increase. Substitution of foreign by domestic goods (for reason of improved competitiveness) is thus an important contributor to growth in employment, alongside cost reductions per unit of GDP. It might also be telling that the growth of the employment rate in Ctax scenarios starts when they achieve GDP growth above the baseline trend in exports (1.81 from 2005 to 2035), after which the REER goes below its BY value – though this has not been further analysed. The analysis of Ctax scenario outcomes below will show that it is in fact the type of cost reduction, and particularly how carbon tax revenue recycling schemes manage to reduce the price of primary factors relative to the price of foreign goods, that counts for total GDP growth. It will be shown that scenarios which combine high GDP growth with relatively low GDP per worker achieve the highest growth in employment.

4.2.2. The role of structural and technological change in RP

After having explained at an aggregate level GDP growth and employment results of RP in the previous sub-section this sub-section discusses how these and other results, particularly the amount of CO₂ emissions, follow from structural and technological change at the sectoral level. For this reason this sub-section first clarifies in detail what technological and structural change is obtained in RP, which then helps to explain respectively results for CO₂ emissions, for employment by skill and household class, and for income inequality.

Explaining GDP growth and the DIM on the basis of changes at the sectoral level

The combined impacts of structural and technological change lead to the results for RP for growth in labour output productivity and in the domestic income multiplier presented in section 4.2.1, which together explain the GDP growth found for RP. The average growth in labour output productivity is the average of sectoral growth in labour output productivity weighed by GDP resulting from the assumptions about productivity growth (section 3.6.3) and trade-offs in production (which are discussed in more detail below). The explanation for the aggregate result for the DIM is more complex and the topic of the current paragraph is how it originates from sectoral developments.

At the sectoral level the DIM is highest for energy sectors, HSS and MAN. For energy sectors this is due to an increase in value per unit of supply of 64% (Table 4.11), in other words: the average real

price increase. This can be related to the price increases of coal, electricity and to a lesser extent refinery products (due to the increased coal and oil prices), as previously discussed in sections 3.1.3 and 3.6.3. A part of these price increases for energy products lies in the increase of production costs, which means that the share of income in total resources is reduced. Due to an increase of foreign prices and a real devaluation of the Rand (decrease of the REER) the price increases do not negatively affect the share of domestic output in supply of energy products to the South African economy. The DIM for energy sectors is, on average, 1.48 for RP relative to BY (Table 4.10).

For the HSS sector the increase of domestic income over the volume of goods supplied originates mainly from average price increases (+6.1%) and cost decreases (+6.8%). The former, the average price increase is mainly caused by increased labour costs (Table 4.11). The increase of labour costs is the consequence of the price of labour increasing more (44%) than HSS' reduction in labour intensity (16%). Normalized per unit of GDP (primary income) the changes in the costs structure of resources of HSS lead to an increase of primary income relative to non-income components. Thanks to the devaluation of the REER this price increase does not have negative consequences for international competitiveness, and the resulting DIM for HSS for RP relative to BY is 1.135 (Table 4.10).

Table 4.10 Calculation of DIM by sector for RP, vs BY

	Energy sectors	EIN	MAN	LSS	HSS	TRA	Aggregate economy
Value per unit of supply	+64%	+0.1%	-5.4%	-2.2%	+6.1%	-0.6%	+4.0%
<i>Total resources relative to income****</i>	<i>+12%</i>	<i>-1.8%</i>	<i>-6.7%</i>	<i>-7.0%</i>	<i>-6.4%</i>	<i>-9.0%</i>	<i>-5.2%</i>
Income relative to total costs****	-11%	+1.8%	+7.2%	+7.5%	+6.8%	+9.8%	+5.5%
Primary income over supply volume**	+47%	+1.9%	+1.4%	+5.2%	+13%	+9.2%	+9.7%
Share of domestic output in supply	+0.9%	+3.5%	+10%	+0.1%	+0.2%	+0.1%	+1.9%
Multiplier for domestic income per unit supplied*** (DIM)	+48%	+5.5%	+11.1%	+5.2%	+13.5%	+9.3%	+11.8%

Comments: * Supply concerns total resources, in volume terms it consists of Y+M, whereas for energy sectors it is measured by dividing the value of supply by a price index for total energy resources. For the aggregate economy the volume of supply measures GDP growth. The values of average units of supply have been calculated as change in per worker values; ** The change in final demand per unit of supply is calculated by multiplying: (1+ change in value per unit of supply) * (1+ change in income relative to total resources); *** Multiplying the change in final demand per unit of supply times the change in the share of domestic output in supply gives the GDP multiplier per unit of supply; **** Income relative to total costs is the inverse of total resources relative to income.

In the MAN sector it is not the increase of value per product unit that drives income growth, but the opposite effect: Namely, domestic production cost reductions leading to price competitive substitution of imports, which can be observed in Table 4.11 as a reduction of import costs, whereas domestic production costs per unit supplied to the South African economy do not increase. The growth of domestic income for the MAN sector therefore mainly originates from import substitution, which leads to a growth of 10% of the share of domestic output in the total supply of MAN products to the markets of the South African economy (Table 4.10), leading to a DIM for the MAN sector of 1.111 for RP relative to BY.

In the remaining sectors, TRA, EIN and LSS, different causes for growth of the DIM can be identified too, but their contributions are either a modelling artefact, like in the case of TRA, or relatively small,

as is the case in LSS and EIN. For the latter two sectors, similar explanations as for growth of the DIM for MAN and HSS can be given (see Table 4.10 and Table 4.11), but these will not be further discussed here. The increase of the DIM for the TRA sector only originates mainly from cost reductions thanks to higher receipts of transport margins paid by other sectors (mainly the COA sector). This means that a larger share of production costs is dedicated to after-factory gate (and before-sales) transport services, and that costs of the TRA sector are transferred to other sectors. The total change in transport margins per unit of GDP is zero (see Table 4.11).

Overall the conclusion is that South Africa achieves additional GDP growth beyond the growth of factor (in the discussion here: Labour) output productivity, meaning of the DIM (domestic income over units supplied to the South African economy), by: 1. real price increases which do not negatively affect demand; which 2. are concentrated in primary income components of the cost structure of resources; and 3. substitution of imports. The price increases lead to income growth in energy sectors and HSS, whereas cost reductions are mainly achieved in MAN, LSS and HSS, while import substitution is almost entirely on the account of the MAN sector (Table 4.10).

Table 4.11 Change in resources per unit supplied by sector for RP relative to BY

	Energy sectors ⁽¹⁾	EIN	MAN	LSS	HSS	TRA	Aggregate economy ⁽⁵⁾
Energy IC costs ⁽¹⁾	+18%	+2.8%	+0.2%	+0.8%	+0.1%	+7.9%	+1.6%
Mat IC costs ⁽²⁾	+0.4%	-1.5%	+0.0%	-4.7%	-1.8%	-1.8%	-5.1%
T&C margins ⁽³⁾	+20%	+0.0%	-0.9%	-1.5%	id.	-12%	-0.0%
Import costs	+14%	-1.8%	-5.0%	-0.1%	+0.0%	+1.0%	-1.7%
Total "non-income"	+53%	-0.5%	-5.7%	-5.5%	-1.7%	-4.5%	-5.2%
Labour costs	+2.5%	+0.5%	+0.4%	+3.8%	+6.6%	+2.8%	+1.2%
Capital write offs	+7.9%	-0.2%	-0.1%	-0.4%	-0.5%	-0.4%	-0.2%
NOS & spec.margins	+0.6%	+0.3%	+0.1%	-0.1%	+0.8%	+1.6%	-0.7%
Total indirect taxes ⁽⁴⁾	+0.3%	-0.1%	-0.1%	+0.0%	+0.8%	-0.2%	-0.3%
Total primary income	+11%	+0.6%	+0.3%	+3.3%	+7.7%	+3.8%	+0.0%
Resources per unit	+64%	+0.1%	-5.4%	-2.2%	+6.1%	-0.6%	-5.2%

Comments: (1) Costs for intermediate consumption (IC) of energy, and energy sectors, encompass COA, OIL, GAS, REF and ELC; (2) Mat is the aggregate of Materials & services, and consists of EIN, MAN, LSS, HSS, and TRA; (3) T&C margins are Transport & Commercial margins, and consist of an after-factory gate transfer or payment of transport and trade (commerce) costs levied over domestic products and imports; (4) Indirect taxes are fuel levies, a sales tax (VAT) and other taxes minus subsidies on products – taxes minus subsidies on production have been included in this category here too. (5) For the aggregate economy the volume of supply measures GDP.

Technological change

The value for the DIM and the just described changes in the cost structure of RP are a consequence of technological and structural economic change. It is worth considering into more detail what technological and structural change can be found in the results of RP in order to better understand the results for GDP growth and other results, like the CO₂ intensity of the economy and employment by skill (the latter two are discussed below). The in engineering terms most correct indicator for technological change are changes in physical output productivity (or input intensity of production) by factor or input. Numbers for the evolution of technological coefficients can also be used to evaluate

the realism in physical terms of projections for future production (this will be done for energy intensity in RP and Ctax scenarios in section 5.5). It should be clear from the model description in Chapter 3 that these changes in physical intensities of inputs and factors over physical output follow from assumptions about output productivity gains on the one hand, and from price-elastic substitution in production on the other hand.

The increase in labour costs per unit of supply in all sectors presented in Table 4.11 (above) follows from an increasing share of domestic output, and from the fact that in RP domestic production in all sectors observes an increase of the price of labour that is bigger than the decrease of labour intensity (Table 4.12). The evolution of labour intensity itself largely follows the exogenously assumed change in labour productivity by sector (see Appendix C.1). Some variation in labour intensity relative to the assumed exogenous change can be related to price elastic trade-offs.¹⁴² Similar differences in the change in capital intensity and materials and services intensity also follow from differences between sectors in exogenously assumed capital output productivity gains and changes in relative prices and elasticities of substitution. Capital intensity decreases more than might be expected on the basis of the relative evolution of the price of capital goods, which makes capital cheaper relative to other inputs and factors. This can be explained from its complementarity with labour (see section 3.2.1).

The table furthermore shows that energy price increases are compensated to some extent by decreases in energy intensity (which will be further studied in section 5.5). In the case of energy intensity, the entire change follows from price-elastic trade-offs, with differences between sectors being caused by differences in price elasticities and relative prices between factors and inputs. Especially the MAN and HSS sectors – which have high price elasticities for substitution between the capital-labour aggregate on the one side and energy on the other side – see their energy intensity reduced in RP (Table 4.12), while this is hardly the case for the TRA and REF sectors.

Table 4.12 Change in input/factor intensity with change in perceived costs, RP vs BY, by sector

	COA	GAS	REF	EIN	MAN	LSS	HSS	TRA
Growth in volumes of inputs per unit of output in production by sector ...								
Energy Goods	-15%	-1.3%	-2.9%	-11%	-30%	-22%	-37%	-4.2%
Materials & Services	-6.9%	-3.8%	-2.4%	-6.6%	-7.1%	-6.6%	-6.2%	-5.7%
Fixed Capital	-5.7%	+3.2%	+4.5%	-5.7%	-8.6%	-4.2%	-1.2%	-2.1%
Labour	-27%	-22%	-19%	-28%	-31%	-19%	-16%	-21%
Change in unit costs of inputs/factors for production by sector ...								
Energy Goods	+99%	+44%	+94%	+78%	+69%	+63%	+85%	+48%
Materials & Services	-0.4%	-0.5%	+0.1%	-0.0%	-1.7%	+0.2%	+1.5%	+1.2%
Fixed Capital	-4.6%	-4.6%	-4.6%	-4.6%	-4.6%	-4.6%	-4.6%	-4.6%
Labour	+40%	+45%	+44%	+41%	+41%	+41%	+44%	+43%

¹⁴² For instance, exogenous trends for labour output productivity are the same for LSS and TRA, but the resulting labour intensity is different due to different elasticities of trade-offs between KL and E (see Appendix C.3) and differences in the relative evolution of factor and input prices to which these sectors are confronted (Table 4.12): Due to higher relative prices of energy products and a higher elasticity of substitution LSS has a lower decrease of labour intensity than TRA.

The picture thus obtained of technological change in production in the South African economy in RP is one of labour and capital substituting for energy in sectors with low energy intensity (HSS and LSS), while the manufacturing sectors (MAN) are expected to increase efficiency on all fronts. It is also worth noting that the sectors which reduce their energy intensity most, typically have low energy intensity to start with.

Structural change in RP

Results for RP (and other scenarios) depend not only on technological change, but also on change in the economic weight that sectors have in the South African economy. Changes in intermediate consumption, which follow from technological change, are one explanatory element for structural change, but final consumption and international trade play an important role too. In RP structural change in the volume of products consumed increases the role of the MAN, EIN and HSS sectors in the South African economy. These sector's output volumes increase respectively 129%, 114% and 109% from BY to RP (Table 4.13, last column).

Two out of these three sectors have among the highest Domestic Income Multiplier (DIM) values, namely MAN and HSS. However, increase of the DIM is on average highest for energy sectors in RP, but these sectors see their volume of output increase least of all sectors, due to low growth in domestic demand for their products (only 54% to 84%: Table 4.13, 6th column). Domestic demand (IC, FC, and Investment) stimulates especially demand for MAN and HSS products (domestic demand for both grows 109%: Table 4.13, 6th column). Change in the volume of international trade (exports minus imports) stimulates domestic output most for EIN, REF and COA (respectively 162%, 199% and 146%: Table 4.13, 8th column).

Table 4.13 Growth in volume of uses (dom. demand & exports) and supply (imports & dom. output), RP vs BY

	Total IC	FC by Hhs	FC by Gov	Investment	Total dom. uses	Exports	Overall trade* (X-M)	Imports	Dom. output
COA	+55%	-100%			+54%	+142%	+146%	+20%	+82%
OIL	+76%	-			+76%		(-76%)	+76%	id.
GAS	+84%	-			+84%		(+41%)	+41%	+106%
REF	+82%	+49%			+70%	+123%	+199%	+36%	+81%
ELC	+74%	+44%			+67%	+57%	+55%	+92%	+66%
EIN	+99%	+93%			+99%	+123%	+162%	+52%	+114%
MAN	+100%	+112%			+109%	+104%	(+46%)	+67%	+129%
LSS	+100%	+101%		+126%	+106%	+88%	+55%	+103%	+105%
HSS	+95%	+77%	+166%		+109%	+100%	+112%	+89%	+109%
TRA	+96%	+69%			+92%	+113%	-854%	+92%	+95%

*Comments: In case the resulting net volume of international trade is negative for a product this is indicated by a number put in-between brackets.

The increase in domestic demand for MAN products is mainly a consequence of growth in the volume of investment (demand for capital goods: +126%), and final consumption (+112%). The volumes

consumed for investment follow from average growth in domestic output and the change in average capital intensity of production. Growth of output of HSS turns out to be especially a result of growth of government final consumption (+166%). Final consumption by government results from the assumptions about change in government expenditure relative to GDP (see sections 3.5 and 3.6).¹⁴³

Impacts of structural and technological change on CO₂ emissions

From the above it became clear that growth in the volume of domestic output for products of energy sectors and of the TRA sector is lower than average in RP, and that this is mainly caused by a reduction in domestic demand. This is one of the explanations for the reduction in the CO₂ emission intensity of the South African economy, which is the topic explored here into more detail. Another energy-intensive sector, EIN, sees its domestic output increase above average thanks to improved international competitiveness. However, like other sectors, EIN reduces the energy intensity of its production (see Table 4.12 before). Reduction of demand for energy products was shown to be caused partly by technological change. Technological change in energy sectors themselves also reduced their energy intensity and therefore these sectors' CO₂ emission intensity. Together these developments cause the CO₂ emission intensity of South Africa's GDP to decrease from 0.28 in BY to 0.19 kgCO₂/ZAR₀₅ in RP.

I calculate the relative contributions of (direct) technological and (indirect) structural change to this reduction of CO₂ emission intensity of South Africa's GDP (Figure 4.7). This serves as a point for comparison when discussing Ctax scenario results (in section 4.3.1). The relative contributions of technological and structural change by sector are calculated as follows:

1. The change (vs BY) in a sector's CO₂ emissions per unit of GDP is calculated as (Eq.65):

$$ChgCO2intGDP_j = \frac{eCO2_{j,t}}{\sum_j(GDP_{j,t})} / \left(\frac{eCO2_{j,0}}{\sum_j(GDP_{j,0})} \right) \quad (65)$$

, with:

$eCO2_{j,t}$ a sector j 's CO₂ emissions at time t ($0 =$ Base Year value), see Eq.27 on p.86;

$\sum_j(GDP_{j,t})$ total GDP at time t .

2. I define the measure for a sector j 's change in CO₂ emission intensity due to technological change as following (Eq.66):

$$ChgCO2tech_j = \frac{eCO2_{j,t}}{Y_{j,t}} / \left(\frac{eCO2_{j,0}}{Y_{j,0}} \right) \quad (66)$$

, with:

$Y_{j,t}$ a sector j 's output volume at time t .

3. I define a sector's change in CO₂ emission intensity due to structural change as (Eq.67):

¹⁴³ This in theory could correspond to a higher level of provisions of free or partially paid services by government, which consumers would otherwise have to insure or pay for themselves.

$$ChgCO2struct_j = \frac{Y_{j,t}}{\Sigma_j(GDP_{j,t})} / \left(\frac{\bar{Y}_{j,0}}{\Sigma_j(\bar{GDP}_{j,0})} \right) \quad (67)$$

4. To obtain the relative contribution of technological and structural change to the change in a sector's CO₂ emission reduction per unit of GDP the natural logarithms of the measures for are calculated and divided by the natural logarithm of the overall CO₂ emission reduction (Eq.68-69):

$$RelContrCO2tech_j = \frac{\ln(ChgCO2tech_j)}{\ln(ChgCO2intGDP_j)} \quad (68)$$

$$RelContrCO2struct_j = \frac{\ln(ChgCO2struct_j)}{\ln(ChgCO2intGDP_j)} \quad (69)$$

5. These relative contributions (shares) are multiplied by the absolute change in a sector's CO₂ emissions per unit of GDP to obtain the absolute change in a sector's CO₂ emissions per unit of GDP due to technological and due to structural change (Eq.70-71):

$$AbsContrCO2tech_j = RelContrCO2tech_j * \left(\frac{eCO2_{j,t}}{Y_{j,t}} - \frac{\bar{eCO2}_{j,0}}{\bar{Y}_{j,0}} \right) \quad (70)$$

$$AbsContrCO2struct_j = RelContrCO2struct_j * \left(\frac{eCO2_{j,t}}{Y_{j,t}} - \frac{\bar{eCO2}_{j,0}}{\bar{Y}_{j,0}} \right) \quad (71)$$

6. For change in direct CO₂ emissions of households per unit of GDP no distinction between technological and structural change is made;
7. For reason of the close association of sectoral activity (weak inter-sectoral boundaries, see sector definitions in section 3.1.1) I combine COA, GAS, and EIN sectors in this analysis;
8. For reason of their relatively small contribution to direct CO₂ emissions, the MAN, LSS and HSS sector's are combined in this analysis too.

The results of this calculation (Figure 4.7) show that the ELC sector is responsible for the largest part of the reduction in CO₂ intensity of GDP, especially due to a reduction in demand for ELC (structural change, see Figure 4.7).

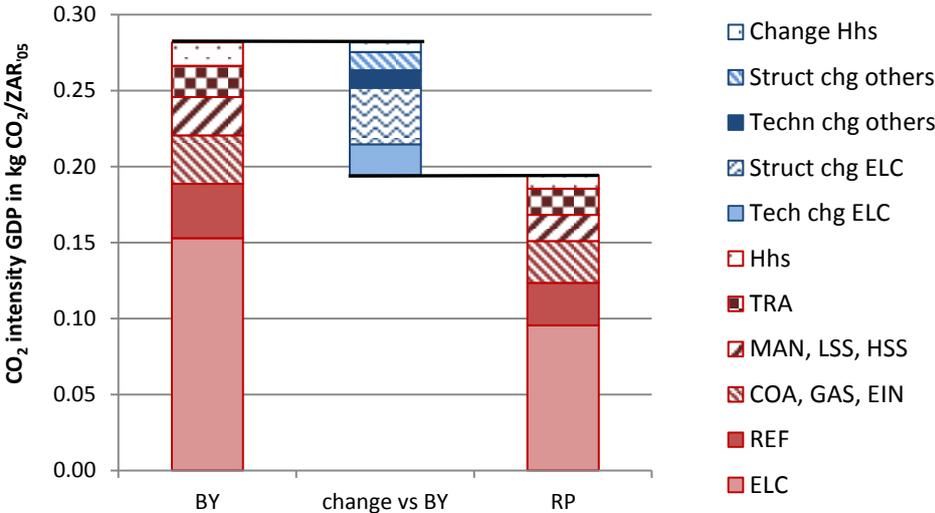
Obviously, ELC's role in the decarbonisation of South Africa's GDP needs to be big, because power generation produces 54% of South Africa's direct CO₂ emissions in BY and still 49% in RP. Of the 37% reduction of ELC's CO₂ emissions per unit of GDP, 13 percent points are due to the (exogenous) decrease in CO₂ intensity per PJ of electricity: from 285 (in BY) to 241 ktCO₂/PJ¹⁴⁴ (in RP). This follows from the realisation of the Updated IRP (2010) in the consulted run of SATIM (see section 3.1.2). The largest part of the reduction of ELC's CO₂ emissions per unit of GDP (24 pct. points) is due to a reduced demand for electricity relative to GDP (-26% vs BY). It was shown just before (see Table 4.13 above) that domestic output of ELC grows below average compared to output growth of

¹⁴⁴ ktCO₂/PJ = kilotonne CO₂ emissions per Petajoule of energy content of electricity (or any other fuel).

other sectors due to the limited growth of ELC consumption by households, in intermediate consumption.¹⁴⁵

Other sectors do not contribute much to the decrease of CO₂ emissions per unit of GDP. This is caused on the one hand by a lack of technological change in energy intensive sectors (EIN and TRA), while the sectors that do observe significant energy efficiency gains see their domestic output grow more than average (MAN, EIN and HSS), meaning that they hardly contribute to reduced CO₂ emission intensity through structural change.

Figure 4.7 Composition of CO₂ intensity of GDP for direct* emissions and it's change, from BY to RP



Comments to figure: * The adjective direct has been added to signal that technological change only concerns the reduction in use of fossil fuels within a sector, and e.g. not the indirect CO₂ emissions from the use of electricity – which are part of structural change in demand for ELC.

From structural and technological change to employment by skill and by sector

If one combines the technological change leading to change in labour intensity of production (see Table 4.12 before) with the change in output by sector (Table 4.13 above), one obtains the change in employment by sector (Table 4.14). MAN witnesses the biggest relative increase in output, followed by EIN and HSS, but it is HSS which observes the biggest increase in employment (Table 4.14), due to MAN and EIN’s high growth in labour productivity growth.

Table 4.14 Growth in total employment (nr of jobs) by sector, RP vs BY

	COA	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA	Avg.
Employment growth, RP vs BY	+34%	+60%	+46%	+107%	+54%	+58%	+65%	+75%	+55%	+66%

Growth in employment by level of skill of labour in most sectors is strongest for medium skill labour: This is the case in EIN, MAN, LSS and TRA (Figure 4.8). However, due to the bigger weight of the

¹⁴⁵ The limited growth of demand for ELC related to international trade is of little importance considering the small size of exports and imports relative to domestic ELC demand.

HSS sector in BY high skill employment (53%) than in medium skill employment (27%) – and with the HSS sector observing the highest growth rate for both medium and high skill labour – the (intersectoral) average growth rate of medium and high skill employment turn out to be about equal, both at +68%. Low skill employment grows less fast than medium and high skill labour in all sectors except MAN and LSS, where it's growth is equal to that of high skill employment.

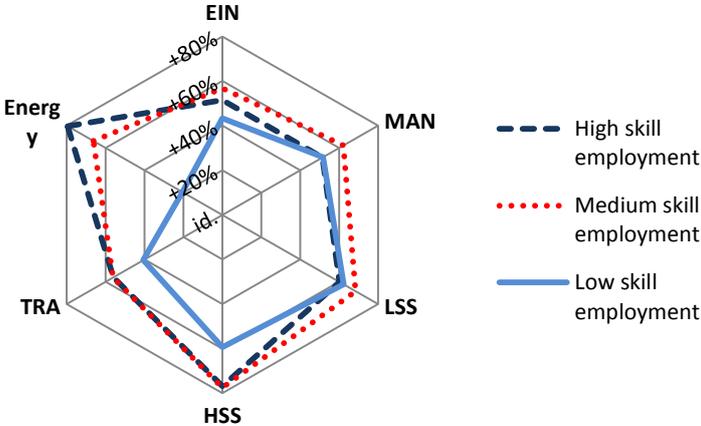
The numbers for growth in employment by skill and sector presented in Figure 4.8 are a result of on the one hand by growth in sectoral output, and on the other hand the complex trade-offs of the nested CES production function. The energy sectors results are an exception, as exogenous assumptions determine labour intensity of the electricity sector (ELC, see section 3.1.3). The results for skill intensity of employment growth of other sectors, however, can be explained at the hand of several elements. I briefly mention the most important ones:

1. For the HSS and TRA sectors, high *and* medium skill labour intensity change at the same pace, because at the bottom of the nested-CES function part of the KL aggregate (recall Figure 3.3 in section), the capital-high skill labour aggregate (KL3) and medium skill labour experience hardly any change in relative prices. On the contrary, the KL23 aggregate of capital, high and medium skill labour sees the relative price of it's productivity decrease compared to that of low skill labour, explaining the lower growth of low skill employment in these sectors;
2. In the MAN and LSS sectors medium skill labour employment grows faster than high skill labour employment, because medium skill labour's productivity increases much more than it's price in these sector. This makes medium skill labour to become relatively cheaper and thus more attractive as a factor of production in comparison to the capital high skill aggregate in these sectors. Furthermore, the relative price of low skill labour (corrected for it's productivity) does not increase relative to that of the KL23 aggregate in these sectors. As a consequence, low skill labour remains as attractive as a factor of production as the KL23 aggregate, which explains that low skill labour employment grows relatively as much as high skill labour employment in MAN and LSS (Figure 4.8);
3. EIN, finally, takes in an in-between position: It experiences some price increase of the KL3 aggregate relative to that of the medium skill labour factor (when also taking into account productivity growth), but not as much as in the MAN and LSS sectors; and it experiences some increase of the price of low skill labour relative to that of the KL23 aggregate, but not as much as in the HSS and TRA sectors.

While medium skill employment grows fastest or at least equally fast as high skill employment in all sectors, for the economy as a whole employment grows at the same rate for these two skill categories in RP (68% relative to BY: Table 4.15). This is caused by the fact that the HSS sector, in which employment grows fastest of all sectors (75%) has a much bigger weight in the high skill labour

category (56% of total high skill employment in RP) than in the medium skill labour category (only 28%). This explains the high average growth of high skill employment.

Figure 4.8 Relative increase in employment per level of skill of labour and sector, RP vs BY



Together these developments explain that the decrease in broad unemployment in RP is strongest for high skill labour: a 70% decrease in its broad unemployment rate, going from a compared to the other labour skill categories relatively low 26.5% in BY to 8.0% in 2035. For medium skill labour the relative decrease of the broad unemployment rate is 33%, resulting in a 29.4% unemployment rate in 2035. Low skill labour finally witnesses a 28% decrease in its broad unemployment rate to 29.7%. Through the wage-unemployment curves (recall section 3.3.2) this leads the real wage rate for high skill labour to increase stronger than for medium and low skill labour, namely by 51%, with the average wage rates of the other sectors respectively increasing 40%, and 41%.¹⁴⁶

Employment by skill and household class

Due the chosen allocation of labour by skill over the five household classes, the outcomes show employment increasing most in absolute (3.4 million jobs) and relative terms (+68% employment) for household class 5. The reason is a high share of high and medium skill employed in this socio-economic category (Table 4.15).

Table 4.15 Employment (thousands of jobs) by skill and household class

Household class	Hh 1	Hh 2	Hh 3	Hh 4	Hh 5	All	vs BY
Part of total pop in RP*	9%	18%	19%	32%	21%	100%	-
High skill (x1000)	0	0	168	1 511	4 535	6 214	+68%
Medium skill (x1000)	84	168	1 301	4 578	3 690	9 821	+68%
Low skill (x1000)	479	1 801	1 357	639	160	4 436	+60%
All (x1000)	563	1 969	2 826	6 729	8 385	20 471	+66%
Relative to BY	+61%	+61%	+64%	+67%	+68%	+66%	-

* Due to the allocation mechanism of employed and unemployed labour by skill to the different household classes, with non-active population following suit, the shares in total population for household classes 1 to 5 slightly change from the BY shares of respectively 10%, 20%, 20%, 30% and 20%.

¹⁴⁶ Recall that for low skill labour a more flexible labour market has been assumed, with consequentially more responsive wages, i.e. a higher real wage-unemployment elasticity at 0.15 against 0.1 for high and medium skill labour, which explains the stronger wage rate increase compared to that of medium skill labour, despite a relatively smaller decrease in its unemployment rate.

Impacts on income distribution by household class

Four developments have an impact on income inequality:

- Technological and structural change favour high and medium skill employment (see before), while high skill salaries increase faster than medium and low skill salaries;
- Labour's share in Value Added (VA) increases due to the combination of (on average) increasing labour costs and decreasing production costs, with the latter leading to relatively smaller net profits through the fixed profit mark-up rates;
- Due to a reduction of intensity of production in physical capital, investment decreases relative to GDP, while profit rates and rates of returns on equity (interests and dividend) increase;
- Due to the modelled, historically low net saving rate, households net asset positions decrease relative to household's gross disposable income after taxes (Table 4.16, last line).

It can be shown that the combination of these developments leads to a slight increase (by 7%) of income inequality between class 5 and class 1, while the income gap is reduced between on the one side the lower middle classes (Hh3 and Hh4) and on the other side the household class representing what can be considered "upper middle class" up to the very rich (Hh5): The former two's GDI after taxation increases by respectively 81% and 92% (to 10.0 and 18.8 kZAR₂₀₀₅ per capita), vs. only 53% (to 118 kZAR₂₀₀₅ per capita) for Hh5.

Table 4.16 Per capita net asset positions (in R'05) for BY and RP by Hh class

Household class	Hh 1		Hh 2		Hh 3		Hh 4		Hh 5		All	
	BY	RP	BY	RP	BY	RP	BY	RP	BY	RP	BY	RP
Per capita GDI after taxation (kZAR ₀₅)	2.0	2.6	4.1	6.1	5.8	10.0	10.4	18.8	81	118	21	34
Share of wages	12%	18%	21%	26%	36%	39%	61%	61%	57%	65%	55%	61%
Share of GOS*	3%	4%	6%	6%	11%	10%	18%	15%	17%	16%	16%	15%
Share of RK**	0%	0%	1%	1%	2%	1%	3%	3%	21%	15%	17%	12%
Other income	84%	78%	72%	67%	52%	51%	18%	21%	5%	4%	12%	12%
Per capita net assets (kZAR ₀₅)	0.1	-0.0	0.6	0.5	1.2	1.0	4.2	5.6	266	194	52	43
Total Hh class assets (pct. of after tax GDI)	4%	-0.0%	15%	7%	21%	10%	41%	30%	327%	165%	250%	127%

Comments: * GOS means Gross Operating Surplus, and includes mixed income and imputed rents, in South African SAM data a part is allocated to households (StatsSA, 2010a); ** RK means returns on capital, but consists of interests and dividends calculated as a rate over net assets.

The main reason is that these two household classes (Hh3 and H4) have a relatively high share of labour income as part of their total revenue, and it increases faster than for Hh5 because of decreasing unemployment (in BY data Hh5 already counted very few unemployed). Also, Hh5 does not see its per capita property income increase much despite an increase in the rate of returns to capital. Of course, this is due to saving behaviour, which in the case of Hh5 is assumed to be too low to maintain the same high net asset position (relative to revenue or GDP) as in BY data. For Hh3 and Hh4 interests dividends (RK) are less important as a source of income. (See Appendix D.1 for further details).

4.2.3. Summary of the Reference Projection

In summary, IMACLIM-ZA's Reference Projection (RP) has an average real GDP growth of 2.7% per year between 2005 and 2035, leading to a GDP 2.25 times bigger than in BY. This corresponds to growth of real *per capita* GDP of 80%. The share of high skill services sector's in GDP, which was already high in 2005, increases even further, and except for the electricity sector which in 2005 was still marked by a period of under-investment, all other sectors see their share in GDP decrease, indicating a slight structural reform of the economy. Manufacturing sees its output grow fastest of all sectors, but this does not translate into a higher share in South African GDP, because the manufacturing sector strongly reduces its production costs, including a reduction of labour costs and even profits (due to the fixed profit mark-up rates) per product sold.

CO₂ emissions from the use of fossil fuels increase in RP, but less than GDP itself, with 55% vs BY and also on a *per capita* basis (from 9 to 11.5 tonne CO₂). For this reason, the Reference Projection can rightfully be called "unsustainable", and far off from South Africa's Nationally Determined Contribution to the Paris Agreement. Nevertheless, CO₂ intensity of GDP decreases 31%, to 1 kg of CO₂ per USD₂₀₁₃ of GDP, for the largest part because of a reduced intensity in electricity use of production, and only moderate growth of household electricity demand.

Employment increases by 8.15 million jobs, causing the broad unemployment rate to decrease from 39% in 2005 to 24% in 2035. For this and other reasons there is growth of real income and welfare in all household classes, though high energy prices constrain the increase in household consumption of fuels and electricity. The income gap between the poorest and the richest household class increases by 7%. Nevertheless, the lower middle class (about the middle 50% of population in terms of per household income/expenditure) sees a very large income gap with the richest 20% of population reduced in RP, because labour income grows faster than capital income.

The rate at which South Africa's economy grows in RP does not follow intuitively from assumptions of IMACLIM-ZA's prospective parameterisation. For instance, labour's productivity is assumed to grow 28% on average for all sectors, while the labour force grows 34%. Combining this would amount to GDP growth of only 71%. Three other economic mechanisms need to be taken into account too to explain RP's GDP growth: South African economic sectors see (on average) the gross value of their products supplied (produced plus imported) increase; also, the share of primary income in a sector's total resources increases relative to non-income cost components; and finally, domestic production partly substitutes imports. Together this means that the (real) domestic income per product supplied to South African markets (including export markets) increases by 11.8% relative to BY.

It can be demonstrated that this indicator (multiplier) for change in domestic income per unit supplied relative to BY correlates strongly with results for GDP growth in results of all IMACLIM-ZA scenarios. Moreover, through the use of this indicator causes for GDP growth in RP can be found more easily: First of all, resources (or costs) per unit of GDP decrease thanks to input efficiency gains for

materials & services (Mat) inputs, while costs for imports also decrease (relative to primary income components of the cost structure). The latter is partly self-referring, because it is driven by a real devaluation of the South African Rand.

The devaluation of the Rand however is a consequence of GDP growth too. The devaluation of the Rand mechanically functions to adjust South African GDP growth relative to the trend in the volume of international trade in the scenarios of IMACLIM-ZA in this thesis. The value of South African trade balance is namely constrained at a certain percentage of South African GDP through assumptions which determine the current account: Once GDP growth is close to or bigger than the assumed trend for the volume of international trade devaluation of the South African Rand (it's Real Effective Exchange Rate, REER) is mechanically necessary so the trade balance equates to the negative of the sum of foreign investment and income transfers, which are approximately fixed over GDP.¹⁴⁷

The third explanation for GDP growth, the increase of the average price of South African products is more complicated to explain, but structural change, and likely a relative increase of exports of energy products at higher prices (mainly coal and refinery products), and the increase of government expenditure on high skill services (in comparison to GDP growth), contribute to this development.

Due to devaluation and the increase of the value of South African products being dependent on the reduction of costs, that is: of the total value of resources per unit of GDP, the former can be called the main driver of GDP growth, besides average factor output productivity growth. Due to trade-offs in production (rebound effects), average labour productivity growth is slightly lower than originally assumed, namely 26%. Per worker GDP growth is found to be 35% in RP. This means that South Africa's GDP of 2035, which is 2.25 times bigger than in BY, requires a 66% increase of the employed labour force, corresponding to the mentioned 8 million jobs. Trade-offs in production and in the labour market cause this increase in employment to be slightly more concentrated in medium and high skill jobs than in low skill jobs. Labour income also increases relative to capital income, this results in household classes 3 and 4, representing what could be called the lower middle class, sees their per capita income after taxation growing a bit faster than other household classes. The richest household class (Hh5) however sees it's income grow faster than the poorest two household classes, meaning that inequality does increase somewhat.

4.3. Ctax scenarios and their results

4.3.1. Introduction to scenarios for carbon tax revenue recycling

Eight *main* carbon tax (Ctax) scenarios for the recycling of carbon tax proceeds (*revenue recycling*) are presented. These are called "main" scenarios, to signal that these exclude the investment in skills option discussed in section 4.5, and to mark the difference with *ex post* developed alternative scenarios of Chapter 5. They are meant to evaluate different types of plausible, mainly fiscal, policies – each

¹⁴⁷ Note that the fact that the average price elasticity of imports and exports is >1 contributes to the required decrease of the REER.

assumed to have distinguished macro-economic impacts and/or to compensate different socio-economic groups in the South African society. I introduce them here shortly, before discussing them into more detail next:

RDEF	Reduction of the public deficit (possibly leading to a budget surplus);
RVAT	Reduction of the sales tax on final consumption; ¹⁴⁸
RGOV	Increase of government expenditure;
RSUM	Lump-sum transfer to households on an equal <i>per capita</i> basis;
RTIF-fix	Reduction of taxes on profit or income of firms while firms do not change their profit mark-up rates;
RTIF-low	Reduction of profit or income taxes of firms who respond by reducing profit margins;
RTaY	Carbon tax revenue is used to reduce taxes on production, up to the extent that production is subsidised (see explanation below);
RTSC	Carbon tax revenue is used to reduce social security contributions paid as a rate over net wages, up to the extent that labour is subsidised.

The details for the modelling of the different revenue recycling scenarios and a short motivation for their choice are as follows:

- **RDEF** is the option closest to “preference neutral”. In CGE models with one aggregate household (class), a per capita lump-sum transfer is often considered the reference option for carbon tax recycling option because it is supposed to be neutral in terms of final consumption preferences. With 5 household classes however, “preference neutrality” no longer exists, for the reason that preferences and carbon tax burdens differ between classes. By recycling the carbon tax proceeds to the public deficit, the recycling scheme itself does not have a direct impact on the tax burden and household preferences (e.g. by changing relative prices beyond the impact of the carbon tax), although indirectly it will affect international lending and borrowing and the trade balance, which will affect different household classes in different ways. It is therefore not neutral either, but a key motivation to include this option is that the public deficit, and obtaining finance is currently a significant issue in South Africa, which is therefore looking for ways to increase government revenue in the short term;
- **RVAT** explores the economic inefficiencies associated with a carbon tax vis-à-vis that of a sales tax. RVAT can be seen as an overcompensation of households, who, through the sales tax cuts, receive back not only their own carbon tax payments, but also those of the polluting firms (for which they of course partly pay partly indirectly through higher prices). But, as a sales tax ultimately is a tax on (both domestic and foreign) production, it also counts indirectly

¹⁴⁸ South Africa has a Value Added Tax (VAT), which (technically) is not a sales tax, as the latter only applies to final consumption. However, the VAT has been modelled as a sales tax to simplify matters.

as a tax on all firms, who benefit from its reduction by an increase in activity (sales);

- **RGOV** explores increased public spending and thus, theoretically, increased provision of public services, although the feedbacks of such services (e.g. of infrastructure, health care, police services and education) on economic activity are not modelled—except for the option additional to the main revenue recycling schemes discussed here, namely that of investment in education and training that is discussed in section 4.5;
- **RSUM** is meant as a more progressive version of recycling: rather than benefitting households in proportion of their consumption budget it equally shares the total carbon tax proceeds among all residents of South Africa. This way, South Africa’s large economic inequality might be addressed while reducing CO₂ emissions;
- In **RTIF**, the tax rate on property income and revenue for firms (τ_{IS}) is reduced when a carbon tax is levied. The budget deficit target of -3% of GDP is respected, and household revenue & property income taxes are set at their value projected in RP. Two variants of this scenario have differences in how profit mark-up rates (for net operating surplus, τ_{NOS}) respond:
 - In one variant, **RTIF-fix**, no reduction of profit mark-up rates (τ_{NOS}) takes place: Firms benefit from reduced taxes and see their after tax profits increase (gross disposable income, GDI_S). These can either be used for investment (depending on the demand for physical capital), or they can be transferred to firm’s asset holders in the form of interests or dividends (RK_{Fi});
 - In the other variant, **RTIF-low**, firms reduce their profit mark-ups, for instance because of price competition. This means that τ_{NOS} is reduced exogenously, while the rate of interests and dividends that firms pay to their asset holders ($\tau_{i_{Fi}}$) and the ratio of returns to capital by firms (RK_S) over gross operating surplus after taxes are kept as close as possible to the values in RP (respectively 12% and 26%);^{149,150}
- **RTaY** targets the tax (or subsidy) on production of non-energy companies, τY_i . It is assumed to represent efforts by the South African government to support companies by subsidising a part of their activity, via reducing taxes on production, or even by turning it into subsidies to production. In this scenario, Ctax revenue leads to a reduction of a certain number of percentage points of τY_i with sectors i being non-energy sectors. Sectors that already received net subsidies before, now see them increased;

¹⁴⁹ This has been performed by trail-and-error, using steps of 2.5% change of the rate of τ_{NOS} for the R100 Ctax case, and steps of 5% change in τ_{NOS} for the R300 Ctax case.

¹⁵⁰ The measures for evaluation of firm profitability in the second variant are a choice, because other measures for rentability of investment or capital are available too: e.g. the rate of returns over an estimate of the capital stock K . For any of these measures arguments for and against can be found. A precise modelling of profit decision rules and capital markets was outside the scope of this thesis, and the simple objective of this variability in the RTIF recycling option is only to show the sensitivity of outcomes to the profit mark-up rule, without taking it for given that markets function well. Because IMACLIM-ZA models mark-up rates as *constant before profit or property income taxes*, an exogenous reduction of τ_{NOS} is a way to simulate constant *after tax* profit rates. It could be considered to reflect a company’s decision to keep the part of after tax gross operating surplus going to shareholders or investors constant.

- In **RTSC**, the carbon tax is used to reduce the rate of charges for social security contributions over net wage (τ_{SC}). This recycling option is a way to turn the carbon tax directly into a benefit for South Africa’s labour force and labour intensive sectors, and thereby directly tackle South Africa’s unemployment rate. Because social security charges for labour are low in South Africa, this quickly translates into a subsidy on labour, equalling approximately 1.7% of net wages for a R100 Ctax, whereas previously charges added a cost of 1.6% to net wages.

The rule-of-thumb to determine the change in the targeted tax rate or income transfer in all recycling options except RDEF, is that the public budget deficit is maintained at 3% of GDP, as in RP (public budget neutrality). This way, scenarios are neutral concerning the share of government in the economy.¹⁵¹ This “contextual” neutrality of carbon tax revenue recycling is necessary because it is not possible in IMACLIM-ZA to calculate the amount of carbon tax revenue to be recycled into the reduction of another tax as an absolute (fixed) amount (value), which would then be equated across scenarios. The reason is that the amount of revenue from other taxes (such as those targeted by Ctax revenue recycling) depends on GDP growth, its structure (which sectors grow most), and on the distribution of primary income between economic agents. Such “moving targets” cannot be used to determine the exact amount of tax reduction, and reference projection values for these taxes will no longer be valid as soon as GDP growth is different or changes in structure. An exception to this revenue recycling rule is the RDEF scenario, in which all taxes are maintained at their rates of RP and the government’s budget deficit is reduced.¹⁵²

All scenarios are analysed for the implementation of a carbon tax at two different levels, namely 100 ZAR₀₅/tCO₂ and 300 ZAR₀₅/tCO₂ (see Table 4.17 for comparison to present-day values of Rand and US dollar). These rates have been chosen to cover a rate that is reasonably close to the South African carbon tax policy proposal of a tax of 120 ZAR₁₈/tCO₂, for reason of availability of runs (scenarios) with comparable carbon tax rates of SATIM and, finally, for reason of comparability to a previous study with IMACLIM-ZA by Schers et al (2015).

Table 4.17 Ctax levels in 2035 for revenue recycling scenarios, for different monetary units

	ZAR ₀₅ /tCO ₂	ZAR ₁₃ /tCO ₂	USD ₁₃ /tCO ₂
Low carbon tax	100	170	18
High carbon tax	300	510	55

4.3.2. Description of main Ctax scenarios

Key outcomes

The Ctax scenarios show big differences in terms of outcomes for GDP growth, unemployment and CO₂ emissions, but little variation in CO₂ intensity of GDP, and similarly little variation in income

¹⁵¹ Depending on GDP growth some variability between scenarios in the relative size of the public debt and in the part of budget that goes to interest payments (with an endogenous government τ_i interest rate) is still possible.

¹⁵² Technically speaking, government’s its self-financing capacity (SFC_G) goes up in the RDEF scenario.

inequality, with the exception of RSUM (Table 4.18). The scenarios with a R100 Ctax achieve only between 18% and 26% reduction of CO₂ emissions compared to RP (3rd column of Table 4.18), short of South Africa's NDC (a 49% reduction in CO₂ emissions relative to the reference projection when translated to 2035)¹⁵³. However, for a carbon tax rate of about 300 ZAR₀₅/tCO₂ scenarios either meet (RDEF, RTIF-fix, RSUM and RGOV) or come within a 10% range of the target (RVAT, RTaY, RTIF-low, RTSC). The impacts of Ct100 scenarios on average annual GDP growth rates range from negligible to moderately negative: between 0.06 and 0.4 percent point less annual GDP growth. This translates into GDP in 2035 being 4% to 11% lower than in RP (2nd column of Table 4.18). On the contrary, the impacts of the R300 Ctax rate on GDP growth range from moderately to very significantly negative, with 0.27 to 1.33 percent point less annual growth. In this case GDP in 2035 is 13% to 32% lower than in RP. CO₂ intensity of GDP depends on the rate of carbon taxation, with only small differences across different revenue recycling scenarios for a specific rate (Table 4.18).

Table 4.18 Key outcomes for main Ctax revenue recycling scenarios

Scenario	Total '05-'35 GDP growth	Broad unemployment	Jobs per mn R GDP	CO ₂ emissions (Mt)	CO ₂ emissions vs. RP	kgCO ₂ /\$ ¹³ of GDP	Hh5 / Hh1 income pp	Hh1 prim. E* cons (GJ/cap)	Hh1 non-E** comp cons/cap vs RP
BY (2005, no Ctax)	-	38.8%	7.8	443	-36%	1.54	41.7	1.7	-26%
RP (2035, no Ctax)	+125%	24.1%	5.8	687	id.	1.06	44.6	1.8	id.
Ctax rate 100 ZAR₀₅/tCO₂									
RDEF	+100%	32.6%	5.8	511	-26%	0.89	42.9	1.7	-8%
RVAT	+111%	28.5%	5.8	534	-22%	0.88	43.9	1.7	-4%
RGOV	+103%	31.3%	5.8	514	-25%	0.88	43.1	1.7	-7%
RSUM	+102%	31.9%	5.8	515	-25%	0.89	31.6	2.0	+29%
RTIF-fix	+101%	32.1%	5.8	514	-25%	0.89	43.8	1.7	-3%
RTIF-low	+115%	26.9%	5.8	548	-20%	0.88	44.0	1.7	-7%
RtaY	+111%	28.3%	5.8	538	-22%	0.88	44.0	1.7	-4%
RTSC	+115%	26.7%	5.9	542	-21%	0.88	43.8	1.7	-3%
Ctax rate 300 ZAR₀₅/tCO₂									
RDEF	+52%	49.0%	5.8	306	-56%	0.70	38.6	1.6	-20%
RVAT	+85%	36.9%	5.8	361	-47%	0.68	42.3	1.6	-12%
RGOV	+63%	45.0%	5.8	318	-54%	0.68	39.7	1.6	-17%
RSUM	+63%	45.2%	5.8	323	-53%	0.69	23.1	2.1	+51%
RTIF-fix	+57%	47.2%	5.8	313	-54%	0.69	40.5	1.6	-18%
RTIF-low	+94%	33.9%	5.9	379	-45%	0.68	42.7	1.6	-10%
RTaY	+86%	36.6%	5.8	364	-47%	0.68	42.4	1.6	-12%
RTSC	+96%	31.8%	6.0	377	-45%	0.67	42.4	1.6	-8%

* Primary energy is calculated as the amount of GJ of REF + 2.5 times the amount of GJ of ELC per capita, to take into account efficiencies of conversion and indirectly the useful work of energy. ** Non-energy is counted as the volume index (Quasi units) of non-constrained non-Energy consumption (COMP in the nested CES tree of Figure 3.4)

¹⁵³ South Africa's INDC consists of a 42% reduction in CO₂ emissions relative to BAU by 2025 followed by no more increase in absolute levels, depending on foreign assistance – in section 5.2 this will be calculated to correspond to a 49% reduction in 2035 compared to IMACLM-SA's BAU, which is RP.

Unemployment numbers largely follow GDP growth outcomes. RTIF-low and RTSC result in the lowest unemployment rates, whereas scenarios with the lowest GDP growth such as RDEF and RSUM turn out to result in the highest unemployment rates (Table 4.18). There is some variance in the “job intensity” of GDP growth between the scenarios, due to differences in technological and structural change (see section 4.2.2). Compared to RP, these unemployment outcomes are significant, and like GDP growth sensitive to the choice of the recycling mechanism. A last point to highlight is that income inequality largely varies with GDP growth too, which suggests that GDP growth in IMACLIM-ZA’s RP and Ctax scenarios turns out to benefit the rich more than the poor, for reasons which will be explained in the next section. The exception is RSUM, which strongly reduces inequality (Table 4.18).

Changes in macro-economic structure

Section 4.1 showed that in RP the South African economy moves towards decarbonisation, with a 31% decrease in CO₂ emission intensity of GDP relative to BY (see Table 4.18 above). It was shown that this decarbonisation was partly due to structural change, as the South African economy diversified. This diversification consisted of output growing most for industrial (EIN) and manufacturing (MAN) sectors, as well as for the high skill services sectors (HSS, including public services). The latter also saw the biggest growth in its share in GDP.

In the Ctax scenarios, the pattern of development is slightly different: There is less “industrialisation” or growth of the manufacturing sector, but growth in labour intensive sectors is relatively stronger. Output in volume terms still grows strongest for manufacturing sector (MAN) in all scenarios for a R100 Ctax, and in the majority of scenarios for a R300 Ctax, but it grows less than in RP. (For some R300 Ctax scenarios it is the HSS sector whose output volume grows fastest.) Carbon taxation, as expected, turns out to have a less negative impact on activity in labour intensive sectors LSS and HSS than on activity in energy sectors and the energy intensive sectors EIN and TRA. MAN takes in an in-between position (Table 4.19). Despite these changes in growth of output volume HSS’ share of GDP does not increase relative to RP.¹⁵⁴ The reason is that due to the carbon tax, a higher share of gross national (primary) income is earned over energy sector’s output. Energy sectors therefore increase their share in GDP relative to RP.¹⁵⁵

In the Uses composition of GDP only small changes take place relative to RP (see Appendix D.2.1). In RDEF, the trade balance increases its share of GDP. In RGOV, it is government final consumption (FC) that increases its share, while in RSUM it is household final consumption (Hh FC).

Change in the trade balance surplus (Table 4.20, line 2) is, for the at a R300 Ctax rate four economically best performing scenarios, caused by change in the relative size of the flow of returns on

¹⁵⁴ Recall that to obtain changes in GDP from changes in output, one needs to combine them with changes in changes in factor productivity and real factor payments and changes in other real primary income (rates of taxation and profit margins) over output.

¹⁵⁵ GDP by sector is measured through the so-called “income approach” which counts gross labour income, gross capital income and tax income from taxes on production and over a sector’s sold products as primary income, and therefore GDP, per sector.

assets (RK_{ROW}) (Table 4.20, line 4). In RTaY and RVAT this results from a higher foreign indebtedness compared to GDP (which can be linked to lower GDP growth rates and the weight of past debt repayments).¹⁵⁶ Another mechanism is that the rate of returns to ROW is higher (in RTIF-low and RTaY). In RTSC, the trade balance surplus is smaller relative to GDP as a consequence of firstly a lower rate of returns by firms, which is positively related to the rate of returns going to ROW, and secondly relatively lower foreign indebtedness thanks to higher GDP growth. In these changes the Real Effective Exchange Rate (the REER) plays a role as well, this will be discussed in section 4.4.

First conclusion on carbon tax revenue recycling

In brief, labour subsidies (RTSC) and a reduction of profit tax rates with decreased profit mark-up rates (RTIF-low), are expected to obtain the best policy outcomes if one only considers GDP growth, reduction of CO₂ emission intensity of GDP, and growth of employment. In theory, to achieve a significant reduction in poverty and inequality some elements in the spirit of the RSUM scenario would need to be added. The carbon tax rate would have to move to a rate beyond 300 ZAR₀₅/tCO₂ (55 USD₁₃/tCO₂) to achieve South Africa's NDC. Analysis in section 5.2 will show that setting CO₂ emission reduction targets instead of targeting a certain carbon tax level slightly reduces the differences in outcomes between the scenarios, but not radically, and therefore does not change this conclusion about which revenue recycling scheme best achieves the chosen policy objectives.

Table 4.19 Change in 2035 domestic output compared to RP by sector and Ctax scenario

Scenario	Sector Ctax \	COA	OIL	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
RDEF	R100	-18%	id.	-21%	-13%	-16%	-12%	-13%	-10%	-10%	-12%
	R300	-43%	id.	-49%	-35%	-38%	-35%	-39%	-31%	-31%	-33%
RVAT	R100	-16%	id.	-17%	-10%	-12%	-9%	-8%	-6%	-5%	-8%
	R300	-35%	id.	-38%	-24%	-27%	-22%	-22%	-16%	-15%	-20%
RGOV	R100	-19%	id.	-20%	-13%	-16%	-12%	-13%	-10%	-7%	-11%
	R300	-42%	id.	-47%	-32%	-36%	-33%	-35%	-27%	-24%	-30%
RSUM	R100	-19%	id.	-20%	-12%	-15%	-12%	-12%	-9%	-9%	-11%
	R300	-42%	id.	-46%	-31%	-35%	-32%	-34%	-26%	-26%	-30%
RTIF-fix	R100	-19%	id.	-20%	-13%	-16%	-12%	-13%	-10%	-9%	-11%
	R300	-42%	id.	-48%	-33%	-37%	-34%	-37%	-29%	-28%	-32%
RTIF-low	R100	-12%	id.	-12%	-6%	-8%	-3%	-2%	-1%	-1%	-3%
	R300	-28%	id.	-30%	-17%	-19%	-11%	-9%	-5%	-5%	-10%
RTaY	R100	-16%	id.	-16%	-9%	-12%	-8%	-7%	-5%	-5%	-7%
	R300	-35%	id.	-38%	-24%	-27%	-21%	-20%	-15%	-15%	-19%
RTSC	R100	-15%	id.	-16%	-8%	-11%	-7%	-6%	-4%	-3%	-6%
	R300	-32%	id.	-36%	-21%	-24%	-18%	-16%	-11%	-9%	-16%

¹⁵⁶ In RP, a high RK_{ROW} is based on a high rate of returns.

Table 4.20 The trade balance surplus as pct. of GDP and related variables for RP and selected scenarios

	<i>Unit</i>	RP	Ct300 RVAT	Ct300 RTIF-low	Ct300 RTaY	Ct300 RTSC
Trade balance surplus	<i>Pct. of GDP</i>	3.4%	3.5%	3.5%	3.7%	3.3%
Net international borrowing	<i>Pct. of GDP</i>	0.05%	0.05%	0.05%	0.05%	0.05%
Returns to ROW (RK_{ROW})	<i>Pct. of GDP</i>	2.8%	2.9%	2.9%	3.1%	2.7%
Net debt of SA with ROW	<i>Pct. of GDP</i>	39%	45%	44%	45%	43%
Rate of returns* to ROW	-	7.3%	6.3%	6.7%	6.8%	6.2%
Rate of returns* paid by firms	-	12.0%	10.4%	11.0%	10.9%	10.3%
Returns by firms (RK_s) over GOS after taxes	<i>Pct. of GOS_s</i>	26.4%	24.7%	25.6%	29.1%	23.6%

* Returns are interests and dividends, and the rate is calculated over total net assets (negative net debt)

4.4. Decomposition analysis of main Ctax scenarios

Despite small differences in CO₂ intensity of GDP, big differences exist between scenarios in terms of outcomes for GDP growth (see section 4.3.2). This means that the scenarios for the different carbon tax revenue recycling schemes have different impacts on the components which together make up GDP growth. Decomposition analysis shows how different scenarios affect components of GDP growth. It thus helps explain *why* some scenarios function better than other scenarios. This is the subject of this sub-section, which starts by showing how the components of GDP growth change 4.4.1. Next, to obtain the complete explanation for differences in GDP growth and other key results, the impacts of different revenue recycling mechanisms on inter-sectoral structural change and on technological change will be shown, and linked to changes in trade-offs relative to RP 4.4.2. After which (in the same sub-section), the impacts of structural & technological change on results for CO₂ emissions and employment and inequality are discussed. To simplify matters, the outcomes are analysed only for RP and Ctax scenarios at a R300 Ctax. This choice is made, because this level of a Ctax is found to almost achieve South Africa's NDC. The same analysis for R100 Ctax scenario outcomes would reveal the same developments, though with a lower amplitude.

4.4.1. Explaining GDP growth by Ctax scenario

Section 4.2.1 introduced the Domestic Income Multiplier (DIM) as an indicator that aggregates and quantifies a few elements which help explain the GDP growth observed in IMACLIM-ZA scenarios. The difference in the DIM between Ctax scenarios and RP is roughly proportional to the difference in GDP between Ctax scenarios and RP (see Figure 4.6 above and Table 4.21 below). Some deviations in this relationship can be associated to differences in the trade balance surplus. Note that difference in the DIM vs RP also correlates to difference in the REER vs RP (see section 4.2.1).

The present sub-section analyses how these difference in the DIM and in GDP between R300 Ctax scenarios and RP can be explained by discussing differences in the components of the DIM into more detail, notably at the sectoral level. To structure this analysis, the Ctax scenarios will be categorized in

two groups: One category consists of scenarios with relatively low GDP growth (RDEF, RTIF-fix, RSUM and RGOV); The other of scenarios with medium to relatively high GDP growth (RVAT, RTaY, RTIF-low, and RTSC).

Table 4.21 Change in the DIM, its 3 principal elements, and in GDP and REER, for R300 Ctax scenarios vs RP

Change vs RP for R300 Ctax scenarios	Low growth Ctax scenarios				Medium to high growth Ctax scenarios			
	RDEF	RTIF-fix	RSUM	RGOV	RVAT	RTaY	RTIF-low	RTSC
i. Value per unit of supply	-2.0%	-2.3%	-2.7%	-2.6%	+0.6%	-1.2%	-1.1%	-1.2%
ii. Income over Resources	-0.6%	-0.4%	-0.3%	+0.1%	-2.6%	-0.8%	-0.9%	-0.7%
iii. Domestic over total supply	-2.8%	-2.9%	-3.1%	-2.9%	-1.6%	-1.4%	-1.2%	-1.2%
iv. DIM*	-5.3%	-5.5%	-6.0%	-5.2%	-3.6%	-3.4%	-3.2%	-3.0%
v. GDP	-32.4%	-30.2%	-27.6%	-27.5%	-17.6%	-17.2%	-13.9%	-12.7%
vi. REER	+10.4%	+10.6%	+11.3%	+10.4%	+5.0%	+4.9%	+3.6%	+2.8%
vii. Trade balance over GDP	+1.8%	+0.6%	-1.3%	+0.1%	+0.1%	+0.3%	+0.1%	-0.1%

* DIM = Domestic Income Multiplier; It measures domestic income per unit of goods & services supplied to South African markets relative to BY. It is calculated by multiplying elements i to iii (more precisely: $1 + iv = (1+i)*(1+ii)*(1+iii)$).

In brief, what the analysis in this section finds is that carbon tax-induced transfer of primary income from non-energy sectors to energy sectors is stronger in the four scenarios with highest GDP growth, whereas it is practically non-existent in the four low growth scenarios. In fact, the four low growth scenarios can be considered as scenarios in which the carbon tax is recycled into an income transfer, with different recipients in each scenario, whereas in high growth Ctax scenarios carbon tax revenue is recycled back into production. As a consequence, South Africa's international competitiveness and domestic purchasing power are better in the four scenarios with revenue recycling back into production, than in the four scenarios with revenue recycling in a type of income transfer. GDP growth is therefore higher. The following changes in the elements of the DIM reflect this:

1. Change in value per unit of supply

To explain the difference in value per unit of supply for the Ctax scenarios one has to bear in mind that the approach for decomposition of GDP growth used in this thesis conceptually and mathematically separates the change in (GDP price index deflated) value per average volume unit of supply on the one hand, and the change in the ratio of primary income over total resources per unit of supply on the other hand. The latter equates, for the aggregate economy, to a cost reduction per unit of GDP (see section 4.2.1). Due to this conceptual separation the increase in value per unit of supply necessarily represents a proportionally equal increase of the average price and of primary income earned over the volume of supply of goods and services supplied to the South African economy (including its export markets).

The question asked here is what explains the average increase in the value of goods and services. The answer to which is not very intuitive. Technically speaking, when income per (average) volume unit of supply and average prices increase at the same rate, this implies that the price index for all goods supplied to the South African economy (including its export markets) increases relative to the GDP price index, and in this thesis without changing the share of primary income in total resources. In turn, this implies – assuming no changes in technology of production – that the average price of goods

consumed in intermediary consumption increases relative to the average price in final demand. To fully understand the evolution of both price indexes and its causes requires an elaborate analysis of structural change and e.g. of I-O matrix multipliers for value added and import costs. A simpler analysis however can already give a good impression of why this variable contributes more to income growth in some scenarios than in other. This analysis consists of a comparison of the sectoral changes in the value of supply variable.

This simplified analysis starts with the observation that in Ctax scenarios, in general, the value per unit of supply evolves roughly similar to the DIM and the REER, all relative to their values for RP (see Table 4.21 above). The exception to this rule-of-thumb is the RVAT scenario, the reason for which is explained below. A look at what happens with value per unit of supply at the sectoral level gives a clue for the explanation of the change in average value per unit of supply (Table 4.22 shows this for R300 Ctax scenarios): The Ctax scenarios with the highest GDP growth (RVAT, RTaY, RTIF-low, and RTSC) show a bigger increase in value per unit of supply relative to RP in all sectors than the four scenarios with the lowest GDP growth (RDEF, RTIF-fix, RSUM and RGOV). There is one exception (besides the already mentioned exception of the RVAT scenario), namely the HSS sector in the RTSC scenario, which is due to its revenue recycling mechanism being particularly advantageous for sectors with a high share of wages in their cost structure, notably HSS.¹⁵⁷

Combine the previous with the explanation for the contribution of cost reductions per sector to income growth by Ctax scenario under point 2 below, which teaches us that the revenue recycling mechanisms of the four higher growth Ctax scenarios succeed in a transfer of primary income from the HSS, LSS and MAN sectors to the energy sectors. Then the conclusion is that not structural changes or differences by sector are determinant, but that the change in average value of supply discussed here shows that the transfer of primary income between sectors takes place around an elevated average value of supply in the high growth scenarios.

Table 4.22 Change in value per unit of supply* (average price), Ct300 scenarios vs RP

	COA	OIL**	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA	Avg***
RDEF											-2.0%
RTIF-fix	+67%	id.	+61%	+15%	+34%	+1.1%	-5.1%	-4.8%	-5.8%	+1.5%	-2.3%
RSUM	+69%		+62%			+1.0%	-5.3%	-5.4%	-5.9%	+1.6%	-2.7%
RGOV											-2.6%
RVAT	+75%	id.	+70%	+22%	+34%	+5.8%	-1.1%	-2.2%	-4.2%	+6.5%	+0.6%
RTaY	+73%	id.	+67%	+20%	+35%	+2.3%	-3.0%	-4.1%	-5.1%	+3.4%	-1.2%
RTIF-low	+71%	id.	+66%	+20%	+35%	+2.2%	-2.2%	-4.2%	-4.8%	+3.6%	-1.1%
RTSC	+72%	id.	+69%	+21%	+35%	+3.7%	-1.5%	-3.6%	-5.8%	+4.3%	-1.2%

Comments: * per worker; **OIL has no employees, but its value per unit does change due to changes in the import price and due to carbon taxation – this effect is not taken into account, though its impact on the value of resources per unit of REF (the only sector that consumes OIL) i; *** Calculated on the basis of change in aggregate (GDP deflated) value of supply per worker, divided by the geometric mean of BY and RP GDP share weighted average sectoral change in volume of supply per worker

¹⁵⁷ It is important what happens in the HSS and LSS sectors for the change in average value per unit of supply. Together these two sectors form about 60% of South African GDP. The other sectors: MAN, EIN, TRA, and the combined energy sectors, have comparable sizes in the R300 Ctax scenarios: each 8 to 12% of GDP.

Of course, so far this does not teach us very much about the differences in averages yet. Another element therefore needs to be considered, namely: As the change in the “average value of supply” supposes (as mentioned) that non-primary income components of resources (IC and imports) increase at the same rate as primary income, and as in an open economy all resources can ultimately be reduced to imports and primary income (value added plus indirect taxes) (discussed in section 2.1.4), the value of imports (deflated by the GDP price index) has to increase relative to the volume of supply. That this is much more the case for the four Ctax scenarios with higher GDP growth than for the four economically less performing scenarios, can be explained mainly by the decrease in the REER. This causes import prices to be relatively higher in high growth scenarios, while the low REER also allows primary factor prices to increase without negative repercussions for exports.

The exception of the RVAT scenario can be explained now as well: The reduction of the VAT rate in particular reduces the price index for final consumption and primary factors relative to average prices. However, the fact that it does not discriminate between domestic output and imports is disadvantageous for domestic output and value added, which will be shown under the next point.

2. Change in the cost structure of resources per unit of GDP

In some scenarios the negative impact of increases in primary factor prices (and of real income per primary factor unit) relative to primary factor productivity due to carbon taxation is bigger than in other scenarios. Here, I present an analysis of the composition of changes in total resources per unit of GDP and I explain differences between scenarios. For this analysis, costs per unit of GDP are divided into: (a) *non-income components* of the cost structure of total resources (total supply), consisting of intermediate consumption (IC) of energy (E) and materials & services (Mat), and imports (M); and (b) *income components*, which consist of labour income, consumption of fixed capital (CFC), net operating surplus (NOS) and taxes (minus subsidies) on production and products (indirect taxes, which includes the carbon tax). By definition, total income “per unit” of GDP is constant, but there are changes in the shares of each income component, just like there are changes in non-income components per unit of GDP.

First of all, one can observe that low growth scenarios (RDEF, RTIF-fix, RSUM and RGOV) mainly reduce labour costs (income) per unit of GDP to absorb the increase in tax income due to the carbon tax (Table 4.23). In parallel, costs for imports per unit of GDP increase in these scenarios, something which could be expected on the basis of the for South Africa’s competitiveness detrimental evolution of the REER (see Box 5 before). On the other hand, costs for inputs of materials & services per unit of GDP decrease compared to RP, but this is a consequence of the decrease of unit labour costs (gross wages) in their production. Energy costs per unit of GDP do not increase more than in the four scenarios with higher GDP (Table 4.23). This can be explained for a large part by the higher REER, which reduces import prices, and therefore the relative cost of OIL imports.

Table 4.23 Comparison of composition of change in unit costs of GDP with GDP growth vs RP for Ct300 scenarios

Ct300 scenario	RDEF	RTIF-fix	RSUM	RGOV	RVAT	RTaY	RTIF-low	RTSC
Costs per unit of GDP vs RP, of which:	+0.6%	+0.4%	+0.3%	-0.1%	+2.6%	+0.8%	+0.9%	+0.7%
Imports	+1.5%	+1.5%	+1.6%	+1.3%	+1.2%	+0.7%	+0.5%	+0.5%
Energy	+1.1%	+1.0%	+0.9%	+0.8%	+1.2%	+1.1%	+1.2%	+1.1%
Materials and services	-2.0%	-2.1%	-2.1%	-2.2%	+0.1%	-1.0%	-0.8%	-0.9%
Total of non-income components vs RP	+0.6%	+0.4%	+0.3%	-0.1%	+2.6%	+0.8%	+0.9%	+0.7%
Indirect taxes* (carbon tax)	+1.5%	+1.5%	+1.6%	+1.5%	+0.2%	+0.6%	+1.5%	+1.5%
Labour costs	-1.4%	-1.3%	-1.4%	-1.3%	-0.6%	-0.6%	-0.4%	-1.5%
Consumption of fixed capital	+0.2%	+0.2%	+0.1%	+0.1%	+0.2%	+0.2%	+0.2%	+0.2%
Net Operating Surplus	-0.3%	-0.3%	-0.3%	-0.3%	+0.2%	-0.2%	-1.4%	-0.2%
Total of (real) income components vs RP	-0.0%							

Comments: * Indirect (or product) taxes here include taxes on production (and also include subsidies). In most scenarios their total increases per unit of GDP due to the carbon tax, but in some scenarios this increase is mitigated by a decrease in either product taxes (in RVAT), or through subsidies on production (RTaY).

Moving on to the four scenarios with medium to low GDP losses relative to RP (RVAT, RTaY, RTIF-low and RTSC), one observes that RVAT and RTaY manage to avoid a forced decrease in labour costs through a reduction of other taxes. In RVAT the cost of (or expenditure on) imports remains high though, whereas in RTaY, the recycling of carbon tax-driven price increases per unit of GDP is incomplete (we will see why this is the case in the next sub-section). RTIF-low assumes a reduction in profit mark-ups and therefore in Net Operating Surplus, which absorbs the largest part of the carbon tax-driven cost increase. Finally, the RTSC scenario shows a decrease in labour costs per unit of GDP, but this time it is not the consequence of a forced decrease in net wages, but due to carbon tax revenue being recycled into labour subsidies.

Costs for intermediate consumption of materials & services (Mat) are relatively higher in the four high growth scenarios. This is a consequence of these two developments: First of all that the decrease of labour costs, which is an important component of the cost structure of Mat sectors, tends to be lower for the four high growth scenarios than for the four low growth scenarios. This in turn is due to the higher GDP growth rates and corresponding employment and wage rates. Secondly, in the EIN and MAN sectors substitution of imports by domestic output also leads to a substitution of import costs by costs for domestic materials and services, which therefore necessarily increase per unit of GDP.

Nevertheless, though less than in the four low growth scenarios, also in the four higher GDP growth Ctax scenarios the average costs per unit of GDP increase relative to RP. The reason is first of all, that the costs of the carbon tax “progress” through (or, are multiplied by) the I-O matrix, especially through the consumption of energy products (especially ELC). Secondly, wages are relatively higher as they are indexed on the CPI, which causes the price of labour to increase relative to productivity. The cost increase caused by the carbon tax can therefore not be completely compensated by decreasing costs for other non-income components (e.g. materials & services inputs). In fact, the underlying

reason for the multiplication of carbon tax costs throughout the economy is rigidity in consumption is of energy and energy-intensive goods: The quantity consumed of CO₂ emitting energy products decreases less than energy prices increase.¹⁵⁸

3. The ratio of domestic production over supply, the REER and international trade

Furthermore, due to the REER being higher in Ctax scenarios than in RP, foreign products substitute South African products, both domestically (through imports) and internationally (in export markets), and the share of imports in total resources increases in comparison to RP. The explanation for this third aspect of the DIM is that a combination of changes in the domestic cost structure, and as mentioned, notably in the average price of primary factors' "productivity" causes a loss in competitiveness. Under the assumption of an almost constant trade balance and current account this is also indicated by an increasing REER (see Table 4.21 above). Exceptions to this loss of competitiveness at the sectoral level are the LSS and HSS sectors in the RTSC and RTIF-low scenarios, and the HSS sector in the RTaY scenario. These sectors benefit from the revenue recycling mechanisms and manage to increase their exports in relative terms. However, with these two sectors only being about 1/7th of import and export value in RP, this hardly compensates the loss of competitiveness for other sectors. As a consequence, the ratio of the volume of domestic production (Y) over the volume of total supply (Y+M) decreases in all scenarios, and most in those scenarios that do not recycle revenue in a cost reduction for domestic production elsewhere in the South African economy than in energy sectors. This third aspect therefore reduces the DIM for all Ctax scenarios.

Consequences for employment

The Ctax scenarios with the highest growth in GDP per worker do not necessarily obtain the highest GDP growth (Table 4.24 below). In fact, almost the inverse is true. If one decomposes GDP growth on a per worker-basis one can note first of all that there seems to be a correlation between a decreasing share of costs for imports in total resources, a decrease in the REER, and an increase in GDP. As discussed in section 4.2.1, this relationship represents improvement of international competitiveness, but also in domestic purchasing power (of primary income).

In Table 4.24 this relationship can be observed in the 2nd item (3rd column), which shows the volume of supply (Y+M) per worker over the volume of output (Y) per worker: When this ratio is low, there are less imports relative to domestic output, and GDP growth (in the last column) is high in these cases. If one multiplies this change in volume of supply over output per worker with growth in output per worker (1st item), with value of supply per unit of supply (3rd item), and with the increase of the share of income in value of supply (5th item: the decrease of total resources (or costs) per unit of GDP), one obtains the change in (real) GDP per worker (6th item in Table 4.24).

Scenarios that obtain *low* GDP growth (RDEF, RTIF-fix, RSUM and RGOV) have high GDP per worker, and as a consequence of this combination, a low growth in employment. This indicates that

¹⁵⁸ This expresses that price elasticities of substitution between energy and the capital-labour factor aggregate (KL) are <1.0.

these scenarios succeed less than other scenarios to make labour an attractive factor of production. Or, put differently: they do not succeed in making the products of labour intensive sectors attractive to consume or export. In the completely opposite case, the RTSC scenario, labour is subsidized and labour intensity of production therefore increases. In parallel, RTSC's reduction of production costs in energy-extensive sectors reduces for a large part the loss of South Africa's competitiveness and domestic purchasing power relative to RP. The RTSC scenario therefore obtains high GDP growth in combination with a high labour intensity.

Preliminary conclusion on Ctax revenue recycling

The conclusion is that, to maintain constant GDP, at equal productivity an increase in income per volume unit of supply of energy sectors due to carbon taxation requires an decrease of income per volume unit of supply in other sectors. If not, the increase in resources per unit of GDP leads to a reduction of domestic purchasing power and to a deterioration of the international competitiveness of South African products. Such a decrease in income per unit of supply can be found to some extent, but never completely) in the RVAT, RTaY, RTIF-low and RTSC scenarios, but not in the four low growth scenarios: RDEF, RTIF-fix, RSUM and RGOV. Obligatory, total domestic and foreign demand decrease, and therefore economic activity or GDP. As a consequence, while the international purchasing power of South African primary factor income increases, the domestic purchasing power decreases, and along with it economic activity, employment and average real wage.

Table 4.24 Decomposition of GDP growth for RP and R300 Ctax scenarios

<i>Item</i>	1	2	3	4	5	6	7	8	9	10
<i>(Values are relative to BY)</i>	<i>Per worker output volume (Y)⁽¹⁾</i>	<i>Supply volume (Y+M) over Y / worker⁽²⁾</i>	<i>Value of resources (costs) per unit supplied⁽³⁾</i>	<i>Value of supply per worker⁽⁴⁾</i>	<i>Decrease of costs per unit of GDP⁽⁵⁾</i>	<i>GDP per worker⁽⁶⁾</i>	<i>Active pop⁽⁷⁾</i>	<i>Employment rate⁽⁸⁾</i>	<i>GDP⁽⁹⁾</i>	<i>Memo: DIM⁽¹⁰⁾</i>
RP	1.26	0.98	1.04	1.28	1.06	1.35	1.34	1.24	2.25	1.118
Ctax rate	300 ZAR₀₅/tCO₂									
RDEF	1.26	1.01	1.02	1.30	1.05	1.36		0.83	1.52	1.058
RTIF-fix	1.26	1.01	1.02	1.29	1.05	1.36		0.86	1.57	1.056
RSUM	1.26	1.01	1.01	1.29	1.05	1.36		0.90	1.63	1.051
RGOV	1.25	1.01	1.01	1.28	1.06	1.35	1.34	0.90	1.63	1.059
RVAT	1.25	1.00	1.05	1.30	1.03	1.34		1.03	1.85	1.078
RTaY	1.25	1.00	1.03	1.28	1.05	1.34		1.04	1.86	1.079
RTIF-low	1.25	0.99	1.03	1.28	1.05	1.34		1.08	1.94	1.082
RTSC	1.23	0.99	1.03	1.25	1.05	1.32		1.11	1.96	1.084

Comments: (1) Per worker output volume is calculated as the geometric mean of BY and projected GDP share weighted sectoral changes in labour output productivity vs BY; (2) Supply volume per worker is calculated in the same way as output volume per worker, but for Y+M now, and divided by output per worker; (3) Value of resources per unit of supply per worker is obtained by dividing the change in GDP deflated value of total resources by the total change in workers, it is divided by the change in supply per worker to obtain the change in value of resources per worker vs BY; (4) Value of supply per worker is the GDP deflated value of resources per worker and is equal to the multiplication of the previous three items; (5) The decrease of costs per unit of GDP is the reduction of the value of total resources relative to primary income (GDP); (6) GDP per worker is the multiplication of the previous two items; (7) The change in active population is assumed exogenously and the same for RP and all scenarios; (8) The employment rate is the change in employed population relative to the change in active population; (9) GDP (vs BY) is a RP and scenario result, and can be obtained by multiplying the previous three items; (10) The DIM is calculated by dividing the product of items 3 and 5 by item 2.

4.4.2. Structural and technological change in Ctax scenarios

Structural change (inter-sectoral) is relevant, because it co-determines variables such as output per

worker, the average cost structure per unit of supply, the composition of GDP per worker in terms of income distribution, and the CO₂ intensity of GDP. Technological change, as was shown for RP, takes in a key role in IMACLIM-ZA in explaining GDP growth and indicators like the CO₂ intensity of GDP. Zooming in on how these two types of change evolve in the different scenarios can teach us more about the success or failure of revenue recycling mechanisms. A focus on structural and technological change also allows us to explain detailed results for employment, income inequality and CO₂ emissions.

Technological change in Ctax scenarios

Technological change, observed here through differences in primary factor and intermediate input intensities in comparison to RP, turns out to be rather similar for all Ctax scenarios (see Table 4.25 and Table 4.26). Technological change by sector has about the same order of magnitude in all scenarios, in summary:

- Energy intensity decreases strongly for MAN and HSS (around 30%), a bit less for LSS (around 15%), only moderately for COA and EIN (around 7%) and hardly for TRA, GAS and REF (3% to almost 0%);
- Materials and services intensities vary between observing no change relative to RP and only small increases (up to 7% for GAS);
- Labour intensity sometimes increases relative to RP (for GAS, REF, EIN and MAN) and sometimes decreases relative to RP (for LSS, HSS and TRA in general). Only in the RTSC scenario labour intensity increases for all sectors;
- Capital intensity, finally, tends to increase for all sectors, but most for GAS, EIN and MAN.

The differences that can be observed between scenarios are that RDEF, RSUM and RTIF-fix tend to have the highest increases in capital intensity, and the lowest increases in labour intensity. The next biggest increase in capital intensity can respectively be found in the RGOV, RVAT and RTaY scenarios. RTaY relatively favours an increase in capital intensity, just as materials & services intensity, over labour intensity. The scenarios that turn out best for labour intensity, accompanied by relatively low increases in capital intensity, are respectively RTIF-low and RTSC. Between the latter two scenarios, RTIF-low can be observed (Table 4.26) to lead to higher materials & services intensity than the RTCS scenario.

It should also be noted that carbon taxation drives technological and structural change (discussed next) in the same direction: Scenarios which enhance energy-saving technological change tend to stimulate output of energy extensive sectors more than of other sectors. For instance: RTSC promotes the use of labour, and therefore causes higher energy efficiency in all sectors. At the same time, labour intensive sectors benefit more from this measure especially compared to energy intensive sectors, and their products will be relatively more in demand than those of the latter.

Table 4.25 Change in input and factor intensities by sector Ct300 RDEF, RTIF-fix, RSUM and RGOV vs. RP

Item \ Sector	COA	GAS	REF	EIN	MAN	LSS	HSS	TRA	
RDEF	Energy input intensity	-6.8%	-1.7%	-0.4%	-7.1%	-31%	-15%	-33%	-2.4%
	Materials & Services intensity	-0.1%	+6.9%	+0.8%	+0.4%	+0.1%	-0.1%	-0.2%	+0.6%
	Labour intensity	-0.6%	+17.3%	+1.0%	+1.2%	+1.7%	-2.1%	-0.5%	-1.2%
	Capital (CFC) intensity	+4.8%	+21.8%	+4.7%	+6.7%	+7.4%	+5.8%	+3.2%	+4.2%
RTIF - fix	Energy input intensity	-6.8%	-1.7%	-0.4%	-7.1%	-31%	-15%	-33%	-2.4%
	Materials & Services intensity	-0.1%	+6.9%	+0.8%	+0.4%	+0.1%	-0.1%	-0.2%	+0.6%
	Labour intensity	-0.5%	+17.4%	+1.0%	+1.3%	+1.8%	-1.9%	-0.5%	-1.1%
	Capital (CFC) intensity	+4.5%	+21.6%	+4.6%	+6.5%	+7.3%	+5.6%	+3.0%	+4.0%
RSUM	Energy input intensity	-6.8%	-1.7%	-0.4%	-7.1%	-31%	-15%	-33%	-2.3%
	Materials & Services intensity	-0.1%	+6.9%	+0.8%	+0.4%	+0.1%	-0.1%	-0.2%	+0.6%
	Labour intensity	-0.6%	+17.3%	+0.8%	+1.2%	+1.8%	-2.0%	-0.5%	-1.1%
	Capital (CFC) intensity	+4.5%	+21.7%	+4.6%	+6.5%	+7.2%	+5.5%	+3.0%	+4.0%
RGOV	Energy input intensity	-6.9%	-1.7%	-0.4%	-7.1%	-31%	-15%	-33%	-2.4%
	Materials & Services intensity	-0.1%	+6.9%	+0.8%	+0.4%	+0.1%	-0.1%	-0.2%	+0.6%
	Labour intensity	-0.1%	+18.2%	+1.6%	+1.9%	+2.5%	-1.2%	-0.2%	-0.5%
	Capital (CFC) intensity	+3.8%	+21.2%	+4.3%	+5.9%	+6.7%	+4.9%	+2.6%	+3.5%

Table 4.26 Change in input and factor intensities by sector Ct300 RVAT, RTaY, RTIF-low, and RGOV vs. RP

Item \ Sector	COA	GAS	REF	EIN	MAN	LSS	HSS	TRA	
RVAT	Energy input intensity	-6.7%	-1.7%	-0.5%	-7.1%	-31%	-16%	-33%	-2.6%
	Materials & Services intensity	-0.2%	+6.7%	+1.0%	+0.3%	+0.0%	-0.1%	-0.3%	+0.5%
	Labour intensity	+0.1%	+18.2%	+2.3%	+2.2%	+2.8%	-0.6%	-0.0%	+0.0%
	Capital (CFC) intensity	+3.6%	+21.3%	+5.1%	+5.9%	+6.7%	+4.6%	+2.5%	+3.7%
RTaY	Energy input intensity	-6.8%	-1.7%	-0.5%	-7.1%	-30%	-15%	-32%	-2.5%
	Materials & Services intensity	-0.1%	+6.9%	+1.1%	+0.4%	+0.1%	-0.0%	-0.1%	+0.7%
	Labour intensity	-0.3%	+17.6%	+1.6%	+1.7%	+2.3%	-1.0%	-0.3%	-0.4%
	Capital (CFC) intensity	+3.5%	+21.1%	+4.7%	+5.7%	+6.4%	+4.4%	+2.4%	+3.5%
RTIF-low	Energy input intensity	-6.5%	-1.6%	-0.5%	-6.9%	-29%	-14%	-31%	-2.4%
	Materials & Services intensity	-0.0%	+6.8%	+1.3%	+0.5%	+0.1%	+0.1%	+0.1%	+0.8%
	Labour intensity	-0.1%	+17.3%	+2.0%	+2.0%	+2.8%	-0.0%	-0.0%	+0.3%
	Capital (CFC) intensity	+2.3%	+19.9%	+4.2%	+4.6%	+5.3%	+2.9%	+1.6%	+2.6%
RTSC	Energy input intensity	-7.4%	-1.7%	-0.6%	-7.5%	-32%	-18%	-35%	-2.9%
	Materials & Services intensity	-0.2%	+6.9%	+1.1%	+0.3%	-0.0%	-0.2%	-0.3%	+0.6%
	Labour intensity	+1.5%	+22.1%	+4.8%	+4.4%	+5.0%	+1.5%	+0.9%	+2.0%
	Capital (CFC) intensity	+0.8%	+19.5%	+3.9%	+3.7%	+5.0%	+2.8%	+0.9%	+2.0%

Structural change in Ctax scenarios

The structural change observed in R300 Ctax scenarios reflects changes in relative prices between sectors (Figure 4.11 below): This can be illustrated by looking at the change in domestic output per sector relative to total GDP growth. When one compares these ratios for Ctax scenarios with those of

RP one observes which sectors have an advantage or a disadvantage in a certain scenario (Table 4.27).

Table 4.27 Difference in the rate of domestic production (Y) over GDP with RP, for Ct300 scenarios

	COA	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
RDEF	-15.2%	-24.1%	-3.4%	-8.2%	-3.4%	-9.1%	+1.9%	+2.3%	-1.4%
RTIF-fix	-17.3%	-25.1%	-4.4%	-9.2%	-4.9%	-9.1%	+1.8%	+2.9%	-2.3%
RSUM	-19.9%	-26.1%	-4.8%	-10.1%	-6.8%	-8.4%	+2.4%	+2.8%	-2.7%
RGOV	-19.7%	-26.7%	-6.5%	-11.1%	-7.0%	-10.5%	+0.4%	+5.2%	-3.7%
RVAT	-21.2%	-25.2%	-8.3%	-11.9%	-5.5%	-5.1%	+1.8%	+3.4%	-3.2%
RTaY	-21.9%	-25.2%	-8.3%	-11.5%	-4.5%	-3.5%	+2.3%	+3.1%	-2.8%
RTIF-low	-20.8%	-24.3%	-8.7%	-11.6%	-4.2%	-3.2%	+2.6%	+3.0%	-2.7%
RTSC	-22.7%	-26.2%	-9.8%	-13.5%	-6.1%	-3.8%	+1.8%	+3.9%	-3.5%

This leads first of all to the observation that in all scenarios growth in the volume of domestic output is relatively higher in LSS and HSS, while the volume of output over GDP is relatively lower for energy sectors, EIN, MAN and TRA compared to RP (Table 4.27). This development is stronger in scenarios with relatively high GDP growth than in scenarios with relatively low GDP growth, though there is some variation in this pattern between the scenarios:

- The RSUM scenario evokes a relatively strong stimulus for LSS and sees output by MAN decrease less compared to other low growth scenarios. In RSUM this is due to the relatively stronger role of the four poorest household classes in final consumption;
- In RGOV sectoral output over GDP growth is relatively strong for the HSS sector, while other non-energy sectors see their output over GDP relative to RP turn out lower than in all other scenarios (Table 4.27). The reason is that final consumption by households and exports has a relatively small role for demand for products of HSS, whereas government final consumption is attributed a big role. HSS therefore grows stronger than other sectors, whose supply is more aimed at exports (EIN) or final consumption by households (MAN). Recycling into government spending does not stimulate imports as much as revenue recycling in the other three low growth scenarios. The reason is that the direct (1st degree) import multiplier of HSS is small, with HSS importing little of its total supply, and a large part of its cost structure consisting of value added, indirect taxes and intermediate consumption of its own products;
- The relative shift in domestic production towards HSS is also stronger in RVAT than in other scenarios, except for RGOV and RTSC (Table 4.27). In this case the reason is that RVAT reduces the CPI and thereby labour costs relative to other factor or input costs, which is advantageous for sectors with high labour costs as part of the cost structure (especially HSS, and to a much lesser extent LSS: see BY calibration data in Appendix B.4). Furthermore, these sectors are less affected by decreasing international competitiveness than in low growth

scenarios due to the carbon tax.¹⁵⁹

- The last scenario which shows considerable deviation from the pattern of an increasing shift from energy and energy-intensive sector output to LSS and HSS is the RTSC scenario. In RTSC, the decrease is much stronger than in RTIF-low, for instance, while the differences in GDP growth and change in the REER are very small (see Table 4.21 above). Compared to the RTIF-low and also the RTaY scenarios, the decrease in output of energy sectors and of EIN, MAN and TRA is stronger in the RTSC scenario, while there is not much of an increase in output for LSS. The reason for this stronger change is the very strong beneficial impact for output of the HSS sector of labour subsidies, of which the LSS sector profits relatively less, because wages are very low in this sector, causing the share of labour costs to be smaller than in HSS. Looking at the details of changes in demand and supply, it can be noted that this change improves the position of HSS in all fields, whether it consists of substituting imports by domestic output, increasing exports of HSS, or in final consumption by households: the position of HSS improves, while that of other sectors relatively deteriorates.

The role of technological and structural change for CO₂ emissions

Results presented in section 4.3.2 showed that there were only small differences between Ctax scenarios in the CO₂ intensity of GDP. This outcome can be explained from the lack of difference in structural and in technological change between Ctax scenarios in other sectors than ELC. Sectors other than ELC turn out to have only minor contributions to the decrease in CO₂ emission intensity of GDP in Ctax scenarios, in comparison to RP:

In RP structural change (relative to BY) was seen to contribute to the decrease in CO₂ emission intensity to a large extent, especially because of a reduced demand for electricity per unit of GDP (see the discussion about CO₂ emission intensity of RP in section 4.4.2). Technological change in ELC and other sectors, and structural change in demand for output of other sectors' products also contributed considerably to the reduction CO₂ intensity of GDP in RP. However, in R300 Ctax scenarios exogenous technological change in ELC determines almost the entire decrease in CO₂ intensity of GDP relative to RP, while structural change in demand for ELC is only a small part of the decreasing CO₂ intensity. This is true both for the Ctax scenario with the highest (RDEF) and with the lowest (RTSC) CO₂ intensity of GDP (Figure 4.9).

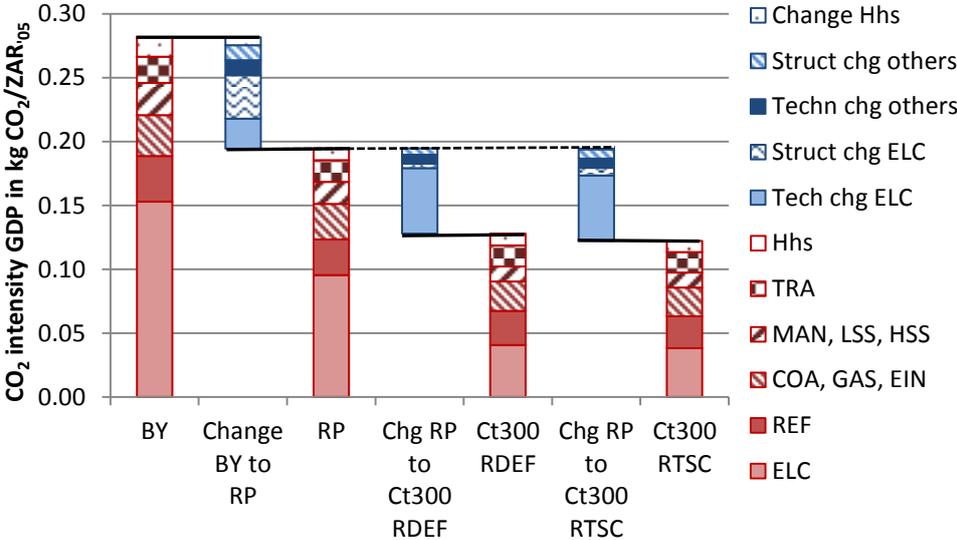
Regarding technological change, of course, the ELC sector plays a very big role in the decarbonisation of South Africa's GDP, because power generation produces 49% of South Africa's direct CO₂ emissions in RP (54% in BY). In Ctax scenarios, ELC reduces the CO₂ emission intensity of power generation by 54% compared to RP, to 112 ktCO₂/PJ for a R300 Ctax. For other sectors the discussion of technological change above already showed that the reduction of energy intensity of their

¹⁵⁹ In the three other medium to high growth scenarios (RTaY, RTIF-low, and RTSC) the revenue recycling mechanism compensates the carbon tax-driven cost increase through to some extent for multiple sectors.

production is limited to only a few percentage points change relative to RP (see Table 4.25 and Table 4.26 before). Of the five sectors¹⁶⁰ whose energy use is responsible for the biggest CO₂ emissions in RP after ELC, only MAN strongly reduces its energy intensity in R300 Ctax scenarios relative to RP.

Also, structural change and change in household final consumption do not add much to a reduction of CO₂ intensity of GDP in Ctax scenarios. Electricity (ELC) consumption per unit of GDP does not reduce much beyond the reduction achieved in RP. Structural change leading to change in demand for other products than ELC does not contribute much either – its contribution is more significant in the RTSC scenario than in RDEF (Figure 4.9).

Figure 4.9 Composition of (direct)* CO₂ intensity of GDP and its change, for BY, RP and Ct300 RDEF and RTSC scenarios**



Comments to figure: * The adjective direct has been added to signal that technological change only concerns the reduction in use of fossil fuels within a sector, and e.g. not the indirect CO₂ emissions from the use of electricity – which are part of structural change in demand for ELC; ** Relative contributions of sectors have been determined in the same way as for Figure 4.7 before.

Why does a carbon tax not reduce demand for ELC and other energy and energy-intensive products per unit of GDP very much? The biggest difference between on the one hand the transition from BY to RP, and on the other hand the differences between RP and the R300 Ctax scenarios is that RP already witnesses a strong dematerialisation of South African GDP, with income per unit of supply increasing on average and materials & services intensity of supply decreasing in all sectors: The trend in materials & services (Mat) efficiency gains in combination with price-elastic trade-offs leads to a 7% lower Mat intensity in RP than in BY for non-energy sectors, while price-elastic trade-offs in a R300 Ctax cause less than a 1% additional reduction in Mat intensity. As a result, RP’s GDP is produced with a lot less intermediate consumption than BY GDP, which reduces energy consumption per unit of GDP as well. While in Ctax scenarios have no additional autonomous decrease in material intensity compared to RP and everything depends on price-elasticity.

¹⁶⁰ These sectors respectively are: REF, TRA, EIN, MAN and GAS.

Furthermore, the relative price signal of the carbon tax turns out to be smaller than the price signal coming from the exogenous price increase in energy imports in RP compared to BY: Average energy prices increase 65% in RP (vs BY), while a R300 Ctax adds maximally another 50 percentage points to the price increase from BY to RP, which is only a 30% increase relative to RP (compare Figure 4.11 for the Ct300 RTSC scenario¹⁶¹ with Figure 4.10).^{162,163}

For the contribution to reduced CO₂ intensity of GDP of structural change in demand for non-energy sectors' products it matters that domestic production per unit of GDP of EIN, MAN and TRA – the sectors responsible for the highest CO₂ emissions in RP after ELC and REF – decreases in comparison to RP, both for RDEF and RTSC (like in other scenarios, see Table 4.27 above). Differences in the developments in relative prices between scenarios are small though, which largely explains the low variation in CO₂ emission intensity between scenarios. RTSC, and to a lesser extent the RTIF-low and RVAT scenarios, manage to reduce labour costs more strongly and thus stimulate substitution of energy and energy-intensive inputs by labour and labour-intensive products more than other scenarios. But, this only has a limited impact due to the limited relative price impact of the carbon tax: The evolution of the average price of EIN and TRA relative to that of HSS is even in the Ct300 RTSC scenario limited to about 10%. (To see this, compare the change in average prices (value per unit of supply) relative RP by sector and scenario in Table 4.22 on p.160.) This is insufficient to cause big changes in final consumption or the composition of exports and imports.

The impact of household consumption on the CO₂ emissions, finally, is not very big. First of all, households are responsible for only a very small part of CO₂ emissions: about 5% in BY and RP, and 7 to 8% in R300 Ctax scenarios. Secondly, the changes in household CO₂ emissions, are smaller than those in direct emissions of intermediary consumption, and (partly) compensated for by a change in household's share in GDP, which is not depicted in Figure 4.9.

In RP, households per capita direct CO₂ emissions of REF consumption increase 6% vs BY. But, household's CO₂ emissions over GDP still decrease due to a reduction of household final consumption's share in GDP from 63% in BY to only 55% in RP, while government final consumption and the trade balance surplus increase their share in GDP. In R300 Ctax scenarios, household's per capita direct CO₂ emissions (from FC of REF) decrease between 16% (RTSC) and 30% (RDEF) compared to RP. But, despite this considerable reduction in per capita emissions,

¹⁶¹ Ct300 RTSC is the scenario with the highest energy price increase relative to BY or RP after Ct300 RVAT.

¹⁶² The price impact for individual products can be larger. While average cost of supply of COA increases 64% from BY to RP and of REF 46%, Ct300 RTSC adds respectively 118 pct pt to the price of COA (+70% vs RP), but only 32 pct pt to the price of REF (+21% vs RP).

¹⁶³ A third explanation for a lack of a structural change induced reduction of ELC demand (equivalent to a lack of technological change in ELC inputs to production in other sectors and to Hh FC), is that the EIN sector – responsible for 61% of IC of ELC and 46% of total ELC demand in RP – seriously reduces its consumption of electricity (of a very polluting electricity sector) between BY and RP, while the relatively smaller reduction of consumption of a cleaner ELC sector in Ct300 scenarios compared to RP causes a much smaller reduction in absolute terms. Part of this explanation is that electricity and other energy consumption – and therefore CO₂ emissions – are more concentrated in energy-intensive sectors in RP and even more in the Ctax scenarios, compared to BY. Energy consumption in these sectors is assumed to be relatively price-inelastic (see Appendix C.3).

household's share in South Africa's CO₂ emissions increases to 7% (RTSC) to 8% (RDEF).¹⁶⁴ The reason is firstly that in Ctax scenarios energy and therefore CO₂ emission intensity of domestic production is reduced relatively stronger in IC of the MAN, LSS, and HSS sectors (see Table 4.25 and Table 4.26 before) and even more in ELC (see section 3.1.2). Secondly, in total supply, imports substitute to some degree for domestic production compared to RP, thereby reducing real income per unit of supply (Y+M), but (see Table 4.21 above) also CO₂ emission intensity of supply.

Figure 4.10 Change in resources per unit of supply (= average price) from Base Year to RP

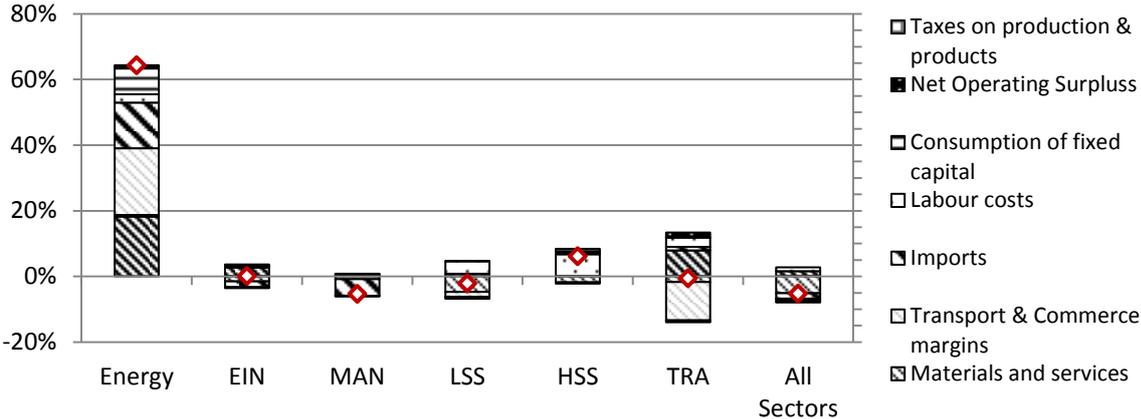
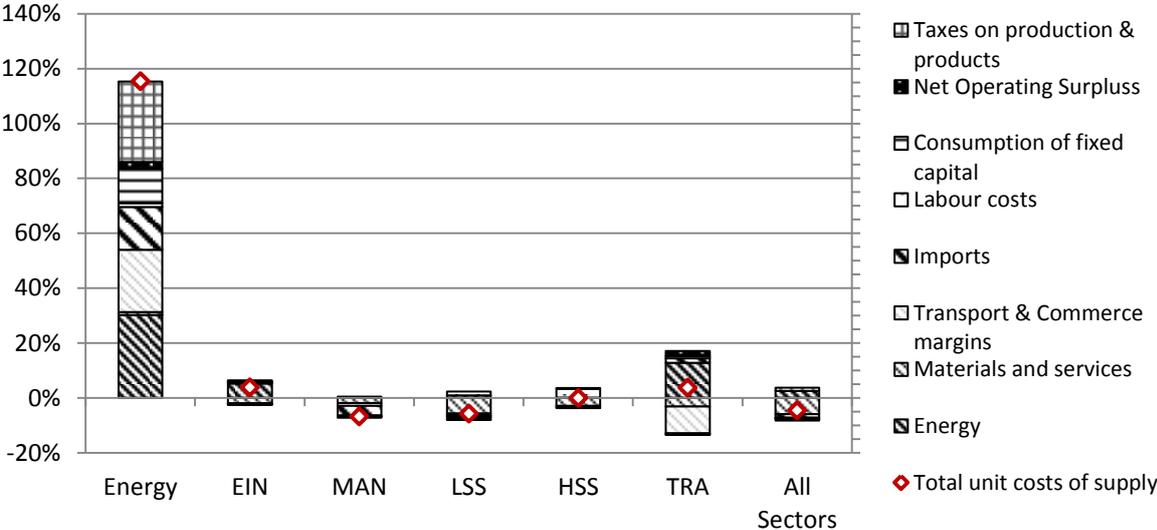


Figure 4.11 Change in resources per unit of supply (= average price) from Base Year to Ct300 RTSC scenario



Explaining employment by skill and income inequality

For the distribution of labour by level of skill it is relevant that technological change causes capital intensity to increase faster than labour intensity in R300 Ctax scenarios (see Table 4.25 and Table 4.26 before). In parallel, the volume of supply per worker is generally speaking not necessarily lower than in RP due to substitution of domestic production by imports (see Table 4.24 above). Furthermore

¹⁶⁴ Household's per capita ELC consumption increases 15% between BY and RP, and decreases between -14% (RTSC) and -26% (RDEF) in R300 Ctax scenarios.

relevant for the distribution of labour by level of skill, is the fact that in all Ctax scenarios the High Skill Services sector (HSS) increases its output volume (as well as its share in GDP) more than other sectors, also compared to the Low Skill Sectors (LSS) (Table 4.27). By consequence, high skill labour sees its share in employment increase a bit from 30% in RP to 31%-32% in Ctax scenarios. This is less the case in RTSC where labour subsidies manage to maintain the low skill labour's share in employment at 22%, like in RP.

Finally, income inequality is not much affected by structural and technological change. The discussion in section 4.3.2 already showed that differences in the income gap between the poorest and the richest household class are relatively small, and that they correlate to GDP growth. In this sense it can be noted that income inequality is marginally lower in RTSC e.g. compared to RTIF-low and RVAT (which has lower GDP), a result related to lower wage differences between the different levels of skills, and a relatively smaller difference in net wage between low and medium skill labour. The reason for the correlation between income inequality and GDP growth is firstly that with lower GDP growth the rate of interests and dividends that households earn over their net assets is lower. Secondly, real wages decrease along with unemployment (and with GDP), whereas social security benefits, a large part of income for the poorest household class, are indexed on the CPI. This means that the gap between labour income and capital rents (Hh5) on the one side and social security (Hh1) on the other side becomes smaller. Only RSUM causes a radical change in income inequality for obvious reasons (see section 4.3.2).

4.4.3. Summary of Ctax scenarios

General observations

The analysis of results of carbon tax revenue recycling scenarios in this Chapter showed that the different revenue recycling schemes have a considerable impact on GDP growth, but that apart from the differences in GDP growth, the differences in CO₂ intensity and employment intensity of GDP between scenarios are relatively small. The revenue recycling mechanism that best achieves combining economic development and a reduction in CO₂ intensity of the South African GDP is the scenario in which carbon tax revenue is recycled into a labour subsidy (RTSC). The reason is that RTSC, more than other scenarios, stimulates technological change towards less energy intensity, and the right type of structural change in the sense that it promotes consumption and exports of HSS rather than of energy products or energy intensive products.

It is furthermore important to notice that the impacts of carbon taxation on economic growth and employment, albeit measured in comparison to an unsustainable reference projection without CO₂ emission control, are significant, and increasing with the rate of the carbon tax. It is thus important to understand the principle mechanisms that determine the economic impacts of carbon taxation and its revenue recycling. Analysis in this section provides insights, with each scenario having a story to tell.

First of all, decomposition analysis of reference projection (RP's) GDP growth highlights the

importance of cost reductions in parallel to cost increases caused by carbon taxation. The decomposition analysis showed that the costs per average unit of domestic production (GDP) decreased thanks to a combination of output productivity growth and a net reduction of primary factor prices – which represent “claims for payments” by primary factors expressed in purchasing power of foreign products – relative to growth of output productivity. This represents an improvement of both domestic purchasing power and of international competitiveness of South African products. Furthermore, in RP, GDP growth is higher than the trend in the volume of exports (growth of world trade), this leads to a decrease in the South African Rand’s real effective exchange rate (REER), which reinforces the improvement of international competitiveness of South African sectors. Together, the costs reduction of production and the decrease of the REER cause growth of demand for domestic production per volume unit of products supplied to South African markets. The latter has been called the Domestic Income Multiplier (DIM) (per unit of supply) in this thesis.

It was shown that carbon tax scenarios which only recycle carbon tax revenue into income transfers observe a strong decrease of the DIM as a consequence of the combined impacts of a reduction of income relative to productivity and due to loss of international competitiveness. On the other hand there are scenarios that manage to compensate the increase in average prices (or resources) per volume unit of products caused by the increase of energy prices due to carbon taxation. They achieve this by reducing costs and average prices in other sectors.

In terms of national accounting this represents a shift in primary income (GDP) from non-energy sectors to energy sectors. When this shift is strong enough, or when the price-elastic response that drives demand from consumption of energy and energy-intensive sector’s products to non-energy intensive products is strong enough, the net effect on GDP growth could be zero. However, the price-elasticity of substitution between products of energy-intensive and energy-extensive sectors turns out to be smaller than 1.0, meaning that for each percent increase in the relative price of energy-intensive products over energy-extensive products there is less than 1 percent increase in demand for the latter over the former. Briefly, South African production and consumption are rigid in energy use, which causes a progression of carbon tax costs through the input-output matrix, and in parallel a net increase of costs relative to output productivity. The latter translates, through consumer price indexation, into higher labour prices, while labour productivity remains unchanged.¹⁶⁵ This means that average productivity gets more expensive, which translates into a loss of domestic purchasing power and international competitiveness, and thus also an increase of the REER.

Summary by Ctax scenario

I summarize how the previously described developments look like for each of the revenue recycling schemes of the Ctax scenarios:

¹⁶⁵ Average labour productivity does observe very small changes due to structural change, or: the relative weight of sectors in the economy.

RTIF-low

The two Ctax scenarios with the highest GDP growth, RTIF-low and RTSC, each manage to reduce the negative macro-economic impact of a carbon tax in their own way. In RTIF-low carbon tax revenue is recycled into a proportional reduction of profit tax rates which is assumed to induce firms to reduce their profit mark-up rates accordingly. This revenue recycling scheme relatively benefits all sectors for which profits are, on average a considerable part of the costs structure. This especially concerns LSS, EIN and TRA, for which profit mark-up rates are relatively high, because net operating surplus makes up a higher share of value added in these sectors.¹⁶⁶ In comparison to other Ctax scenarios this revenue recycling scheme turns out to be relatively advantageous for domestic output in COA, EIN, MAN, LSS and TRA sectors (see Table 4.27), and this scenario obtains almost the highest GDP growth out of all scenarios. In fact, GDP growth in this scenario is higher than for RTSC at a R100 carbon tax, but lower at a R300 carbon tax. The reason of this relative deterioration of the scenario's macro-economic projection with an increase of the carbon tax rate is that the CO₂ intensity of the RTIF-low scenario is higher than for the RTSC scenario. In fact, RTIF-low's revenue recycling mechanism does not discriminate against energy sectors as it partly recycles Ctax revenue back to these sectors. It therefore indirectly weakens the strength by which the carbon tax is felt (see section 5.2 on equal CO₂ emission objectives by scenario for more on this point).

RTSC

The subsidy of labour costs in RTSC on the other hand increases the change in relative prices between energy inputs and labour in the trade-offs in production, and between energy-intensive products and labour-intensive products (especially HSS) in final consumption and exports. This therefore increases the implicit price-elasticity of domestic production between energy-intensive and energy-extensive production and thus reduces the attachment to energy of the South African economy more than other scenarios, and which also explains why this scenario obtains the lowest carbon intensity of GDP.

Still, the stimulus for technological change and change in demand towards less CO₂ emission intensity which the RTSC scenario offers is insufficient to lower the price of primary factor "productivity" relative to RP, and therefore no strong double dividend can be obtained. A part of the explanation for this is that price-elasticity is too weak to cause big technological and structural change outside the electricity sector, and that even in RP the decarbonisation is caused for a large part by autonomous material & services input efficiency gains of South African production. These are assumed to be unaffected by carbon taxation. This analysis therefore highlights the importance of a correct representation of technological change for modelling the impacts on GDP growth of climate policy.

¹⁶⁶ Recall that profit mark-up rates are calibrated over IC and labour costs of domestic production. In for instance LSS (with in original SAM data Agriculture and Trade having relatively high profits compared to e.g. labour income), this leads to relatively high profit mark-up rates. With other costs not very much increasing, the average total profit mark-up per unit of supply turns out a lot lower in RTSC. In contrast, in HSS, profit mark-ups make up a lower share of value added, though they are equally important in total costs of domestic production. The profit mark-up rate is lower. Furthermore, HSS sees its labour costs remain relatively high, whereas it does not benefit from relative cost reduction of Mat inputs as other sectors do. This means that the profit mark-up rate of HSS is relatively lower, and is calibrated over a base that remains relatively costly. Profits therefore decrease less per unit of supply for HSS than for LSS.

In connection to this last remark section 5.5 presents an analysis of the sensitivity to different assumptions on energy efficiency gains.

RTaY

In RTaY similar changes as in RTIF-low take place, though now not company profit taxes and profit margins are reduced, but sectoral taxes on production are reduced percentage pointwise, and this tax even turns into a subsidy for some sectors. In RTaY revenue recycling reduces taxes on production and products across all non-energy sectors (Table 4.22). The revenue recycling scheme indeed turns out to promote non-energy sector output relatively equally for all sectors, though a bit more production of the MAN sector in comparison to other revenue recycling mechanisms (Table 4.27). This is a logical outcome considering that materials & services inputs make up a large part of the MAN sector's domestic cost structure (72% in RP), which is much more than for other sectors (e.g. for EIN and LSS this is respectively 56% and 51%). Furthermore, RTaY turns out to promote capital intensity (Table 4.26), which makes sense because materials & services products, and especially MAN products are an important component of the capital good. However, materials & services intensity of domestic production increases less than for RTIF-low (Table 4.26), but still more than for the RVAT and RTSC scenarios. The latter two scenarios promote labour at the expense of energy as a factor of production and HSS at the expense of energy, EIN and TRA in final demand (Table 4.27). The explanation for this difference with the RTIF-low in terms of Materials & services intensity lies in the fact that the latter also reduces energy sectors' costs, and therefore the production costs of more energy-intensive intermediate inputs like EIN and TRA, which is beneficial for Mat consumption too. The RTIF-low scenario thus comes out better in terms of GDP growth at equal carbon tax rates, but not in terms of emission reduction. Considering that the CO₂ emission intensities of both scenarios are about the same (Table 4.18), it is very likely that they have similar GDP outcomes when equal CO₂ emission objectives are set (a discussion of this objective is provided in section 5.2).

RVAT

Out of the four high growth Ctax scenarios RTSC, RTIF-low and RTaY render one or more *non-energy* sectors relatively less expensive than other sectors (Table 4.22). The RVAT scenario is an exception, which can partially be considered to resemble revenue recycling through income transfer, and partially revenue recycling through a reduction of production costs. The reason that RVAT's Ctax revenue recycling scheme is partially considered to be an income transfer is that it only renders final consumption less expensive, without creating a direct benefit for domestic producers relative that compensates the negative impacts of a carbon tax. However, the RVAT scenario indirectly does create some competitive advantage, in contrast to the four low growth scenarios. The indirect advantage for international competition is that labour costs are indexed on the CPI, and the price of labour therefore turns out relatively (versus what happens in the low growth scenarios) lower compared to the price of other factors and inputs – which have a bigger import costs-component in their costs structure.

RDEF

Four scenarios have revenue recycling mechanisms that recycle carbon tax revenue into a kind of an income transfer, instead of recycling it into cost reductions elsewhere in production (as in the previously described four scenarios). In the RDEF scenario however this might be least clear, as this scenario involves recycling of carbon tax revenue into deficit reduction or public debt repayment and not an income transfer to other economic agents. It should rather be considered as an income transfer to future generations, which do not need to repay these debts anymore. However, it is a revenue recycling mechanism that reduces GDP growth the most out of all revenue recycling mechanisms analysed. The reason is that in this scenario, increased saving in South Africa (in this case by government) actually equates to reduced net borrowing from the rest of the world (ROW). This, in turn, implies a reduction of funds available for consumption and investment in the present – hence a lower GDP. However, this revenue recycling into deficit reduction also leads to a slightly higher trade balance surplus, which could be a sign of foreign demand stepping in to replace domestic final consumption and investment in driving GDP. However this impact is not strong enough, and it has a negative impact on South Africa’s economic structure, seen from the objective of reducing CO₂ emissions. RDEF’s slightly more export-driven economy namely has a relatively stronger role for the COA, EIN and TRA sectors (Table 4.27), which implies a relatively strong “attachment” to energy.

RGOV

In the RGOV scenario, like in RDEF, government budgets play a central role too. This time however with government increasing its expenditure (government final consumption) thanks to carbon tax revenue. Government final consumption concerns HSS only, which is the sector that also contains administration and public services like health care and education in IMACLIM-ZA. This policy could therefore encompass different kinds of government expenditure. This increase in government expenditure is (as mentioned in section 4.3.1) not assumed to have economic impacts other than its impact on economic structure, e.g. no increase in primary or secondary factor productivity, neither does this scenario measure any impacts on poverty through the increased provision of public services. Reduced to a change in the structure of final demand, this scenario becomes an income transfer from those who pay carbon taxes to public expenditure. Like the other three scenarios whose revenue recycling mechanism is only an income transfer (RDEF, RTIF-fix and RSUM), RGOV results show a significant reduction in GDP growth, though less than in the other three scenarios. The reason is that the economic re-structuring towards more high skill services reduces the “attachment” of the South African economy to energy consumption as well as to imports (OIL, MAN) more than revenue recycling in the other three scenarios.

RTIF-fix

The RTIF-fix scenario assumes, in contrast to the RTIF-low scenario, that a reduction of company profit taxes has no impact on company’s profit mark-ups. This means that this scenario lacks a proper

mechanism for cost reduction in domestic production, as in RTIF-low, RTSC, RTaY. Instead, it's revenue recycling mechanism effectively turns out to be an income transfer, namely one from those who pay carbon taxes to those who earn capital rents, which are mainly the richest household class and ROW. Besides the negative impact of the income transfer type of carbon tax revenue recycling on GDP growth, RDEF's specific type of income transfer leads to stimulus in especially export and high income household class oriented output, or respectively: COA, EIN and TRA, and HSS. Demand for output of the former three leads, as for the RDEF scenario, to a strong attachment of the South African economy to energy use and thus CO₂ emissions, the latter – final consumption of HSS – however has an opposite effect as this sector is the least energy-intensive out of all sectors and reduces the economy's attachment to energy somewhat. This likely also explains that GDP growth is higher in RTIF-fix than in RDEF.

RSUM

Finally, of the four Ctax scenarios with the lowest GDP growth, RSUM contains the most obvious type of income transfer through carbon tax revenue recycling, namely in the form of a *per capita* lump sum transfer. Like in the other three scenarios with income transfer-type revenue recycling RSUM obtains a strongly negative impact on GDP growth. The strongly egalitarian impact of this type of revenue recycling leads to a relatively larger share of lower household classes' consumption in final consumption, which is advantageous for the MAN and LSS sectors. With these sectors showing medium to low energy intensity and demand for energy-intensive products in their intermediate consumption, this means that the attachment of the South African economy to energy and CO₂ emissions in RSUM is less than in RDEF and RTIF-fix. This partly explains that it's GDP growth is higher than for the former two, and almost as high as in RGOV. The biggest advantage of the RSUM scenario is however that it strongly reduces inequality and poverty by strongly improving income for the lowest income household classes.

Employment results

Two last remarks should be made concerning employment results of Ctax scenarios: Firstly, their results for employment impacts are likely a bit too pessimistic. The reason is that the assumption that wages increase with *median* inter-sectoral productivity growth causes them to actually increase more than average labour productivity. This renders labour relatively more expensive in the projection for 2035 than in base year calibration data (for 2005). This is both the case for RP and Ctax scenarios, but due to the role of labour costs in reducing energy-intensive production and consumption of energy and energy-intensive products this assumption increases the order of magnitude of employment impacts. An evaluation of this aspect is performed in section 5.6.3.)

Secondly, employment results are also an outcome of the assumption of exogenous labour output productivity gains which represent a continuation of (low and medium skill) labour-saving technological change irrespective of the carbon tax. Possibly this is too pessimistic as well, and maybe

the Energy-Labour price-elasticity of production will be higher on the long term, in face of lasting higher costs of energy use.

If, on the contrary, the assumption about unchanged autonomous increase in labour output productivity is realistic, and if the labour factor's price-elasticity relative to other factors has been estimated correctly, then the results of scenario analysis presented here imply that a GDP with a constrained potential for growth will be produced and earned in the future by a relatively smaller group of people. Measures should therefore be envisioned to give the unemployed the possibility to participate in the productive process too. Most importantly, the costs of the production of gross output, especially labour should decrease. Labour subsidies, as shown here, are one way, but possibly investments that improve aggregate productivity should be considered too. This is the topic of the next section.

4.5. Revenue recycling with investment in skills

This section examines how investing a part of carbon tax revenue in skills differs from recycling the entire carbon tax revenue through one of the main Ctax revenue recycling schemes discussed in the previous sections. Two approaches for conducting such an analysis are presented, each in a separate sub-section, which are briefly introduced here.

As discussed in section 3.3.1, scientific literature does not offer a basis for quantifying the relation between education, skills, and productivity. A first and important problem is that no study is capable of providing a statistical correlation between investment in education and educational output in terms of people with degrees. This can be related to “inefficiency” of educational spending on enrolment in secondary education (Grigoli, 2014). Quality of education should have an impact on labour productivity too, independent of the level of educational attainment, but the link between investment in education, quality of education, and ultimately labour's (and other factor's) gross output productivities are even less quantifiable.

This section therefore proposes two alternative, counterfactual approaches to modelling investment in skills of labour, fitted to IMACLIM-ZA's labour market model. With the positional labour market approach in IMACLIM-ZA, modelled with a Constant Share of Labour Force (CSLF) definition of skill of labour (section 3.3), two different approaches to model the impact of the above described investment in skills are considered, which are discussed one by one in the following two sections.¹⁶⁷ In the first approach (A) the high skill shortage is reduced quantitatively, by a larger supply of people qualifying for this skill segment. The second approach (B) assumes that the positional character of the South African labour market is unaltered, and that instead, productivity improves for all skill segments. However, lacking a basis on which to calibrate this approach, the analysis is a kind of a sensitivity analysis that seeks the productivity impact required to obtain better outcomes for one or multiple criteria (emissions, employment or growth) than the main Ctax scenario that functions as a

¹⁶⁷ Under a Constant Educational Attainment (CEA) definition of skill of labour this increased spending would translate into an increase in the labour force share of higher educated skill segments of the labour force.

reference here. The results obtained for these approaches illustrate mechanisms that are universal to all scenarios, however the analyses are performed for only two scenarios: RTSC and RVAT.

Multiple types of investment could be imagined, e.g. an improvement of primary and secondary school education, or offering more vocational training of employees and workseekers. For simplicity, and to arrive at a realistic estimate of the size of an investment in skills (for both approaches), the assumption is that the investment enables enrolling (or preventing drop-out) of 200,000 additional students per year in secondary education starting 2015, of up to 1 million additional students in total (for all five years from grades 7 to 12) from 2020 onwards, at an estimated average cost of 7.5 kZAR₀₅ per student: see Appendix C.6 for details. The total additional investment in education is estimated at 7.5 billion ZAR₀₅ per year by 2020, continuing up to 2035. This corresponds to 2.5% of government final consumption in BY data (305 billion ZAR'05, which includes administration and public services. By 2035, in RP this corresponds to only 0.9% of government final consumption and 0.6% of total public expenditure (respectively 1.0% and 0.7 - 0.8% in carbon tax scenarios), and it is about 10% of revenue of a R100 Ctax in 2035.

The findings in brief: 1. a quantitative reduction of South Africa's high skill shortage has potential to generate GDP growth (section 4.5.1); 2. if the investment changes productivity of different skill segments of labour, then the preferred improvement of productivity (and skills) is that of improved efficiency in the use of materials & services and improved energy efficiency, rather than further improving labour's gross output productivity. In specific configurations this even leads to absolute decoupling of GDP growth and CO₂ emissions while also decreasing unemployment (section 4.5.2).

4.5.1. Approach A: Increased access to high-quality education

An assumed improvement in educational enrolment leads to more people qualifying for the high skill labour market segment. Assuming one in five of these graduates to qualify for high skill labour leads the high skill labour segment to increase by 750,000 persons in 2035, while the medium skill labour market segment decreases in size by the same amount (see Appendix C.6). This option is tested for the scenario with the most preferable combination of economic and environmental outcomes, the RTSC scenario, both for a R100 and a R300 Ctax. For reason of comparability with option B this variant is also analysed for the Ct100 RVAT scenario.

Key results approach A

Approach A of modelling impacts of an investment in skills of labour adds 0.75 million high skill workers to an otherwise 6.75 million persons counting high skill active population in 2035 in RP and the main Ctax scenarios. For the Ct300 RTSC scenario this intervention results in a 4.3% higher GDP relative to the "main" Ct300 RTSC scenario. This reduces the difference in future GDP with RP from -13% to only -9% of RP's GDP. For the Ct100 RTCS and RVAT scenarios the economic gain is even stronger, respectively 5.7 and 5.1% (Table 4.28).

Table 4.28 Results for approach A of the investment in skills option relative to equivalent Ctax scenario results

Case	Change in results relative to similar main Ctax scenario				
	GDP in 2035	Unemployment (pct. points)	CO ₂ emissions	CO ₂ intensity GDP	Class 5/ Class 1 income
Ct100 RTSC with skill investment var A	+5.7%	-2.2pt	+4.6%	-1.0%	-2.2%
Ct300 RTSC with skill investment var A	+4.3%	-1.4pt	+3.5%	-0.8%	-2.4%
Ct100 RVAT with skill investment var A	+5.1%	-2.2pt	+4.5%	-1.0%	-2.2%

Employment increases in all scenarios, the least in the Ct300 RTSC scenario with about 580 thousand jobs (3.2% more jobs) compared to the main Ct300 RTSC scenario. (The broad unemployment rate decreases in this case from 31.8% to 30.4%.) There are differences by level of skill of labour: In the mentioned case of the Ct300 RTSC scenario employment increases by 340 thousand jobs for high skill labour, while high skill labour's broad unemployment rate increases from 15.8% to 19.7% due to the increase in labour supply. At the same time, 180 thousand medium skill jobs are added and medium skill's broad unemployment rate decreases from 37.4% to 34.0%. Also, 65 thousand low skill jobs are added and low skill labour's broad unemployment rate decreases from 36.6% to 35.6% in the Ct300 RTSC scenario. The consequence is that, while average real wage increases by 0.2% with this investment in skills-approach compared to the main Ct300 RTSC scenario, average high skill wage decrease by 2.2% due to the higher unemployment rate in this labour market segment. Medium and low skill labour benefit, and their net wage increases by respectively 1.0% and 0.4% in real terms. The result is a reduction of income inequality, measured as richest (Hh5) over the poorest (Hh1) household class' per capita gross disposable income (after taxes) of 2.4%. In the other scenarios, similar developments take place.

The downside of the beneficial macro-economic impacts of the increased high skill labour supply-approach is that CO₂ emissions increase by 3.5% relative to the Ct300 RTSC scenario and about 4.5% in the Ct100 scenarios. This is due to the higher level of economic activity, but the CO₂ emission intensity of GDP decreases by 0.8% to 1.0% in the scenarios analysed. The latter implies that a small increase in the carbon tax rate could result in similar CO₂ emissions as in the equivalent main Ctax scenarios, but with better GDP and employment prospects (see also section 5.2 on this matter).

Explaining higher GDP growth

The results can be explained from the changes in the cost structure of resources that the increase in supply of high skill labour generates. Several changes happen in parallel, which I analyse here for the main Ct300 RTSC scenario. First of all, the initial effect is that the average costs of labour decrease, which makes labour more attractive as a factor of production. High skill labour intensity per unit of gross output increases on average, and along with it capital intensity, while (physical) energy intensity of domestic output decreases.

Thanks to the lower wage of high skill labour, South Africa's competitiveness improves, resulting in

import substitution. This leads to a decrease of the REER, which means that the SA economy can permit itself to see the domestic value of domestic production increase, while internationally South African prices decrease. Growth leads to lower average unemployment, and in the end, average wage is higher, expressed in domestic prices. For this reason, but especially due to substitution of imports, labour costs per unit of GDP increase, and so do costs for materials & services inputs. The combination of changes in the cost structure of aggregate GDP does not change total resources (or costs) per unit of GDP much. The most important change is that import costs reduce relative to primary income.

Translating the changes just described into changes of the DIM (see section 4.2.1), confirms that it is not the change of GDP (or income) over resources which causes higher GDP growth in the case of an investment in skills. Instead, it is the value per average unit of supply, and the ratio of the volume of domestic output over the volume of total supply (domestic output + imports) that increase. The former signifies that income components and non-income components of the cost structure of aggregate GDP increase by about the same amount. Indeed, the bigger availability of high skill labour does not mean that there is less need for intermediate inputs vs output, or that capital productivity would increase.

In contrast, the lower costs of high skill labour increase the attractiveness of complementary physical capital, which explains the increase of capital amortisation costs (write offs) shown in Table 4.29.

Table 4.29 Changes in cost structure of aggregate GDP of skill investment approach A relative to equivalent main Ctax scenarios

	Ct100 RTSC skill inv approach A	Ct300 RTSC skill inv approach A	Ct100 RVAT skill inv approach A
Energy IC costs ⁽¹⁾	+0.02%	+0.01%	+0.01%
Mat IC costs ⁽²⁾	+0.23%	+0.19%	+0.19%
T&C margins ⁽³⁾	-0.00%	+0.00%	-0.00%
Import costs	-0.23%	-0.18%	-0.24%
Total non-income	+0.02%	+0.02%	-0.04%
Labour costs	-0.11%	-0.09%	-0.13%
Capital write offs	+0.09%	+0.08%	+0.09%
NOS & spec.margins	+0.03%	+0.02%	+0.02%
Total indirect taxes ⁽⁴⁾	-0.01%	-0.01%	+0.03%
Total primary income	-0.00%	-0.00%	+0.00%
Resources per unit of GDP	+0.02%	+0.02%	-0.04%

Comments: (1) Costs for intermediate consumption (IC) of energy, and energy sectors, encompass COA, OIL, GAS, REF and ELC; (2) Mat is the aggregate of Materials & services, and consists of EIN, MAN, LSS, HSS, and TRA; (3) T&C margins are Transport & Commercial margins, and consist of an after-factory gate transfer or payment of transport and trade (commerce) costs levied over both domestic production and imports; (4) Indirect taxes are fuel levies, a sales tax (representing VAT) and other taxes minus subsidies on products – in this table taxes minus subsidies on production have been included in this category too.

And while per unit of GDP these costs compensate for decreasing labour costs, the capital write-offs and NOS components of the cost structure increase in all sectors, when calculated per unit of supply. Costs for intermediate inputs increase as well, and the overall result is that thanks to improved competitiveness, the domestic income and value (average price) of all products can increase. The improved competitiveness can also be seen from the fact that the REER decreases. The reduced CO₂ intensity of GDP is caused by the increased attractiveness of the labour-capital (KL) aggregate as a factor of production, thereby encouraging substitution of Energy by the KL-composite.

Table 4.30 Change in GDP multiplier per unit of supply, GDP growth and REER for investment in skill scenarios

	Ct100 RTCS	with skill investm. var A	change	Ct300 RTCS	with skill investm. var A	Change	Ct100 RVAT	with skill investm. var A	Change
Value per unit of supply*	1.035	1.040	+0.5%	1.027	1.031	+0.4%	1.045	1.049	+0.4%
GDP over Resources	1.052	1.052	-0.0%	1.049	1.048	-0.0%	1.043	1.043	+0.0%
Domestic production / supply*	1.015	1.018	+0.4%	1.007	1.010	+0.3%	1.013	1.017	+0.4%
GDP multiplier per unit of supply*	1.106	1.115	+0.8%	1.084	1.092	+0.7%	1.104	1.113	+0.8%
Projected GDP vs BY	+115%	+127%	+5.7%	+96%	+105%	+4.3%	+111%	+123%	+5.6%
REER vs BY	-3.7%	-5.5%	-1.8%	-1.9%	-3.3%	-1.4%	-3.1%	-4.8%	-1.8%
Trade balance (% GDP)	3.4%	3.3%	-2.9%	3.3%	3.2%	-2.5%	3.4%	3.3%	-2.9%

Comments: * Values for ratios are calculated by taking the ratio of per worker values, e.g. ...

4.5.2. Approach B: Productivity improvement within segregation

Investment in skills translating to productivity improvements

In the second approach, the positional character of the labour market is unaltered by the investment. The investment in skills in this case translates into a positive impact on productivity over the full width of labour supply (meaning all skill levels), which is modelled as an increase of annual *growth rates* of productivity of labour and capital. The question that is asked here is what productivity improvement is needed to achieve better economic and environmental outcomes compared to recycling Ctax revenue only according to the main revenue recycling mechanism. In this sense, the analysis presented here is a first sensitivity analysis, more of which follows in section 5.6.

To limit the amount of analysis these improvements are only explored for one scenario, which is the Ct100 RVAT scenario, because it obtains average GDP growth and CO₂ emission reductions and for reason of comparison with Schers *et al.* (2015).¹⁶⁸ This section explores 6 cases of productivity impacts:

1. Primary factor neutral technological change: Workers are assumed to learn how to be more productive in the same worker-machines/infrastructure combination, i.e. workers do not learn how to operate more machines in parallel, but only how to generate more output with the same amount of machines: The ratio of output over factor inputs, as defined by productivity growth multipliers LPF_j and KPF_j in Eq.8 and 9 in section 3.2.1 (page 81-109), increases equally for capital and labour;
2. Primary factor neutral technological change as in the previous case, but with the average additional labour productivity (APF_j or BPF_j , equal to parameter φ_{sk} in Eq.35) not leading to increased wages as defined in Eq.35 in section 3.3.2 (page 93);

¹⁶⁸ In theory, productivity impacts of the skill investment-option are required to be bigger (than for Ct100 RVAT) in case the main scenario to which it is applied resulted in higher GDP growth and decarbonisation (than for Ct100 RVAT) to obtain equivalent impacts to the case without the skill-investment option.

3. Primary factor neutral technological change *with* increase in Materials & Services (Mat) efficiency, meaning that workers learn how to be more efficient with intermediate inputs to production. The case is tested where this leads to an increase of “Mat” efficiency half that of the increase of labour productivity, with Mat efficiency conceptually defined by APF_j in Eq.6 in section 3.2.1 (page 81), for the trade-off between the *KLE* aggregate and the *Mat* aggregate; and by *AMEI* in Eq.15 in the same section;
4. Purely labour-saving technological change, in which only the rate of labour productivity growth increases: This represents the case in which workers learn to generate more output, but not generating more output per machine or unit of infrastructure. They therefore need more machines to realize the productivity gains obtained with the improvement of their skills;
5. Purely capital-saving technological change, in which output by worker does not improve, but workers manage to use less machines to generate output;
6. Similar to the previous two, but for an increase in the annual efficiency gains for material & services inputs.

The option for additional energy efficiency has not been tested, but it’s technological feasibility will be discussed in Chapter 5.

Key results for approach B

In approach B factor neutral productivity growth¹⁶⁹ proves incapable of achieving economic outcomes that are better than Ct100 RVAT revenue recycling without an investment in skills. To obtain GDP growth that is bigger than in Ct100 RVAT without investment in skills, first a threshold in productivity growth needs to be surpassed, in order to compensate for the loss of carbon tax revenue recycled through the RVAT revenue recycling mechanism (see Table 4.31). Beyond this threshold the contribution of output productivity growth to GDP growth diminishes while unemployment increases.

The reason for the weak performance on both GDP growth and employment of factor neutral productivity growth must be sought in the output productivity indexing of net wages: Labour becomes more expensive per unit of output produced (all other things equal), because net wages are indexed on median inter-sectoral productivity growth while the average productivity growth is lower. The parallel growth in capital output productivity appears insufficient to compensate this cost increase of labour.

Once labour output productivity growth is not translated into higher wage indexation, factor neutral output productivity growth with an investment in skills obtains better GDP growth and employment than the main Ct100 RVAT recycling mechanism for an acceleration in output productivity growth as low as 2.0% (Table 4.32). Another promising channel for output productivity growth is the case if the investment in skills also leads to improved efficiency in use of materials & services inputs. This achieves similar outcomes as factor neutral growth without wage indexation, even if this productivity

¹⁶⁹ Recall, factor neutral productivity growth here means that the growth *rate* of capital productivity has to increase faster than the growth *rate* of labour productivity to achieve the same increase of the ratio of output over factor use.

improvement only occurs at half the growth rate of labour and capital output productivity growth (Table 4.33). In this case creates GDP growth is strong, however employment growth is weaker than in the variant of productivity growth with wage moderation.

Table 4.31 Results for cases with factor neutrals productivity growth of skills investment approach B, for Ct100 RVAT

Case	Assumptions*			Change in results relative to main Ct100 RVAT scenario				
	Change in L Prod. growth rate, and final LP	Change in K Prod. growth rate, and final KP	Change in Mat Prod growth rate, and final MP	GDP in 2035	Unemployment (pct points)	CO ₂ emissions	CO ₂ intensity GDP	Class 5/ Class 1 income
Low factor neutral productivity growth	+1.0% 1.352 (+0.3%)	+4.0% 1.081 (+0.3%)	id. 1.078	-0.6%	+0.7pt	-0.7%	-0.1%	-0.3%
Medium-low factor neutral prod. growth	+2.0% 1.356 (+0.6%)	+7.9% 1.084 (+0.6%)	id. 1.078	-0.4%	+0.8pt	-0.6%	-0.1%	-0.2%
Medium-high factor neutral prod. growth	+5.0% 1.368 (+1.5%)	+19.9% 1.094 (+1.5%)	id. 1.078	-0.1%	+1.2pt	-0.3%	-0.1%	+0.1%
High factor neutral productivity growth	+7.0% 1.376 (+2.1%)	+27.8% 1.100 (+2.1%)	id. 1.078	+0.1%	+1.4pt	-0.1%	-0.2%	+0.4%
Very strong factor neutral prod. growth	+10.0% 1.388 (+3.0%)	+39.7% 1.110 (+3.0%)	id. 1.078	+0.4%	+1.7pt	+0.2%	-0.2%	+0.7%

* **Comments:** The assumptions concern increase of productivity growth rates versus the growth rates in RP. The table also shows resulting 2035 productivity multipliers (BY=1.00), and the change versus RP and the Ct100 RVAT scenario (which have the same productivity growth rate assumptions).

Table 4.32 Results for factor neutral productivity growth without further wage indexation with labour output productivity, for Ct100 RVAT

Case	Assumptions*			Change in results relative to main Ct100 RVAT scenario				
	Change in L Prod. growth rate, and final LP	Change in K Prod. growth rate, and final KP	Change in Mat Prod growth rate, and final MP	GDP in 2035	Unemployment (pct. points)	CO ₂ emissions	CO ₂ intensity GDP	Class 5/ Class 1 income
Low neutral w/o further wage indexation on LP	+1.0% 1.352 (+0.3%)	+4.0% 1.081 (+0.3%)	id. 1.078	-0.1%	+0.3pt	-0.3%	-0.1%	-0.2%
Medium-low neutral w/o wage indexation on LP	+2.0% 1.356 (+0.6%)	+7.9% 1.084 (+0.6%)	id. 1.078	+0.5%	-0.0pt	+0.2%	-0.2%	+0.0%
Med-high neutral w/o wage indexation on LP	+5.0% 1.368 (+1.5%)	+19.9% 1.094 (+1.5%)	id. 1.078	+2.2%	-1.0pt	+1.8%	-0.5%	+0.6%

* **Comments:** The assumptions concern increase of productivity growth rates versus the growth rates in RP. The table also shows resulting 2035 productivity multipliers (BY=1.00), and the change versus RP and the Ct100 RVAT scenario (which have the same productivity growth rate assumptions).

However, both of these latter two options (factor neutral with wage moderation, and factor neutral plus materials & services efficiency) cannot achieve an absolute decrease in CO₂ emissions compared to the main revenue recycling scenario. Energy use is not substituted fast enough by use of other factors, despite their growth in output productivity. Some substitution does take place, which can be seen from

a decreasing CO₂ emission intensity of GDP in these skill investment variants. The positive impact on GDP growth should therefore be combined with a higher carbon tax rate (for further analysis of this point, see the analysis in section 5.2 next). The decrease in CO₂ intensity of GDP is strongest for factor neutral productivity growth with material efficiency gains. This suggests that the case with Mat efficiency could obtain a similarly low level of CO₂ emissions as other variants, but with better economic outcomes through an increase of the CO₂ tax rate beyond R100/tCO₂.

Table 4.33 Results for factor neutral productivity growth with equivalently half material efficiency gains, for Ct100 RVAT

Case	Assumptions*			Change in results relative to main Ct100 RVAT scenario				
	Change in L Prod. growth rate, and final LP	Change in K Prod. growth rate, and final KP	Change in Mat Prod growth rate, and final MP	GDP in 2035	Unemployment (pct. points)	CO ₂ emissions	CO ₂ intensity GDP	Class 5/ Class 1 income
Low neutral + material efficiency (half of L prod)	+1.0% 1.352 (+0.3%)	+4.0% 1.081 (+0.3%)	+2.1% 1.080 (+0.15%)	+0.3%	+0.1pt	-0.0%	-0.3%	-0.1%
Medium-low neutral + mat efficiency (half of LP)	+2.0% 1.356 (+0.6%)	+7.9% 1.084 (+0.6%)	+4.3% 1.081 (+0.3%)	+1.3%	-0.4pt	+0.8%	-0.5%	+0.3%
Medium neutral with mat efficiency (half of LP)	+4.0% 1.364 (+1.2%)	+15.9% 1.091 (+1.2%)	+9.4% 1.086 (+0.7%)	+3.6%	-1.5pt	+2.7%	-1.0%	+1.0%

* **Comments:** The assumptions concern increase of productivity growth rates versus the growth rates in RP. The table also shows resulting 2035 productivity multipliers (BY=1.00), and the change versus RP and the Ct100 RVAT scenario (which have the same productivity growth rate assumptions).

Additional analysis

From the results presented so far it should also be clear that there is a difference in the impact that growth in factor's output productivity has on the South African economy. To compare the effects of different factor and input productivity gains, they have also been analysed separately – each with an increase in the productivity growth rate that causes the factor or input's productivity to have increased equally much as is the case for labour output productivity if it's growth rate would have increased by 2% compared to the assumption of RP and the main Ctax scenarios.¹⁷⁰ To make the case of increase in labour productivity gains more comparable to capital productivity growth and material efficiency gains it has also been analysed the wage gains with additional labour productivity.¹⁷¹

This comparison shows that outcomes for GDP growth are very sensitive to growth in material efficiency, while labour saving or capital saving output productivity growth are insufficient, at the rate analysed here, to pass the investment threshold and GDP turns out smaller than in the Ct100 RVAT scenario (Table 4.34). Results for GDP growth, employment and CO₂ emission intensity of GDP are quite similar between labour-saving and capital-saving output productivity growth.

¹⁷⁰ The annual labour output productivity growth rate in RP and main Ctax scenarios was +1% per year, meaning that a 2% increase in its growth rate translate into labour output productivity growing by 1.02% per year.

¹⁷¹ A difference is that labour output productivity gains translate into salary gains, whereas capital productivity gains do not have this effect, because nobody claims the benefits of reduced capital write-offs in IMACLIM-ZA, due to profit margins being assumed to be fixed mark-up rates over total costs of production (IC and labour costs). Similarly, nobody claim the benefits of increased productivity of intermediary inputs. In fact, these benefits fall indirectly to consumers, and via the real cost decrease in supply, they increase all factor income.

The reason for material & services (Mat) efficiency gains to be more beneficial for GDP growth and CO₂ emission reduction than individual factor output productivity growth is first of all that it improves international competitiveness, because no-one claims the income gains of Mat efficiency, the relative prices of South African products decrease compared to international products – the advantage that Mat efficiency has over capital output productivity growth is that it makes up a larger share of the South African economy’s resources. Secondly, Mat efficiency functions like Total Factor Productivity, because it improves real income for everyone (for all earners of primary income), meaning labour, capital and government (through indirect taxes). In this way, it improves factor productivity for the other two factors alike. If one wants to achieve GDP growth through increases of neutral, labour productivity or capital saving productivity growth only, the increase needs to be very high, and it will be accompanied by only small reductions of GDP’s CO₂ intensity relative to the non-investment main Ct100 RVAT scenario case.

Table 4.34 Results for cases with single-factor or input productivity growth, for Ct100 RVAT

Case	Assumptions*			Change in results relative to main Ct100 RVAT scenario				
	Change in L Prod. growth rate, and final LP	Change in K Prod. growth rate, and final KP	Change in Mat Prod growth rate, and final MP	GDP in 2035	Unemployment (pct. points)	CO ₂ emissions	CO ₂ intensity GDP	Class 5/ Class 1 income
Labour saving	+2.0% 1.356 (+0.6%)	id. 1.078	id. 1.078	-0.7%	+0.9pt	-0.8%	-0.1%	-0.3%
Labour saving & no additional wage gain	+2.0% 1.356 (+0.6%)	id. 1.078	id. 1.078	-0.4%	+0.6pt	-0.5%	-0.1%	-0.3%
Capital saving (equiv. to 2% L saving)	id. 1.348	+7.8% 1.084 (+0.6%)	id. 1.078	-0.5%	+0.5pt	-0.6%	-0.1%	-0.2%
Material efficiency only (equiv. to 2% L saving)	id. 1.348	id. 1.078	+8.4% 1.085 (+0.7%)	+2.8%	-1.7pt	+2.0%	-0.8%	+0.5%

* **Comments:** The assumptions concern increase of productivity growth rates versus the growth rates in RP. The table also shows resulting 2035 productivity multipliers (BY=1.00), and the change versus RP and the Ct100 RVAT scenario (which have the same productivity growth rate assumptions).

4.5.3. Conclusion on investment in skills

Results of both skill investment approaches show that a 7.5 billion ZAR₀₅ annual investment in education and training, financed with carbon tax revenue, only needs to achieve a small improvement in either high skill labour supply, or in output productivity of factors and other inputs to have a significant impact on South African GDP. Were such an investment would increase the access of a large number of South African students to the high skill job market, then GDP in 2035 would be 4 to 6% higher than in cases with similar carbon tax revenue recycling but no investment in skills. This is equivalent in the projection year to 130 to 160 billion ZAR₀₅ of GDP, a multiple of the annual investment. This means that even if the investment would be much less successful, the benefits for the South African society would still be worth it.

If, on the other hand, the investment in skills and training cannot change the positional character of the labour market, e.g. because the quality gap in education or other social barriers are not diminished, then the hypothesis of the analysis in this section was that it an investment in education and training would at least improve output productivity thanks to having better trained workers. In this case, the impact of the investment can be positive, if productivity gains are combined with moderate wage gains. Alternatively, additional material efficiency gains can contribute to decreasing unemployment (in theory energy efficiency gains have the same impact). Material and energy efficiency are more effective in reducing the CO₂ intensity of GDP than further increasing labour's output productivity.

Finally, none of the cases analysed for both approaches for investment in skills achieve absolute decoupling of CO₂ emissions and economic growth. Absolute decoupling can likely be achieved through a higher carbon tax rate though, which compensates for the increase in economic activity. The reduction in CO₂ emissions would still obtain a higher GDP and lower unemployment than in the similar Ctax scenario without an investment in skills, because the CO₂ intensity of the South African economy is lower in all analysed cases of an investment in skills of labour.

5. Alternative scenarios and sensitivity analysis

5.1. Introduction

This chapter both analyses alternative policy contexts in which the carbon tax could be introduced, and performs sensitivity analysis to assess what the key parameters are that determine scenario results and how uncertainty in these parameters translates into uncertainty in model outcomes. More specifically this chapter discusses the following topics:

1. Does the comparison between different mechanisms of revenue recycling of the main Ctax scenarios presented in Chapter 4 hold if one fixes CO₂ emission targets and makes the level of the carbon tax dependent on the CO₂ emission reduction target? (Section 5.2)
2. The main carbon tax scenarios of the previous chapter assume no exogenous changes in international prices relative to the reference projection. Yet, that the rest of the world takes action on climate change and faces similar costs for reducing CO₂ emissions as South Africa does? (Section 5.3)
3. On the other hand, what happens if only the rest of the world (ROW) implements carbon pricing and South Africa does not. In this case, ROW might penalise South Africa for unfair competition and impose a border tax on South African exports (section 5.4);
4. In IMACLIM-ZA technology for production in other sectors than electricity is modelled through nested CES production functions. The price elasticities of these nested CES functions are based on common values found in literature. However, as discusses in Chapter 2, such a CES representation of technology likely does not represent the dynamics of technological very well, in particular regarding substitution of energy in production – i.e. energy efficiency of production. Section 5.5 analyses how energy efficiency obtained in IMACLIM-ZA results compares to potentials for energy efficiency found in literature. An alternative scenario for enhanced energy efficiency is presented, and analysed for its impact on GDP growth, employment and CO₂ emissions;
5. Finally, choices in parameterisation influence modelling results and therefore the estimate of the combined impact of carbon taxation and revenue recycling schemes on the South African economy. Section 5.6 presents a sensitivity analysis that is partly quantitative and partly qualitative: It deals with assumptions about technological change in the electricity sector, about productivity improvements in other sectors, about the parameterisation of the wage curve, and in a more qualitative way, with possible impacts on results of parameters for international trade and of the size of government final consumption.

5.2. Imposing a CO₂ emission target which achieves the NDC

Introduction

Chapter 4 presented results for specific carbon tax (Ctax) rates. This approach was chosen for various reasons: To evaluate carbon taxation in a way that resembles how it is designed in a political process, namely envisioning a specific rate rather than a specific emission reduction¹⁷²; To model Ctax rates similar to those of the consulted runs of SATIM for BU-model based technological coefficients of the electricity sector (ELC); And to analyse Ctax rates similar to those used in an earlier study with IMACLIM-ZA (Schers et al., 2015). Furthermore, a practical motivation for analysing fixed Ctax rates rather than fixed CO₂ emission targets with variable Ctax rates, is that the latter requires an elaborate approach in which the bottom-up energy system model SATIM is run in convergence with IMACLIM-ZA to obtain technological coefficients for the electricity sector that correspond to the carbon tax rate applied in IMACLIM-ZA. However, the disadvantage of fixed carbon tax rates is, as results in Chapter 4 showed, that it reduces the comparability of different policy scenarios. Also, it is preferable to verify whether CO₂ intensities of GDP obtained in main Ctax scenarios do not depend on a local equilibrium (due to non-linearity of economic behaviour) and to see whether economic advantages of a certain Ctax revenue recycling mechanisms still hold once the carbon tax rate is increased in order to reduce CO₂ emissions even further.

It is therefore worth to explore whether Ctax scenarios can be made more comparable. Thanks to the results of the main Ctax scenarios in Chapter 4, it is possible to estimate how technological coefficients for the electricity sector are related to the carbon tax rate for each of the revenue recycling schemes. On this basis the alternative scenario analysis for this sub-section could be developed, in which the Ctax is variable and CO₂ emissions for 2035 are fixed, could be developed.

The main lesson from this exercise, the discussion below will show, is that the results for CO₂ intensity of GDP of the main Ctax scenarios of Chapter 4 are a good indicator for the economic success of a revenue recycling scheme when targeting a specific amount of annual CO₂ emissions. This section therefore concludes that the macro-economic preference for a revenue recycling scheme remains with the scheme that decarbonises the South African economy most easily, which is the scenario of carbon tax revenue recycling through labour subsidies (RTSC).

Methodology

To simplify matters the alternative NDC CO₂ emission target analysis of this sub-section is only performed for the RSUM, RVAT, RTIF-low, and RTSC scenarios, which together cover almost the full range of economic and environmental (CO₂ emissions) outcomes within the larger set of Ctax scenarios presented in Chapter 4. These scenarios are modelled in such a way that they achieve the objective of identical CO₂ emissions for South Africa, namely South Africa's NDC translated to 2035 with the additional assumption that the reference projection (RP) of Chapter 4 would be the business-

¹⁷² The latter clearly has been the case in South Africa, where in several years of political debate about the introduction of a carbon tax, the proposed rate has not changed from the initially proposed 120 Rands per tonne CO₂, even despite high inflation.

as-usual case for South Africa's future CO₂ emissions (see section 4.1):

The NDC CO₂ emissions target has been set at **350 Mt CO₂**. This target assumes that CO₂ emissions in RP increase linearly from 2005 to 2035. The target furthermore takes into account that South Africa's NDC requires CO₂ emissions in 2025 to be 42% below South Africa's business-as-usual CO₂ emission level, which would be 605 Mt with the previous assumption of linear growth. A reduction of 42% below 605 Mt equals 350 Mt CO₂. If one sticks to the NDC's envisioned plateau in CO₂ emissions between 2025 and 2035 then CO₂ emissions of 2035 should still equal 350 Mt, which is **51%** below CO₂ emissions in 2035 found for RP (in Chapter 4).

Technically, to model this in IMACLIM-ZA, an additional constraint is added which defines the CO₂ emission target, and the Ctax rate is turned into a model variable. To estimate the technological coefficients of the ELC sector in 2035 which would correspond to the now endogenous Ctax rate the following procedure has been used:

1. For a given endogenous Ctax rate and a given carbon tax revenue recycling scenario, the technological coefficients for ELC obtained from the SATIM runs with the closest Ctax rate just below and just above the endogenous Ctax rate are retrieved. For the purpose of this alternative scenario analysis, a SATIM run with the IRP updated build plan and a R500 ZAR/tonne CO₂ was used in addition to the runs with 100 and 300 ZAR/tonne CO₂;
2. A weighted average of the two sets of technological coefficients that were derived from SATIM is calculated on the basis of the distance from the endogenous Ctax rate to the Ctax rates of the two sets of technological coefficients from SATIM (see section 3.1.3). This averaging is done with the following calculation (Eq.72):

$$TC_{new} = \frac{(Ctax_{end} - Ctax_{low})}{(Ctax_{high} - Ctax_{low})} * TC_{low} + \frac{(Ctax_{high} - Ctax_{end})}{(Ctax_{high} - Ctax_{low})} * TC_{high} \quad (72)$$

, with:

TC_{new} the value for a technological coefficient of ELC (α_{ELC} , κ_{ELC} , or λ_{ELC} , see section 3.2.1) that corresponds to the value of the endogenous carbon tax rate;

$Ctax_{end}$ the endogenous carbon tax rate (model variable);

$Ctax_{low}$ the first lower carbon tax rate used in a run with SATIM relative to $Ctax_{end}$;

$Ctax_{high}$ the first higher carbon tax rate used in a run with SATIM relative to $Ctax_{end}$;

TC_{low} the technological coefficient from calibration data derived from SATIM for the carbon tax rate $Ctax_{low}$;

TC_{high} the technological coefficient from calibration data derived from SATIM for the carbon tax rate $Ctax_{high}$;

3. On the basis of the amounts of CO₂ emissions obtained in the main Ctax scenario analysis (presented in Chapter 4) $Ctax_{low}$ and $Ctax_{high}$ are determined for each scenario.

For example, if in the main Ctax scenario a ZAR 300 Ctax overshoots the NDC target (as e.g. is the case for Ct300 RSUM, the alternative NDC scenario here looks for a carbon tax rate and the corresponding technological coefficients for ELC between a R100 and a R300 Ctax rate.

Results

Decomposition analysis of CO₂ emissions in main scenario results in section 4.4.2 showed that decarbonisation of South Africa's GDP is strongly determined by the capacity of the electricity sector to decarbonise. With changes in the endogenous carbon tax rate, some small changes in the CO₂ intensity of GDP are obtained compared to the *main* Ctax scenario results that came closest to achieving South Africa's NDC (see Table 5.1): The biggest decrease in carbon intensity of GDP is found for the RTSC scenario, where it goes from 0.67 kg CO₂/USD₁₃ in the R300 Ctax main scenario case to 0.64 kg CO₂/USD₁₃ for the NDC target scenario.

The principal explanation for the change in the CO₂ emission intensity of GDP is, as the analysis in section 4.4.2 showed, a reduction in the CO₂ emission intensity of power generation. The reason is that once power generation investments planned in the (updated) IRP build plan have been realised, the consulted SATIM runs are free to determine the composition of prospective power generation technology on the basis of available technologies, their costs, and the objective of realising the intertemporally, for society, least-cost energy system.

Within this context, carbon taxation turns out to determine the pace at which old coal power plants will be discarded and replaced by renewable or nuclear power generation: A change in the carbon tax rate modelled according to the description above, therefore leads above all to a change in the use of coal (ELC's technological coefficient α_{ELC} for IC of COA) and in the capital-intensity of power generation (ELC's technological coefficient κ_{ELC}). In view of the scenario results of section 4.3.2 it is obvious that RVAT, RTIF-low and RTSC must increase the carbon tax rate above 300 ZAR/tonne CO₂ to achieve the NDC target of -51% CO₂ emissions relative to RP, and that they reduce the CO₂ emission intensity of power generation along with the increase of the carbon tax rate. RSUM's NDC scenario on the other hand sees the carbon tax rate increase relative to RSUM's Ct300 scenario of Chapter 4, and its CO₂ emission intensity of power generation increases too.

The strength of decarbonisation the South African economy in comparison to the CO₂ emission intensities obtained in Chapter 4 differs between scenarios. Chapter 4 already showed that the RTSC scenario achieved the lowest CO₂ intensity of GDP at a fixed carbon tax rate. In the NDC scenarios presented here, it are the scenarios with the strongest decrease in CO₂ intensity of GDP additional to the decrease from a reduction of the CO₂ intensity of power generation (ELC), achieve the highest GDP growth. To prevent a rebound effect, these scenarios that are successful at decarbonising the economy need to increase the carbon tax rate more than other scenarios to achieve the NDC target. This does not need to be disadvantageous for the South African economy, because this also means that there are additional revenues which can be recycled into tax reform, investment or expenditure.

Table 5.1 Change in key indicators compared to RP for NDC target scenarios

Scenario	CO ₂ tax in R ₀₅ /tCO ₂	Avg GDP growth	Total GDP growth	Broad unem- ploym.	Jobs per mn. R ₀₅ GDP	CO ₂ emis. (Mt)	kgCO ₂ /\$ ₁₃ GDP	HH5 / HH1 income
BY (2005)	-	-	-	39%	7.8	443	1.54	42
RP (2035)	-	2.7%	+125%	24%	5.8	687	1.06	45
Comparable main Ctax scenarios 300 ZAR₀₅/tCO₂								
RVAT	300	2.1%	+85%	37%	5.8	361	0.68	42
RSUM	300	1.6%	+63%	45%	5.8	323	0.69	23
RTIF-low	300	2.2%	+94%	34%	5.9	379	0.68	43
RTSC	300	2.3%	+96%	32%	6.0	377	0.67	42
NDC CO₂ emission target scenarios								
RVAT	314	2.0%	+83%	38%	5.9	350	0.67	42
RSUM	255	1.7%	+65%	45%	5.8	350	0.74	24
RTIF-low	325	2.1%	+84%	37%	5.9	350	0.66	42
RTSC	339	2.2%	+91%	33%	6.0	350	0.64	42

The NDC variants of RSUM and RVAT show little difference in terms of GDP growth and employment compared to their main Ctax scenario counterparts (Table 5.1). Also, RTIF-low's outcomes for GDP and employment in the NDC scenario are now closer to those of RVAT than to those of RTSC, as it was the case in scenario results of Chapter 4 (Table 5.1). The reduction of overall GDP relative to RTIF-low's main Ctax scenario counterpart is 10 percentage points of base year (BY) GDP. Also, in this scenario broad unemployment is 3 percentage points higher with the increase of the carbon tax rate from R300 to R325.

The finding that RTIF-low does not come out well in the fixed NDC CO₂ target case can be explained from the fact that this revenue recycling mechanism is a profit tax cut that also benefits polluting sectors. This recycling mechanism therefore diminishes the impact of a CO₂ tax. Whereas the RTSC scenario – which does not show much difference in GDP and unemployment rate between the main Ctax case and the NDC target case – uses the higher carbon tax rate to further stimulate the substitution of energy by labour. In the case of RVAT a similar mechanism as in the RTSC scenario is at play, because its recycling mechanism improves the purchasing power of households through a decrease of the CPI and wages relative to other factor prices. This makes labour slightly more attractive as a factor of production and labour intensive products as a good for final consumption. However, RVAT does not prevent outsourcing of CO₂ emissions as much as RTSC does. Because the sales tax reduction is also applied to imported products, RVAT offers much less compensation for the disadvantage of carbon taxation in the trade-off between domestic and imported goods than RTSC.

Consequences of South Africa's NDC beyond 2035

The results of the main R300 Ctax scenarios and the NDC scenarios imply that *per capita* CO₂ emission levels will be between 5.0 and 6.6 tonne of CO₂ per capita in 2035, and total energy-related CO₂ emissions of South Africa 298 to 390 Mt CO₂ per year. These emissions levels are still high:

They are equivalent to those of France, Italy, Spain or Denmark nowadays (2014).¹⁷³ Also, time does not stop in 2035, and further decarbonisation efforts are required beyond that date. It is therefore interesting to know how much further decarbonisation would be required for (very) long term climate policy.

To see what amount of emission reduction is needed after 2035, given these scenario outcomes, one first needs to determine South Africa's remaining carbon budget. Estimates of a *fair* greenhouse gas (GHG) emission budget for South Africa for the entire period 2000 to 2049 vary between 8 and 28 Gt CO₂-equivalent emissions, depending on the approach and ethical principles for their calculation (Winkler and Marquard, 2012).¹⁷⁴ If one assumes that CO₂ emissions make up 76% of South Africa's greenhouse gas emission budget – as it was the case in 2000 (RSA, 2013a) – then a carbon emission budget of 6 to 21 Gt of CO₂ remains for the period 2000-2049. According to historic emission data presented by World Bank (2017), 6.2 Gt have been consumed between 2000 and 2013 (excluding greenhouse gasses from other sources than CO₂), this means that a budget between *zero* and 15 Gt of CO₂ remains for the period 2014 - 2049. In the NDC scenarios emissions reach 350 Mt CO₂ in 2035.¹⁷⁵ Making the simplifying assumption that emissions decrease linearly from 490 Mt of CO₂ in 2014 (see the previous footnote) to 350 Mtonne in 2035, then this implies an annual average of 420 Mt of CO₂ emissions, or cumulatively 9 Gt of CO₂.

Deducting this from the estimated remaining “fair” carbon budget range for 2014 - 2049 the carbon budget remaining for 2036 - 2049 ends up between -9 (a negative budget) and 6 Gt of cumulative CO₂ emissions. Translated into annual emissions for 2036 - 2049 this would be equivalent to -640 and 430 Mtonne of CO₂ emissions per year. A middle-of-the-road greenhouse gas emission budget might be to assume net zero emissions by 2049 (average annual CO₂ emissions of 175 Mt of CO₂ between 2035 and 2049). Clearly, this requires a sharp decline in CO₂ emissions after 2035 also in the case of achievement of South Africa's NDC.

This implies that there is a strong requirement for the South African society to reflect on timely policy measures to enable further CO₂ emission reduction in the future. These are measures that could not be taken into account in IMACLIM-ZA, because they take place in the realm of anticipating investments – e.g. in transport infrastructure, in buildings, and in knowhow and expertise for energy and materials efficiency. The current version of IMACLIM-ZA however does not look beyond its modelled time horizon, looks at relatively instant responses to carbon pricing and has a simplified representation of investment, linking it to capital amortisation. Would anticipation of future emissions have been added, then the economic structure would show a reduction of consumption in favour of investment.

¹⁷³ Source: Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, United States as presented by World Bank data: <https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?end=2014&locations=FR-AT-ES-IT-DK&start=2011>, accessed 29/04/2018.

¹⁷⁴ These are based on historic responsibilities starting in 1970 and excluding LULUCF (Land Use & Land Use Change and Forestry).

¹⁷⁵ In contrast to South Africa's idea of a peak-plateau-and decline trajectory for the NDC, this actually entails a decrease in CO₂ emissions compared to 2013. Actually, the Republic of South Africa assumes a more carbon intensive “business-as-usual” trajectory (with higher growth rates).

5.3. A multilateral carbon tax

In view of the strong impact on growth and employment of a carbon tax rate of 300 ZAR₂₀₀₅/tCO₂ it is a justified question whether the approach of assuming no international carbon tax does not lead to too big a disadvantage for South Africa's exports. I therefore test the case in which the Rest of the World also implements a carbon tax, equivalent to the South African one. The analysis presented in this section shows that foreign carbon taxation indeed improves the economic prospects for South Africa compared to a unilateral domestic carbon tax, but that the improvement does not fundamentally alter results or conclusions compared to the main scenarios. The results in this section also show that energy-intensive sectors are slightly better off if carbon taxation is implemented multilaterally, while energy-extensive sectors witness a decrease in their output relative to the case of unilateral carbon taxation and cost-reducing Ctax revenue recycling (as in the RTSC, RTIF-low, and RTaY scenarios).

Approach

To model a multilateral carbon tax, the approach followed is: I assume that the implementation of carbon taxation in South Africa's trading partners leads to similar relative changes in prices between products as in the case of a unilateral carbon tax in South Africa (presented in section 4.3). Note that this change is additional to the relative changes in international prices between products that are already included in RP and the main (unilateral) Ctax scenarios (see Table 3.7 on p.115).

For non-energy sectors I assume that the additional change of their prices (relative to the import price of HSS) is similar¹⁷⁶ to the average change observed in their average resource price (p_i) relative to that of HSS (p_{HSS}) in South Africa in the unilateral carbon tax scenarios (Table 5.2).

For energy sectors different assumptions are made:

- For the GAS and REF sectors the international products are assumed to be less carbon-intensive than their South African equivalents. I therefore assume lower price increases than for domestic products. In the case of GAS, imports consist of gas from neighbouring countries, whereas in IMACLIM-ZA the domestic product also consists of coke ovens and gas works gas. In the case of REF, imports consist only of products of oil refineries, whereas domestic production includes more carbon intensive Coal-To-Liquids refined fuel products;
- For the import price of coal, an almost two times bigger price increase is assumed than observed for the domestic coal price in the unilateral carbon tax scenarios (see Table 5.2): I assume that the high grade coal traded in international markets with which South Africa's high-grade export coal competes has higher energy requirements in mining and processing than the coal used in South African power plants;
- For ELC I assume a price increase of about a third of that observed in main Ctax scenarios, because I assume imported electricity to consist mainly of gas-fired power and (in the future)

¹⁷⁶ For simplicity, the whole, half or quarter-percentage point values closest to the scenario-average changes in prices have been used.

hydro-power electricity, in contrast to by majority coal-based domestic electricity, therefore only 1/3rd of the domestic price increase is applied to pM_{ELC} ;

- For OIL, for which there is no domestic production, I assume that there is a 5% price increase under the assumption that relative to its energy content (e.g. per PetaJoule of heating value) oil requires less energy to extract and transport than coal or certain types of gas (such as LNG).

An overview of price changes obtained in main Ctax scenarios and price changes assumed between imported goods (relative to the international price of HSS, pM_{HSS}) is presented in Table 5.2.

Finally, to simplify matters the analysis is performed only for two scenarios, but both at a R100 and a R300 Ctax: The scenario that had relatively good economic outcomes, but which did not offer domestic products a compensation of the competitive disadvantage of the carbon tax (the RVAT scenario), and the economically best-performing scenario, RTSC.

Table 5.2 Assumed increases in international prices for a multilateral Ctax equivalent to R100 and a R300 Ctax rates

Sector	COA	OIL	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
Ex ante 2035 pM vs BY, for RP and main Ctax scenarios	+50%	+80%	+100%	+60%	id.	id.	-10%	-10%	id.	id.
Domestic price increase vs. pHSS in R100 Ctax scenarios	+2.2%	id.	+34%	+6.4%	+20%	+4.0%	+1.8%	+1.0%	id.	+2.7%
Assumed impact R100-eq. multilateral Ctax on pM*	+4.0%	+2.0%	+4.0%	+2.5%	+6.0%	+4.0%	+2.0%	+1.0%	id.	+2.5%
Combined ex ante pM vs BY for multilateral R100 Ctax	+56%	+84%	+108%	+64%	+6.0%	+4.0%	-8.2%	-9.1%	id.	+2.5%
Domestic price increase vs. pHSS in R300 Ctax scenarios	+5%	id.	+101%	+17%	+38%	+9%	+3.9%	+2.1%	id.	+7.3%
Assumed impact R300-eq. multilateral Ctax on pM*	+10%	+5%	+10%	+7.5%	+12%	+10%	+4.0%	+2.25%	id.	+7.0%
Combined ex ante pM vs BY multilateral R300-eq. Ctax	+65%	+89%	+120%	+72%	+12%	+10%	-6.4%	-8.0%	id.	+7.0%

Comment: * The (*ex ante*) assumed impact is added to the (*ex ante*) pM increase assumed for RP and all main Ctax scenarios. The *ex post* price change takes into account these assumptions and variation in the Relative CPI (or REER) which differs per scenario.

Results

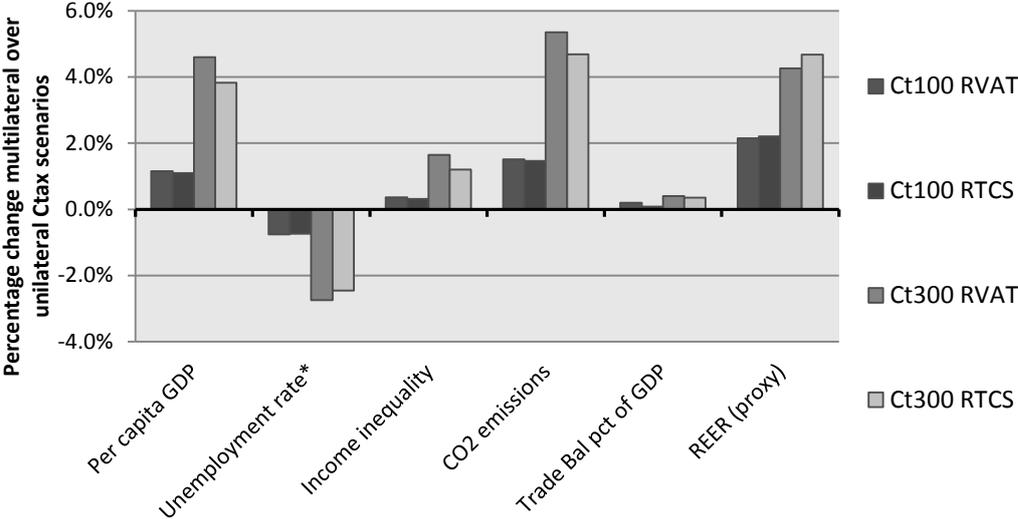
All multilateral carbon tax scenarios tested result in higher *per capita* GDP, lower unemployment, and higher CO₂ emissions and the CO₂ intensity of GDP than the unilateral carbon tax cases (Figure 5.1). Inequality increases as well. Also noteworthy is that the trade balance surplus hardly increases (Figure 5.1). Furthermore, and surprisingly, the real effective exchange rate (the REER) increases, which indicates that South African products have become relatively more expensive.

The explanation for higher economic growth in the multilateral carbon tax scenarios compared to the unilateral ones lies in improved conditions for international trade. The mechanism through which improved international competitiveness improves the economic outlook, however is not intuitive, because the REER increases at the same time.

Technically speaking, would the assumption have been that all international prices were raised with

the same rate, then the model would have eliminated the assumed relative change between international and domestic prices and there would have been no difference between multilateral and unilateral results of Ctax scenarios. The reason is that the *numéraire* of the model would have stayed the same as in the unilateral case.¹⁷⁷ What counts to understand the results of the multilateral carbon tax scenarios is the differentiation in international prices between products.

Figure 5.1 Change in key indicators for multilateral Ctax scenarios versus (main) unilateral Ctax scenario counterparts



* Note: The difference in unemployment rates is expressed in percentage points of unemployment rate, not a percentage change.

The change in relative international prices following the introduction of carbon taxes abroad results in higher exports plus substitution of imports by domestic output in energy sectors (COA, GAS, REF, ELC) and in energy intensive sectors (EIN, TRA) (Table 5.3). However, not all sectors are equally important for the trade balance: EIN, which represents 40 to 41% of export value in the unilateral Ctax scenarios, is clearly the most important sector, followed by MAN (20% of export value), while COA, HSS, LSS, TRA and REF have similar relatively small roles (each 9% to 6% of export value). For imports, MAN is the most important sector, representing about 49% of import value, while OIL, EIN, LSS and TRA have minor roles (between 15% and 9% of import value). The relative improvement of domestic prices vs international prices is much stronger for EIN than the relative deterioration of domestic vs international prices for MAN. Obviously, this price development should lead to a bigger trade balance surplus, and stronger growth of domestic output. (This effect is only slightly reduced by the increase in OIL and MAN imports with stronger GDP growth.) Overall, the evolution of relative prices creates a stimulating effect on exports, and a dampening effect on imports.

The trade balance, however, is constrained by the current account and the broad capital account, as a

¹⁷⁷ The model is price-homogenous, meaning that if all prices change at the same rate, the results stay the same. Furthermore, as discussed in Chapter 2, domestic prices fundamentally consist of import costs and value added (plus indirect taxes). If all international prices increase at the same rate, this would – in model-technical and disequilibrium terms – cause a cascade of increases in domestic prices ultimately resulting in an equilibrium in which domestic prices would have nominally increased with the same rate as international prices, and in which international prices, when expressed in the numéraire (the GDP deflator) have remained unchanged.

part of the international Balance of Payments, and cannot increase very much (see section 3.4).¹⁷⁸ This despite the fact that higher GDP growth tends to lead to higher rates of returns on capital in IMACLIM-ZA, and therefore to higher transfers of returns on capital to the rest of the world. But, the latter is insufficient to change the share of the trade balance over South Africa's GDP much. The endogenous exchange rate therefore – in a balancing exercise between domestic and foreign growth under the given specifications for international trade – adjusts so a higher (real) value for the South African Rand fixes the trade balance at its proper rate. The latter is reflected by the increase of the REER shown in Figure 5.1.

Table 5.3 Changes in relative prices between domestic and foreign products for imports and exports, for the multilateral vs unilateral Ctax scenarios

	COA	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
Change in pY/pM, multilateral vs unilateral scenarios									
Ct100 RVAT	-1.7%	-1.7%	-0.3%	-3.6%	-1.7%	+0.2%	+1.3%	+2.3%	-0.3%
Ct100 RTCS	-1.7%	-1.7%	-0.3%	-3.5%	-1.6%	+0.2%	+1.3%	+2.3%	-0.2%
Ct300 RVAT	-4.9%	-5.0%	-2.4%	-6.8%	-4.7%	+0.6%	+2.4%	+4.7%	-2.2%
Ct300 RTCS	-4.7%	-4.8%	-2.3%	-6.5%	-4.5%	+0.8%	+2.6%	+5.0%	-1.9%
Change in pX/pM, multilateral vs unilateral scenarios									
Ct100 RVAT	-1.7%	-	-0.3%	-3.6%	-1.5%	+0.2%	+1.0%	+2.3%	-0.4%
Ct100 RTCS	-1.7%	-	-0.3%	-3.5%	-1.5%	+0.2%	+1.0%	+2.3%	-0.3%
Ct300 RVAT	-4.9%	-	-2.3%	-6.8%	-4.3%	+0.4%	+1.6%	+4.6%	-2.2%
Ct300 RTCS	-4.7%	-	-2.2%	-6.5%	-4.1%	+0.6%	+1.9%	+4.9%	-2.0%

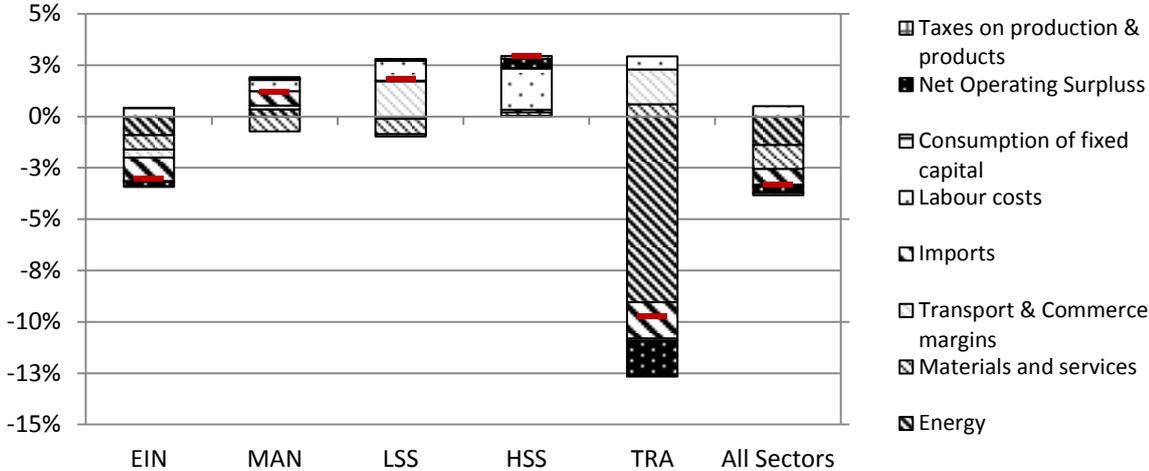
The relatively beneficial evolution of domestic relative to foreign prices for EIN, REF and TRA also explains the increase in the CO₂ intensity of South African GDP. These sectors see their share in the South African GDP increase under multilateral carbon taxation relative to the case of unilateral carbon taxation. Furthermore, higher GDP growth in multilateral Ctax scenarios leads to a decrease in unemployment, which causes an increase in real wages relative to the unilateral scenario cases. This, together with the increase in the REER explains the relative increase of domestic versus foreign prices of the labour intensive sectors LSS and HSS to increase (see Table 5.3 and Figure 5.2, which shows the composition of price changes for the Ct100 RVAT scenario), which contributes to the increase in CO₂ intensity of the South African economy in the multilateral carbon taxation scenarios.

A political consequence of these results is that, if South Africa wants to achieve a certain emission reduction, as e.g. announced in its NDC, it needs to put in place a somewhat higher carbon tax if its trading partners in case the Rest of the World also implement carbon taxes. Though the economic benefits of the multilateral Ctax scenarios are very welcome for South Africa, the higher CO₂ intensity of South Africa's GDP is not and would require a greater effort than in the unilateral case in for

¹⁷⁸ Trade balance increases reflect changes in total Self Financing Capacity (SFC) of domestic agents (firms, government, households) rather than improved international competitiveness (see Chapter 3).

instance promoting cleaner technology of production or possibilities for cost reduction for exporting non-energy intensive sectors.

Figure 5.2 Difference and composition of average resource prices for the multilateral vs unilateral Ct100 RVAT scenario



5.4. In or out of the “Carbon Club”

Approach to modelling foreign carbon-Border Tax Adjustment

A particular aspect not included in RP is the possibility that other countries apply Border Tax Adjustment (BTA) if South Africa does not implement a carbon tax, while the Rest of the World (ROW) does. This is the idea of a “carbon club”: Countries that have a carbon tax apply an additional import tariff on products from countries that do not have one. Theoretically, the consequence is lower exports for the sanctioned countries, creating economic disadvantages that push non-participating countries to joining the club. This section therefore analyses the economic impacts of carbon-based BTA imposed by South Africa’s trading partners, with two scenarios:.

- \$55 Ctax BTA:** a carbon-BTA is applied by ROW on South African exports. This is modelled by increasing the export price as “perceived” by ROW in the Armington specification for trade (see section 3.2.2) with a charge of 55 USD₁₃/tCO₂ (converted to ZAR₀₅). The basis for the calculation of the BTA levy is the direct and energy-sector indirect CO₂ emissions per product (see section Table 4.1). This scenario assumes that South Africa’s trading partners also apply a carbon tax rate equivalent to 55 USD₁₃/tCO₂ – which is equivalent to 300 ZAR₀₅/tCO₂ – in their own countries;
- Aggressive BTA:** Due to the possibility that the impact of a foreign BTA is too small to create sufficient economic disadvantage for South Africa to force it in joining the carbon club a second scenario is developed. In this case, the “aggressive BTA” case, South Africa’s trading partners try to coerce South Africa into implementation of a carbon tax by levying a sufficiently heavy BTA, while applying moderate R300/tCO₂-equivalent carbon tax

themselves. Trial runs have shown that an aggressive BTA of 200 USD₂₀₁₃/tCO₂ (equivalent to a Ctax 1,000 ZAR₂₀₀₅/tCO₂) could have this effect. This is the case discussed here.

Each scenario has two variants: One with the assumption that international carbon taxation can be recycled in such a way that there is no impact on international prices (relative to BY and RP), and another case in which the international carbon tax regime by ROW increases international prices relative to RP in about the same way as domestic prices on average for the eight main carbon tax scenarios with a R300 Ctax (as in Table 5.2 above).¹⁷⁹

Price impacts of carbon-BTA

Before discussing results and their explanation in detail, one must realize that price increases due to a R300-equivalent carbon-BTA are (*ex ante*) relatively small for many South African energy products, because energy only consists of a minor part of their production costs (recall Table 3.2 in section 3.1.1). An *ex ante* price impact is calculated on the basis of the direct CO₂ emissions per unit in production of GAS, REF, ELC and TRA; direct plus indirect CO₂ emissions from ELC production per unit of COA; and direct + indirect emissions of energy sectors and transport services per unit in production of EIN, MAT, LSS and HSS.

The result of this calculation also shows (Table 5.4) that the *ex ante* price impact of a \$55/tCO₂ carbon-BTA levy on South African export prices by 2035 (compared to RP) is relatively small for most products. (However, with 8% it is non-negligible in the case of the biggest export sector: EIN.) For energy products the price increase due to a \$55/tCO₂ carbon-BTA levy is similar, namely 2% for COA, and 10% for REF, while the 57% for ELC does really count, because ELC forms only 1% of South African exports value in RP.¹⁸⁰ In the aggressive carbon-BTA case with a \$200/tCO₂ carbon-BTA levy the larger *ex ante* impact on export prices is proportional to the ratio of the \$200 over \$55 per tonne CO₂ BTA levies.

For MAN, LSS and HSS export prices increase between 4% and 7% compared to their value under a multilateral R300 equivalent carbon tax regime with RTSC revenue recycling, and they are bigger than when they are compared to RP (Table 5.4, see also section 5.3 for the description of the multilateral carbon tax scenario). For TRA, EIN and energy sectors however the increase in export prices is smaller under a \$55/tCO₂ foreign carbon-BTA levy than under a multilateral carbon tax regime, with for EIN only a 3% increase. The reason of the difference in relative prices is that revenue of a domestically applied carbon tax can be recycled in such a way that costs other than energy costs are reduced, as is the case for revenue recycling into labour subsidies in the RTSC scenario (Table 5.4). A foreign carbon-BTA levy does not offer this possibility.

¹⁷⁹ A reason for which international prices in theory would not rise could be the use of export rebates by countries applying a carbon tax, another reason could be sufficient technological change to absorb the cost increases due to the use of fossil energy.

¹⁸⁰ The estimated carbon content for BTA might underestimate the height of the BTA due to taking into account only the “carbon footprint” beyond a sector’s direct energy consumption and/or that of the energy sectors and TRA which supply transformed energy or services to a sector. If second degree carbon content and beyond would have been taken into account, the emission content of South African products would likely be somewhat higher, but the simplifying assumption is made that this difference will be negligible. Another caveat is that the *ex ante* number does not yet take into account economic equilibrium effects such as a change in the real effective exchange rate (REER).

Table 5.4 Ex ante price impacts BTA on export prices (pX) for RP, compared to ex post impact on pX of R300 Ctax for RTSC

	COA	REF	ELC	EIN	MAN	LSS	HSS	TRA
Ex ante change pX vs RP with BTA \$ ₁₃ 55/tCO ₂	+2%	+10%	+57%	+8%	+2%	+2%	+1%	+3%
Ex ante change pX vs RP with aggressive BTA (\$ ₁₃ 200/tCO ₂)	+7%	+38%	+209%	+30%	+8%	+8%	+3%	+12%
Ex post change in pX vs RP for R300 multilateral Ctax + RTSC recycling	+0.4%	+14%	+32%	+5%	-2%	-4%	-6%	+4%
Difference ex ante chg pX BTA \$₁₃55/tCO₂ vs ex post pX multilateral	+1.6%	-4%	+19%	+3%	+4%	+6%	+7%	-1%

Results

Results of the carbon-BTA scenarios show that the Rest of the World needs to use the aggressive carbon-based BTA levy on South African exports' CO₂ content to make joining a “carbon club” economically more attractive than “free riding” on others' climate change mitigation efforts. The reason for this outcome is that exports are only a minor component of total demand and that domestic demand decreases less from a foreign carbon-BTA levy than due to domestic carbon taxation. Only a foreign carbon-BTA at a rate of 200 USD₂₀₁₃/tCO₂ manages to seriously reduce total demand for South African products, and hence South Africa's output and GDP, and its employment even more.

The economic impacts for South Africa of a 55 USD₂₀₁₃/tCO₂ carbon-BTA levied by ROW on South African products are similar to those of a 100 ZAR₂₀₀₅/tCO₂ domestic carbon tax in combination with revenue recycling into labour subsidies (Table 5.5). For a 55 USD₂₀₁₃/tCO₂ carbon-based BTA by ROW the South African *per capita* GDP in 2035 turns out between 57 and 59 kZAR₂₀₀₅ in 2035, respectively when ROW's own prices stay the same or increase due to the carbon taxes levied in ROW. This is at the same level as the 59 kZAR₂₀₀₅ per capita in RP and the 57 kZAR₂₀₀₅ in the Ct100 RTSC scenario with international equivalent carbon tax . Unemployment increases relative to RP in case of a 55 USD₁₃/tCO₂ carbon BTA (Table 5.5).

A carbon-BTA levied by South Africa's trading partners will have similar impacts on GDP growth and employment as an international 300 ZAR₀₅/tCO₂ equivalent carbon tax when its rate is about 200 USD₁₃/tCO₂ (carbon content) or higher. This is shown in the aggressive carbon-BTA case: *per capita* GDP turns out between 52 and 54 kZAR₂₀₀₅, respectively depending on whether international carbon taxation does or does not lead to international price increases relative to BY. Broad unemployment ends up between 31% and 34%, meaning well above that of the case of an international 300 ZAR₀₅/tCO₂ equivalent carbon tax in which South Africa joins (Table 5.5). Furthermore, despite that BTA by ROW is not meant to reduce South Africa's CO₂ emissions, it does achieve a decrease relative to RP with CO₂ emissions ending up between 574 and 677 Mt depending on the height of the BTA rate, and on what happens to international prices (Table 5.5). Of course, South Africa does not get anywhere near achieving its NDC (see section 5.2) without implementing a CO₂ tax domestically.

Table 5.5 Change in key results vs RP for BTA and comparable multilateral Ctax scenarios

	Per capita GDP (chg vs RP) <i>kZAR₀₅ /cap</i>	Broad unemployment <i>pct of broad active pop.</i>	CO ₂ emissions <i>Mt CO₂</i>	CO ₂ intens. of GDP <i>kgCO₂ /ZAR₀₅</i>	REER relative to RP -	Trade balance as pct of GDP -
Reference Projection	59	24%	687	1.06	1.00	3.4%
Ct100 RTSC with internat. Ctax \$18-eq	57 (-3%)	26%	550	0.88	1.02	3.4%
Ct300 RTSC with internat. Ctax \$55-eq	54 (-9%)	29%	395	0.67	1.05	3.3%
Foreign BTA\$55 + pM incr R300 Ctax-eq	59 (-1%)	25%	677	1.05	1.00	3.4%
Foreign BTA\$55 w/o pM increase	57 (-3%)	27%	653	1.04	0.98	3.4%
Aggressve foreign BTA + pM incr R300 Ctax-eq	54 (-9%)	31%	602	1.02	0.95	3.4%
Aggressive foreign BTA w/o pM increase	52 (-13%)	34%	574	1.01	0.93	3.4%

Discussion

The reason that a BTA needs to be aggressively high for foreign carbon-BTA to be economically more disadvantageous for South Africa than applying a carbon tax domestically lies in the fact that the combination of the average price impact and import substitution related to devaluation of the Rand make the change in domestic demand much smaller than the change in exports of energy-intensive products, meaning that domestic demand is less affected than exports.

This can best be shown by looking at the impact that the aggressive foreign BTA has on South African output: Despite a strong decrease in export volume for EIN of 39% relative to RP, the volume of domestic output of EIN only decreases 22% (Table 5.6). For REF a similar observation can be made (ELC exports are very small in absolute terms and can be ignored). Of course, results also show that COA, LSS and HSS sectors see their domestic output decrease more than their volume of exports under an aggressive foreign BTA relative to RP, whereas for TRA and MAN exports and domestic output decrease at about the same rate relative to RP (Table 5.6). However, what counts is that the decrease in export volume in these sectors is much smaller than for EIN and REF, and relatively small even for an aggressive foreign carbon-BTA. The average decrease in export volume relative to RP is therefore only 21% when weighed by sector's shares in export value in RP.

Furthermore, import substitution, which is caused by a decrease of 7% in the REER (Table 5.5), contributes to keeping demand for South African products high. The change in the REER itself, is opposite to what happens in the case of multilateral carbon taxation, as discussed in the previous section. The current account and broad capital account elements of the Balance of Payments do not change much, as in all other scenarios and the trade balance surplus is therefore unaltered compared to RP (Table 5.6). The decrease in export volume this needs to be countered by a devaluation to reduce import dependence, as for instance is strongly the case for OIL (affecting REF) and MAN.

Together, the only moderate decrease in export volume (f 21%) and import substitution lead the

average change in demand for domestic output to decrease not very much, as is reflected in the decrease in the volumes of investment (12%), intermediate consumption (11% to 14%) and government FC (13%), which are all rather constant over GDP, relative to RP (see Table 5.6). Indeed, these changes are similar to the change in *per capita* GDP (-13%) for the aggressive BTA case (see Table 5.5). Obviously, the correct but much lower carbon-BTA levy of 55 USD₂₀₁₃/tCO₂ would have more trouble depressing South African output than the aggressive BTA case.

Table 5.6 Change (vs RP) in volume of supply or demand for Aggressive BTA case without international *pM* increase

	COA	OIL	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
Supply volumes										
Dom. output, Y	-12%	-	-18%	-17%	-17%	-22%	-7%	-12%	-12%	-12%
Imports, M	-16%	-18%	-22%	-22%	-19%	-36%	-29%	-21%	-25%	-20%
Demand volumes										
Exports, X	-5%	-	-	-39%	-26%	-39%	-7%	-6%	+10%	-11%
Investment, I	-	-	-	-	-	-12%	-12%	-12%	-12%	-
Household FC	-	-	-	-12%	-10%	-16%	-17%	-17%	-14%	-11%
Government FC	-	-	-	-	-	-	-	-	-13%	-
Intermed. Cons., IC	-17%	-18%	-19%	-13%	-19%	-14%	-11%	-11%	-12%	-13%

Still, some caution needs to be maintained in interpreting these results. First of all, because the scenarios presented here do not take into account a potential reduction in coal exports following the introduction of carbon taxes in export markets for South African coal. Secondly, it is possible that Armington price-elasticities used for international trade in this study underestimate the price-elasticity of trade for the long-term projection period of 30 years and the relative size of price fluctuations given here. A reason why I think under-estimation of price elasticities is likely is that there are likely no historical equivalents of such long-term disadvantage price developments and the a 30 year time period might allow importers to look for and find alternative suppliers to substitute South African products in their supply chain. If that were the case, foreign BTA could have a bigger impact on South Africa's GDP growth than estimated here. Nevertheless, such substitution would not be capable of preventing devaluation of the South African Rand, which has been observed to partly reduce the impact of the BTA.

5.5. Enhanced energy efficiency scenario

Gains in energy efficiency obtained in the scenarios analysed above differ between carbon tax rates, revenue recycling mechanisms, and sectors. These efficiency gains are an outcome of both the way trade-offs have been defined through KLEM nested CES production functions, and of the chosen elasticities of substitution (see section 3.2.1), and also reflect changes in relative prices between inputs and factors. They however do not necessarily reflect the future potential for energy efficiency gains

when taking into account technical, economic and social constraints that could be found by the use of bottom-up models. The evaluation of how realistic these energy efficiency gains are can only be performed *ex post*, meaning after scenario runs have been completed. It could possibly figure as the basis for a future update of model calibration.

This section therefore presents a sort of sensitivity analysis on some parameters that are important in determining energy efficiency outcomes. The analysis starts by comparing energy efficiency gains found for RP and the main Ctax scenarios with estimations of socio-techno-economic potentials for energy efficiency obtained from scientific and “grey” literature. As an outcome of this comparison an alternative scenario for energy efficiency is defined and implemented under similar conditions to RP and some of the Ctax scenarios and evaluated for its impact on scenario results.

5.5.1. Energy efficiency gains in RP and main Ctax scenarios

In RP and the main Ctax scenarios there is a wide range of energy efficiency gains, measured as changes in intensity of energy use, in volume of energy inputs over a sector’s volume of output (Y). This is calculated for each energy input (COA, OIL, GAS, REF, ELC). The lowest energy efficiency gains (1% to 4%) are obtained in the GAS, REF and TRA sectors (Table 5.7). These sectors are characterised by low elasticities of substitution between the energy-aggregate and the capital-labour aggregate. The highest energy efficiency gains (30% to 37% in RP) are found for MAN and HSS, which can be explained by high elasticities of substitution, and a relatively strong increase in the electricity price, with electricity being the energy carrier they consume most and more than other sectors. With carbon taxation efficiency gains for MAN and HSS become 51% and 58% respectively.

Gains in energy efficiency in IMACLIM-ZA’s RP and main Ctax scenarios are the consequence of trade-offs between energy inputs on the one side, and non-energy inputs and factors of production on the other side (see section 3.2.1). These trade-offs result in RP from price increases for energy in combination with productivity gains in terms of materials & services, capital and labour leads to a relatively lower attractiveness of energy as an input. The gains in energy efficiency shown in Table 5.7 are thus the result of substitution effects. No additional factor-biased technological progress has been assumed. In the case of carbon taxation, the increases in costs for energy and therefore the substitution effects are stronger than for RP (see section 4.2).

Table 5.7 Change in energy intensity of production for RP and main Ctax scenarios* (in PJ per unit of output)

	COA	GAS	REF	EIN	MAN	LSS	HSS	TRA
RP	-15%	-1%	-3%	-11%	-30%	-22%	-37%	-4%
Ct100 main scenario avg	-19%	-2%	-3%	-15%	-41%	-28%	-48%	-5%
Ct300 main scenario avg	-21%	-3%	-3%	-18%	-51%	-34%	-58%	-7%

* OIL is assumed to have no domestic production, ELC’s energy efficiency is derived from BU-modelling.

5.5.2. Estimation and comparison of energy efficiency potentials

Global potentials for energy efficiency gains have been estimated. For instance, Allwood *et al.* (2011) estimate potentials for energy efficiency gains from improvements in production processes. Their estimates range between 23% and 40% for the five materials which together account for a bit more than half of 2006 global industrial CO₂ emissions (steel, cement, plastics, paper and aluminium). All these materials except paper are part of the EIN sector in IMACLIM-ZA. Allwood *et al.* consider further gains in energy efficiency possible, for instance through operational improvements and supply-chain re-design. To what extent the quoted potentials hold for South Africa is not clear. However, for steel production the IEA (2008) estimated that South Africa's energy efficiency potential was similar to the global average.

For South Africa, potentials for energy efficiency gain can be obtained indirectly from a report by the Department of Environmental Affairs (DEA, 2014), who performed a study of the techno-economic potential for greenhouse gas mitigation measures by sector.¹⁸¹ Measures consist partly of fuel switching (for example from coal to gas, or to biomass), but mostly concern reductions in energy demand (increased energy efficiency). The latter category ranges from measures such as improved motor-speed regulation in industry to a modal shift from private vehicles to public transport for passenger transport. The greenhouse gas emission saving potential is relative to a reference, called the WEM scenario ("with existing measures"). In calculating the greenhouse gas saving potential of measures the study tries to avoid double-counting of emission-saving potentials from overlapping measures, although DEA states that this could not be avoided in all cases, especially at the inter-sectoral level (DEA, 2014).

It is hard to calculate an energy efficiency index for South African industries for two reasons: Firstly, the indicator used for results is highly aggregated and expressed as total CO₂-equivalent greenhouse gas emission reduction potential with estimated costs per tonne of CO₂; Secondly, the level of sectoral aggregation in their study is very high, for example: the entire chemical industry, or the entire (non-coal) mining sector. Nevertheless, translation of DEA study results into estimates of energy efficiency potentials is considered acceptable for sensitivity analysis and as an indication for the order of magnitude of such gains.

The DEA study presents greenhouse gas emission-saving potentials against an increasing carbon tax rate. Sector-specific CO₂-equivalent (CO₂-eq) greenhouse gas emission saving potentials can be compared to sector specific reference (WEM) CO₂-eq projections. The most straightforward approach is to assume the entire mitigation potential up to a certain carbon price to be implemented. Meaning that the share of emission reduction potential in reference CO₂-eq emissions (excluding fuel switching measures) can be considered an indicator of sectoral average energy efficiency gains. (Some further

¹⁸¹ Other studies on energy efficiency in South Africa are available (CAMCO and TIPS, 2010; Genesis, 2010; Winkler and Marquard, 2012), but could not be (readily) translated into absolute or relative energy efficiency gains by sector. A full technology assessment by comparison of the different studies is beyond the scope of this thesis.

detail on estimates of energy efficiency potentials with DEA (2014) can be found in Appendix C.7.)

Sectors as defined in IMACLIM-ZA do not match the sectors analysed in DEA (2014) exactly, but there is considerable overlap, although some sectors are not analysed in DEA’s study, and on the other hand a part of DEA’s technology assessment, notably on energy sectors, has not been included in the analysis presented here. Table 5.8 below presents the assumptions regarding the correspondence between sectors in DEA’s analysis and IMACLIM-ZA.

Table 5.8 Correspondence between sectors in IMACLIM-ZA and in DEA (2014)

IMACLIM sector	Sectors in DEA(2014)	Assumption for match in energy efficiency potential
COA	DEA Appendix C not taken into consideration	Energy efficiency potential assumed equal to that of EIN
OIL	DEA Appendix C not taken into consideration	No domestic production assumed in IMACLIM-ZA
GAS	DEA Appendix C not taken into consideration	Energy efficiency potential assumed equal to that of EIN
REF	DEA Appendix C not taken into consideration	Energy efficiency potential assumed equal to that of EIN
ELC	DEA Appendix C not taken into consideration	Energy efficiency and fuel switching based on outcomes of BU modelling of the SATIM model (see section 3.1.3)
EIN	Metals, Minerals, Chemicals, and Mining (non coal)	Average CO ₂ emission intensity decrease is interpreted as energy efficiency gain, and weighted by 2010 output share.
MAN	Only Paper & Pulp industry available in DEA(2014), no other manufacturing	Energy efficiency potential assumed equal to that of EIN
LSS	Construction, and energy use in Agriculture are not included in DEA(2014), but DEA's Commercial buildings sector can be considered to cover Hotels&restaurants, and Trade&retail	The average of EIN and Commercial buildings energy efficiency potentials are assumed to represent LSS's energy efficiency potential
HSS	Commercial and Institutional buildings sector	Commercial and institutional buildings is assumed to be equivalent to HSS
TRA	DEA's Transport sector, consisting of road, rail, and aviation, but excluding marine transport	Reductions of indirect emissions from electricity (for electrified transport, such as rail systems) are taken into account, modal shift too.

The energy efficiency potentials found differ more between sectors than between carbon tax rates (Table 5.9). For instance, for EIN the potential energy efficiency gain without a carbon tax is almost 20%, while at a R300 carbon tax rate this increases only to 25%; for HSS energy efficiency gains are estimated at 41% without a carbon tax, but they do not increase when a carbon tax is implemented (Table 5.9). A reason for this result could be that DEA (2014) assumes an already considerable Autonomous Energy Efficiency Improvement (AEEI) in its WEM scenario, and in addition finds a large share of the mitigation measures in the buildings sector to be possible for negative to zero costs. However, after implementation of CO₂ emission reduction options that have negative to zero costs, mitigation costs rise quickly to a cost equivalent to a carbon tax rate of 400 Rand/tonne CO₂ and higher. For the carbon tax rates chosen for analyses with IMACLIM-ZA, these additional mitigation

options are not taken into account, because the highest carbon tax rate evaluated is R300/tCO₂.¹⁸²

Table 5.9 Change in energy intensity (energy use per unit of output) of production estimated on the basis of DEA (2014)

	COA*	GAS*	REF*	EIN	MAN*	LSS**	HSS	TRA
No carbon price			-20%			-31%	-41%	-23%
R100/tCO ₂			-23%			-32%	-41%	-30%
R300/tCO ₂			-25%			-33%	-41%	-30%

*Energy efficiency potentials for COA, GAS, REF, and MAN are assumed the same as for EIN, which is derived from industry mitigation options in DEA (2014); ** Energy efficiency potential for LSS is assumed to be an average of HSS and EIN.

A comparison of the estimates of energy efficiency potentials with the energy efficiency gains obtained in IMACLIM-ZA (Table 5.7) shows that for EIN and TRA that the efficiency gains estimated on the basis of DEA (2014) are higher than those found in scenario results of IMACLIM-ZA. They are found to be similar for HSS without a carbon tax, and lower for HSS with a carbon tax, as well as for MAN and LSS with and without a carbon taxation. Were these estimates based on the DEA study correct, then the price elasticities assumed for RP and carbon tax scenarios in IMACLIM-ZA (for 2005-2035) would be too low for EIN and TRA and too high for MAN, LSS and HSS. Moreover, the low responsiveness (and even non-responsiveness in the case of HSS and TRA) to carbon pricing of energy efficiency in IMACLIM-ZA's scenario results would be equivalent to having inconstant price elasticities.¹⁸³

5.5.3. Methodological choice to model alternative energy efficiency gains in IMACLIM-ZA

Apart from using exogenous technological coefficients as applied to the ELC sector, two options are available in IMACLIM-ZA to change projections for future energy efficiency: 1. Changing CES price elasticities, especially between energy (E) and the capital-labour composite (KL), to alter the response to changes in relative prices; 2. Changing (non factor-neutral) assumptions about future factor and input productivity (or its inverse: factor or input intensity).

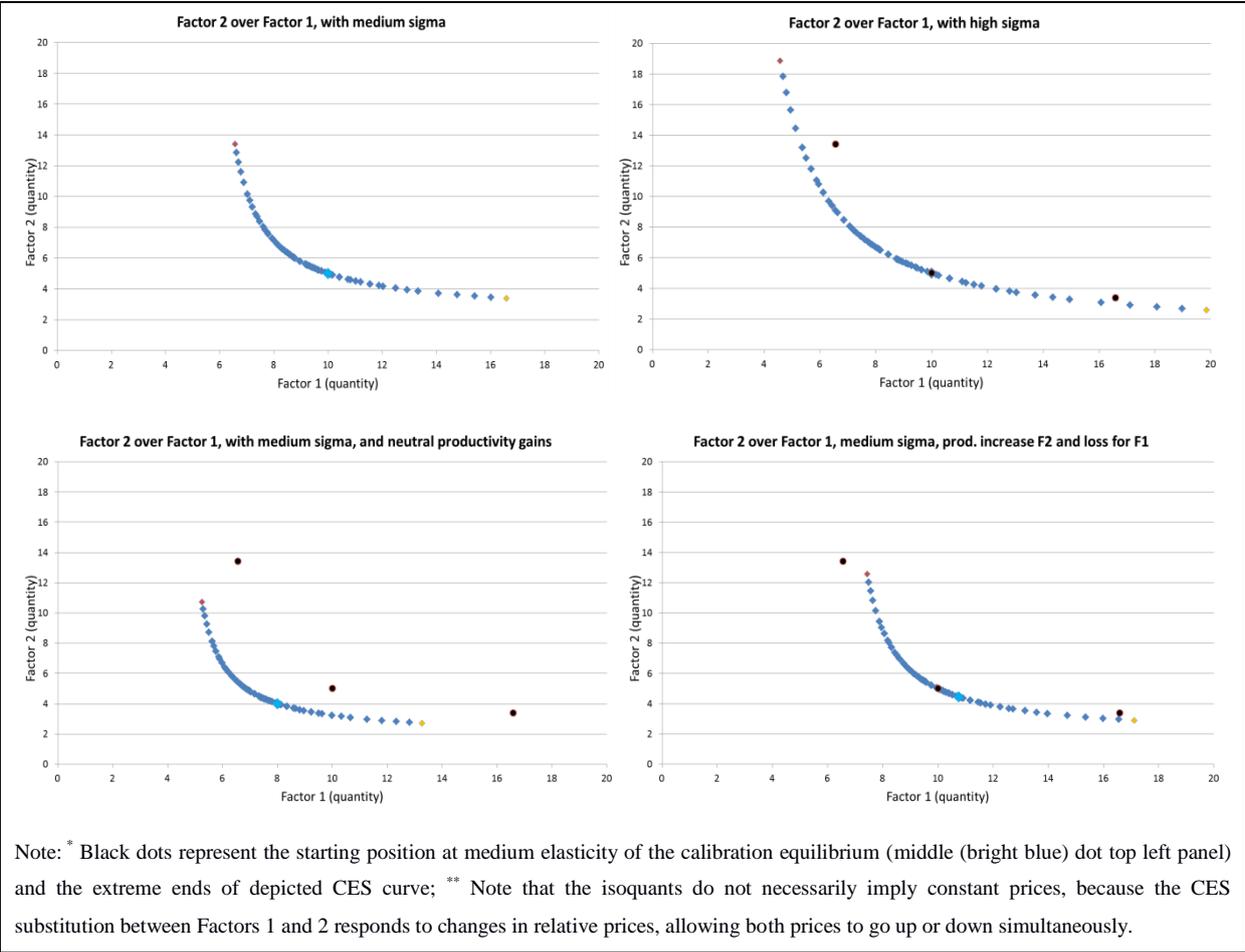
Both options differ in the absolute and relative changes in factor intensities that they obtain. In the first case (price elasticities change), a change in overall productivity and a reduction in costs of production can be achieved *if* the elasticity of substitution between energy and other components is bigger than unity, *and* if the change in relative prices is such that average factor or input costs decrease. In the second case (exogenous decrease in energy intensity), an increase in overall (or average) factor productivity is guaranteed, unless the increase in productivity of energy inputs is accompanied by a decrease in productivity in other factors (e.g. energy replaced by using more capital).

¹⁸² In reality, Marginal Abatement Cost Curves (MACCs) at the aggregate level of sectors of both IMACLIM-ZA and DEA (2014) are probably more gradual and would therefore show gradual improvement in energy efficiency with a carbon tax rate. A justification for more gradual MACCs is reasonable for big sectors with many companies: Due to differences in circumstances between companies within a sector, energy efficiency investments for the same measure will vary in costs too. A better estimation of this gradual character of MACCs is unfortunately out of scope for this thesis.

¹⁸³ Of course, as mentioned, the DEA study is probably unable to capture the gradual evolution of sectoral mitigation costs in MACCs due to the use of *average costs* for a specific measure by sector, which means that for big sectors with multiple companies price elasticities would be smoother in reality than what a MACC curve can capture.

For example, imagine the top left panel in Figure 5.3 describes an initial elasticity of substitution between two factors. Were this elasticity to increase, then the exchange between factors compared to the original equilibrium will be stronger (top-right panel in Figure 5.3), but there will not necessarily be a gain in productivity. However, if there are factor neutral productivity gains (bottom-left panel), the shape of the curve (the elasticity) does not change, but both factors will be needed less in production. In case one uses changes in productivity to model substitution between factors (bottom-right panel – increasing productivity of Factor 2 while decreasing productivity of Factor 1 equivalent to original value shares) the effect is clearly different from the increase in substitution elasticities shown in the top-right panel.

Figure 5.3 CES isoquants of output Y with different elasticities or changed productivity^{*,**}

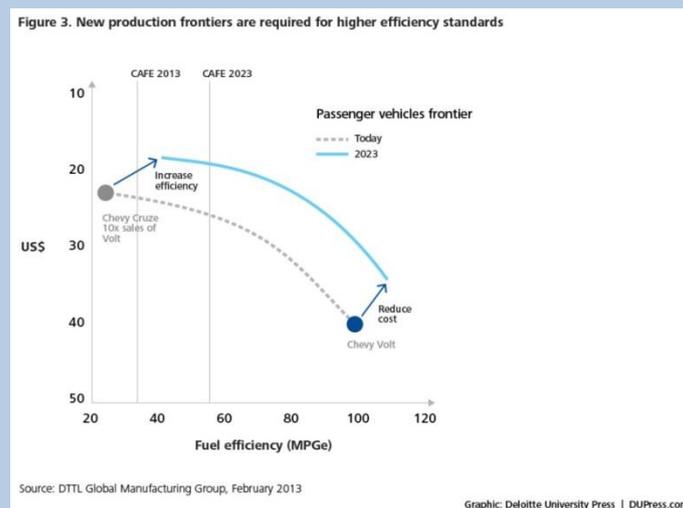


The outcomes of the DEA study (DEA, 2014) suggest that a part of energy efficiency gains is economically profitable or “free”, while still demanding up-front investments. Technically speaking this implies net cost-reducing productivity gains. Another part of energy efficiency gains, however, is only realized in a situation of (explicit or implicit) carbon pricing. In the latter case, productivity gains over energy use (energy intensity reductions) come at the cost of increased intensity in other factors or inputs. (This resembles the change between the top left and bottom right panel in Figure 5.3.) Whether such “free” productivity gains exist has not been studied here, but Box 6 provides a brief discussion.

Box 6 "Free" energy efficiency gains in practice

Whether present-day energy efficiency gains are profitable depends partly on the method to calculate profitability. It is common to calculate the net present value (NPV) of an investment in energy efficiency. Profitability will depend on the height of savings on energy-spending and other costs versus the height of the investment, the duration of the write-off period and the discount rate. Another relevant aspect is expectations about future energy prices. In MACCs, net profitable investments will be shown as options with negative *costs*, as for instance for some measures in DEA (2014). Technological progress should expand the amount of net profitable energy efficiency investment options. Such “free” (meaning profitable, or (net) more productive) energy efficiency then becomes part of the technological horizon. An example of how combined energy efficiency and productivity gains could look like – i.e. more efficiency against similar or lower capital costs – is shown in Figure 5.4 for an assessment of private vehicle technology. Dickson *et al.* (2013) foresee cost decreases of vehicles in parallel to energy efficiency gains to meet energy efficiency standards for different cars.

Figure 5.4 Prospective energy efficiency and production costs for different Chevy cars (Source: Dickson et al. (2013), permission by DTTL University)



Initially, evidence pointed towards *price-inelastic* energy efficiency gains, called “Autonomous Energy Efficiency Improvement” (AEEI). However, closer inspection shows that it is mainly *irreversibility* of energy efficiency gains from periods of high energy prices that explains the “econometric existence” of AEEI (Grubb, 2014, Ch.6). Such irreversibility has for instance been proven for residential energy demand (Haas and Schipper, 1998). However, Grubb points out that also *non-price factors* influence energy efficiency (Grubb, 2014, Ch.4), something also found in innovation studies (see Grubb, 2014, Ch.10). Related concepts that show the inevitability of future, more profitable and more efficient technology are those of experience curves (BCG, 1970), and learning-by-doing (Arrow, 1962). Existence of such “hurdles” implies that “free” in economic terms does not mean that such gains do not require (policy) effort.

The previous suggests that the option of changing productivity exogenously is a more realistic way to represent long-term productivity changes in comparison to changing price elasticities. The use of exogenous productivity change has the advantage that it does not change the substitutability between factors at a given point in time, which would be the case if one would change elasticities of substitution. Changing elasticities of substitution might also create over- or under-sensitivity to price signals. Disadvantages of the use of exogenous productivity changes are that a correct estimation requires detailed information about how (for instance) in the future fuel costs are replaced by capital or labour costs. It could, for instance, imply analysing Marginal Abatement Cost Curves (MACC) by sector, as provided by DEA (2014). Unfortunately, this was out of scope for this thesis.

The approach in this section is therefore to exogenously correct only energy efficiency, and leave exogenous output productivity of capital and other factors unchanged. To this end, an Energy Efficiency Improvement factor (EEI) is introduced in the model, similar to factor productivity gains or the Autonomous Materials & services Efficiency Improvement factor (AMEI) presented in section 3.2.1 (see Eq.6 on p.81). Although the latter term is associated with energy efficiency improvements unexplained by changes in energy prices, here it is used to arrive at future energy efficiency gains as expected by bottom-up information from the DEA study (DEA, 2014). This solution is not perfect, because it provides energy efficiency gains “free of charge”, as mentioned. Also, CES substitution will cause uncalibrated or uncontrolled rebound effects. Yet, as a form of sensitivity analysis the scenario is useful to identify whether adjusted energy efficiency gains have strong impacts on the economic outcomes of scenario analysis.

To estimate the adjustment required in energy efficiency by sector so that energy efficiency outcomes match energy efficiency potentials derived from the DEA study, a two-step procedure is applied: An initial change in EEI is calculated on the basis of the direct difference between the annualized energy efficiency gain expected on the basis of DEA (2014) and the *ex post* annual energy efficiency gain obtained in RP or on average for Ctax scenarios at a specific Ctax rate. Applying this EEI in a scenario result, leads to new energy efficiency projections by sector, though still different from the envisioned ones because of CES rebound effects. The procedure is therefore repeated one more time, to better approximate the objective values. The analysis was not iterated anymore after this second round due to limitations in time, while additional precision seemed unnecessary in light of the already mentioned lack of a correct calibration on the basis of MACCs.¹⁸⁴ For the Ctax scenarios the analysis was only performed for the RTSC scenario.

The intermediate and finally applied exogenous EEI factors and resulting sectoral energy efficiency gains are shown in Table 5.10. Evidently, the resulting efficiencies are closer to the targeted energy efficiencies (Table 5.9). The EEI induces, in correspondence to the targets derived from the DEA

¹⁸⁴ More iteration with the methodology applied here would be needed to arrive at an EEI that achieves the energy efficiencies estimated on the basis of BU information of Table 5.9.

study, energy producing sectors (COA, GAS, REF) and energy intensive sectors (EIN, TRA) to obtain a higher future energy efficiency, while MAN obtains lower energy efficiency with the EEI (compare energy efficiency gains by sector obtained in Table 5.10 with those from Table 5.7). However, for several sectors (HSS, LSS and MAN) still quite some percentage points off from the targeted energy efficiency (see Table 5.9).¹⁸⁵ This is the consequence of price-elastic trade-offs in the production functions, which are difficult to correct, because these sectors are subject to high price elasticities.

Table 5.10 Average annual exogenous energy efficiency improvement (EEI) in enhanced energy efficiency scenarios

	COA	GAS	REF	EIN	MAN	LSS	HSS	TRA
RP 1 st round EEI	0.17%	0.69%	0.64%	0.33%	-0.46%	0.39%	0.19%	0.73%
RP final EEI	0.22%	0.71%	0.66%	0.43%	-0.62%	0.84%	0.58%	0.87%
Resulting RP EE	19.5%	19.7%	19.7%	19.3%	21.8%	24.4%	33.3%	22.5%
R100 Ctax 1 st round EEI	0.17%	0.80%	0.77%	0.35%	-0.88%	0.20%	-0.47%	0.98%
R100 RTSC final EEI	0.21%	0.82%	0.79%	0.44%	-1.30%	0.54%	-0.74%	1.16%
Resulting R100 RTCS EE	22.8%	23.0%	23.0%	22.6%	28.1%	27.6%	44.9%	28.9%
R300 Ctax 1 st round EEI	0.17%	0.87%	0.85%	0.32%	-1.45%	-0.05%	-1.14%	0.93%
R300 RTSC final EEI	0.18%	0.88%	0.88%	0.39%	-2.25%	0.08%	-2.18%	1.09%
Resulting R300 RTSC EE	25.2%	25.2%	25.2%	24.9%	34.3%	31.5%	55.9%	29.0%

5.5.4. Results with enhanced energy efficiency assumptions

As a result of energy sectors and energy-intensive sectors higher energy efficiency gains, GDP growth increases both in RP and in the RTSC Ctax scenarios, while unemployment decreases significantly. A possibly surprising outcome, and a good illustration of the rebound effect, is that there is less reduction in CO₂ emissions, but the positive result is that the CO₂ intensity of GDP turns out lower (Table 5.11).

For the impact of carbon taxation and its revenue recycling relative to RP, a small improvement is observed concerning GDP growth in the enhanced energy efficiency scenario: The negative impact on annual GDP growth of a carbon tax with RTSC revenue recycling (relative to RP) turns out around 0.1 to 0.2 percentage points (pct pt) lower in the energy efficiency scenario – which translates into 1.2 to 2.4 pct pt improvement of total GDP growth by 2035 (relative to also improved reference GDP). A similar improvement is registered for employment: The difference in broad unemployment rate with the reference is 1.5 to 2.6 pct pt less broad unemployment for the improved energy efficiency case (see Table 5.11), compared to the main Ctax scenario results in Chapter 4, or 1.8 to 3.1% of total

¹⁸⁵ As a consequence of production function trade-offs, energy efficiency is reduced for HSS in RP despite its positive EEI.

employment in the new reference case. These results are significant in the light of the relatively small differences in energy efficiency for South Africa's main economic sectors – typically only 2 to 7 pct pt difference for EIN, MAN, LSS and HSS (compare Table 5.10 above with Table 5.7). Of course, differences in energy efficiency of the enhanced energy efficiency scenarios with RP and the main RTSC scenario are considerable.

Table 5.11 Key outcomes of EE scenarios compared to RP and main Ctax scenarios

	Avg annual GDP growth	CO ₂ emissions	CO ₂ intensity of GDP	Broad unemployment rate	Class 5 / class 1 income ratio
<i>unit</i>	-	<i>Mt CO2</i>	<i>kg CO2/USD'13</i>	-	-
RP	2.7%	687	1.06	24.1%	44.6
RP with EEI	3.1%	692	0.97	17.4%	45.4
Ct100 RTSC	2.6%	542	0.88	26.7%	43.8
<i>vs RP w/o EEI</i>	-0.2%	-21%	-17%	+2.6 pct pt	-1.7%
Ct100 RTSC + EEI	3.0%	549	0.79	18.5%	44.9
<i>vs RP with EEI</i>	-0.1%	-21%	-19%	+1.1 pct pt	-1.3%
Ct300 RTSC	2.3%	377	0.67	31.8%	42.4
<i>vs RP w/o EEI</i>	-0.5%	-45%	-37%	+7.7 pct pt	-4.8%
Ct300 RTSC + EEI	2.7%	390	0.60	22.5%	43.6
<i>vs RP with EEI</i>	-0.3%	-44%	-38%	+5.1 pct pt	-4.0%

The positive impact on GDP growth in RP can be explained from decreased (GDP deflated) costs per unit of output. Due to energy efficiency gains in energy sectors and transports, their costs of production decrease (for RP with EEI, Figure 5.5). As a consequence, other materials and services can decrease their costs of production too, especially EIN. For MAN (even despite achieving lower energy efficiency than in RP due to the correction with the AEEI) and LSS the reduction in costs of energy and other inputs is compensated by an increase in labour costs. For HSS there is hardly any reduction in costs of intermediate consumption and labour costs increase due to increased labour intensity and higher real salaries (with lower unemployment). As a consequence of the efficiency gains in RP, unemployment is lower too, while inequality increases, due to strongly increased high skill salaries and higher interest rates (returns on equity). CO₂ emissions increase, but CO₂ intensity decreases in RP with enhanced energy efficiency (0.97 instead of 1.06 kg CO₂/USD₂₀₁₃).

For the Ct100 and Ct300 RTCS scenarios the impact of the EEI looks roughly the same. Compared to RP the RTSC scenario comes out slightly better than under projections without exogenous EEI improvements. All indicators show improvement, except absolute CO₂ emissions. The lower CO₂ intensity of GDP would allow the Ctax to be raised a bit to achieve a similar CO₂ emission reduction as in the scenario without additional EEI, while still obtaining a higher GDP and lowering

unemployment. Of course, real exchange rates, and the costs of imports within total resource costs are relevant too, but this turns out to hardly change the resulting prices in the scenarios analysed here, and the total impact on the resource price shows the same pattern as that of the producers price (Figure 5.5). (Changes in resource price p roughly equal changes in average price of IC and FC , as product taxes do not change in these scenarios.)

Figure 5.5 Changes in producer's costs per unit by component, RP with EEI vs RP

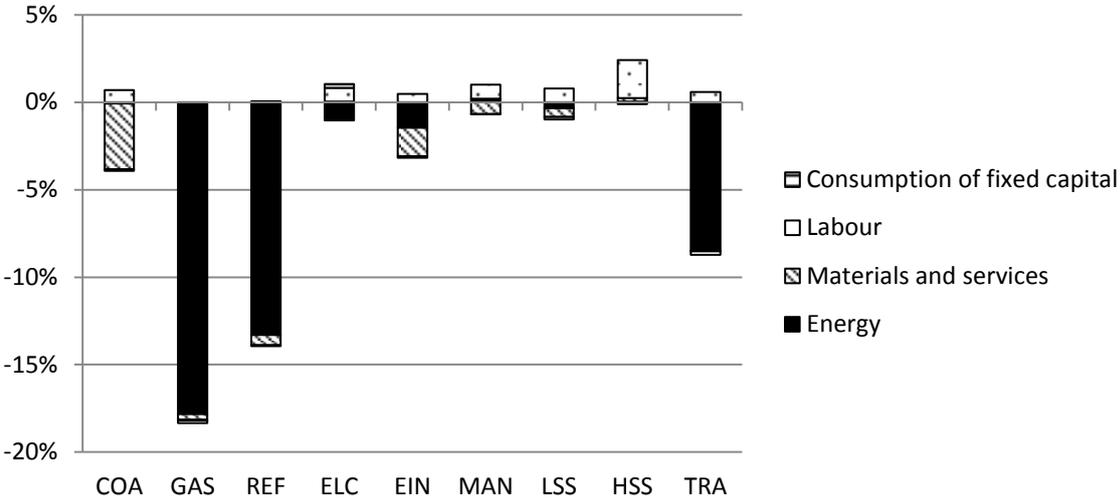


Table 5.12 Change in pY , pM and average (resource) price p for RP and RTSC scenarios, with EEI vs without EEI

	COA	OIL	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
pY in RP	-3.2%	-	-18.4%	-13.9%	-0.0%	-2.7%	+0.3%	-0.2%	+2.3%	-8.2%
pM in RP			+0.7%					+0.7%		
Avg price p in RP	-3.2%	+0.7%	-13.5%	-13.9%	-0.0%	-2.5%	+0.4%	-0.2%	+2.2%	-7.4%
pY in Ct100 RTSC	-4.7%	-	-21.4%	-16.8%	+0.0%	-3.6%	+0.6%	-0.2%	+2.9%	-10.9%
pM in Ct100 RTSC			+0.9%					+0.9%		
Avg price p in Ct100 RTSC	-4.6%	+0.9%	-15.3%	-16.7%	+0.0%	-3.3%	+0.7%	-0.1%	+2.8%	-9.9%
pY in Ct300 RTSC	-5.4%	-	-23.0%	-18.5%	+0.6%	-3.9%	+1.7%	+0.0%	+3.0%	-11.9%
pM in Ct300 RTSC			+1.8%					+1.8%		
Avg price p in Ct300 RTSC	-5.4%	+1.8%	-15.3%	-18.2%	+0.6%	-3.4%	+1.7%	+0.1%	+3.0%	-10.7%

5.5.5. Limitations to the alternative efficiency scenario and conclusion

A limitation of these results is that outcomes with exogenous EEI turn out to have a decrease in (physical) capital intensity for many sectors compared to outcomes without the exogenous EEI – notably those sectors with the highest energy efficiency gains (GAS, REF, TRA). This outcome is a consequence of the CES trade-off, which “rewards” energy for being a more efficient input to

production thanks to the EEI, and thus generates a rebound-effect towards energy use and away from other factors. Though rebound-effects are known to exist in consumer choices, it is unlikely that they correctly represent choices in average sectoral production technology. The common perception is that energy efficient technology comes at higher capital costs, at least when this energy efficient technology is still very new. Were capital costs to increase, then there would be less cost-reduction driven GDP growth and the alternative energy efficiency scenarios presented here would find lower GDP growth. The positive economic results of these EEI scenarios are therefore at best exaggerated. Further study is required to model energy efficiency gains in a more realistic way. Preferably, this is done through better BU model estimates of capital intensity or costs of energy-efficient technology.

Another limitation to the application of the energy efficiency potentials of the DEA study to IMACIM-SA is that “transaction costs” are excluded from the analysis presented here which only assumes that carbon tax rates determine implementation of measures.¹⁸⁶ However, difference in calibration or base year might compensate for this omission: Base years in DEA’s study are 2000 and 2010 for historic emissions and “existing measures”, its projection years are 2020, 2030, 2040 and 2050. Base year and projection year in IMACLIM-ZA are respectively 2005 and 2035. Because the objective is only to obtain a benchmark for potential gains in energy efficiency at a highly aggregate sectoral level, the simplifying assumption is made that cost-effective energy efficiency measures in 2030 will all have been implemented by 2035, assuming that the delay compensates for neglect of transaction costs.

This conservatism regarding assumed technological progress is taken even further by also assuming that the relative reduction in CO₂-equivalent emission intensity in the 20-year period between 2010 and 2030 in the DEA study can be translated into a relative energy efficiency gain in the 30-year period between 2005 and 2035 in IMACLIM-ZA. In this way, two assumptions that can be considered shortcomings in DEA’s study are compensated too, namely: First of all, the DEA study assumes higher economic growth than witnessed in recent years, or foreseen for the near future;¹⁸⁷ and secondly, the DEA study assumes no overlap between the Autonomous Energy Efficiency Improvement (AEEI) assumed in its “with existing measures” scenario (WEM) (calibrated on 2000-2010) (DEA, 2014 Appendix A) and the negative CO₂ mitigation cost options in the technology assessment part of the study (for industries, see: DEA, 2014 Appendix D).

In conclusion, these limitations mainly point at the lack of knowledge around the cost of technologically feasible energy efficiency gains for South Africa. At the same time, the results of the analysis presented here show that small changes in sectoral energy efficiency gains have a significant

¹⁸⁶ Transaction costs are aspects such as the availability and outreach of information, or other barriers to implementation, such as changing habits of citizens, consumers or the users of a service. DEA (2014) excluded measures with important transaction costs from its analysis in a first selection round of measures on the basis of Multi Criteria Analysis.

¹⁸⁷ Economic growth influences the amount of new economic activity, and therefore the share of new capital in the total capital stock, and thus the possibility to modernise and increase average energy efficiency. It might also influence the amount of investment available to invest in energy efficiency measures. GDP growth assumed in DEA’s medium growth scenario describes an average of 3.5% between 2010 and 2020, much higher than the average growth rate of 2.1% per year for 2010-2018, obtained when combining registered GDP growth from 2010 to 2015 (source: World Bank data) and economic growth forecasts for 2016 to 2018 (National Treasury, 2016). In IMACLIM-ZA’s RP relatively moderate average annual GDP growth of 2.7% per year (for the period 2005 to 2035) was obtained.

impacts on projections for GDP growth and the estimation of economic and environmental impacts of carbon taxation and its revenue recycling. This means that this is a very important for future research.

5.6. Sensitivity analysis

The sensitivity analysis in this sub-section provides a discussion of model parameters that represent the principal aspects for modelling economic growth (discussed in section 2.1), specifically: Technological change, particularly for the electricity sector (in sub-section 5.6.1), and through exogenous productivity gains for other sectors (in 5.6.2); The parameterisation of the labour market, in particular the wage curve (in 5.6.3); And finally, in a qualitative way, the possible impacts of changes in assumptions on international trade, and in government final consumption (in 5.6.4).

5.6.1. Technological change in the electricity sector

Introduction and approach

Costs and expected future costs for (photovoltaic) solar power generation have been sharply declining in recent years (Wright et al., 2017). A question is therefore whether this could change the results of the carbon tax scenarios analysed in this thesis. To test this, I model a change in the exogenous technological coefficients of ELC: The assumption is that by 2035 total capital costs of all renewable power generation capital is 33% lower than under the original updated IRP assumptions of the SATIM runs consulted for this thesis. In those runs renewables make up less than half of total capital amortisation costs, with other capital amortisation costs being those for nuclear power generation installations, for thermal coal power plants (which are under-utilised under carbon taxation), and for pumped storage facilities and transmission infrastructure. A 33% reduction in capital costs for renewables translates into approximately 12% lower capital amortisation costs for power generation and transmission in total, for both carbon tax rates and assuming no adjustment in future power generation capacity.¹⁸⁸ To simulate this, the technological coefficient for capital intensity of power generation is reduced by 12% in 2035. To limit the amount of scenario runs, this analysis is only performed for the Ct300 RTSC scenario, which is the economically best performing scenario that gets close to achieving South Africa's NDC.

Analysis of results

These changes result in a reduction of the average price of electricity of 4.9% compared to the Ct300 RTSC scenario. This has a positive impact on GDP growth (compared to the Ct300 RTSC scenario): GDP in 2035 turns out 1.7% higher compared to the Ct300 RTSC, and average annual GDP growth 0.06 percentage points. Broad unemployment decreases by 1.4 points, to 30.4%. On the other hand, CO₂ emissions increase by 2.3% relative to the Ct300 RTSC scenario, the CO₂ intensity of GDP turns out slightly higher (+0.6%), at 0.670 instead of 0.666 kg CO₂ per USD₂₀₁₃.

¹⁸⁸ Note that this is merely a test for the objective of sensitivity analysis and only involves the IMACLIM-ZA model. If the SATIM bottom-up energy system model would have been used to analyse future power generation, the impact on technological coefficients of ELC would likely be higher, due to the increased attractiveness of renewable power generation.

The reduction of the average electricity price translates into and the additional GDP growth combined cause aggregate energy use to increase by 1.9%. This increase in energy use which is higher than GDP growth can be explained from the energy-intensive style of GDP growth: Energy sectors and the energy-intensive industries & other mining sector (EIN) and transport sectors (TRA) see their output grow as much as GDP (1.7%) or more (Table 5.13): In particular ELC and EIN see their output volume grow strongly (with respectively 2.6% and 2.2% relative to the main Ct300 RTSC scenario).

Table 5.13 Change in Y due to 12% lower capital intensity of ELC, in the Ct300 RTSC scenario

	COA	OIL	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
Change in Y vs Ct300 RTSC	+1.7%	id.	+2.5%	+1.7%	+2.6%	+2.2%	+2.0%	+1.3%	+1.6%	+1.7%

The sensitivity of GDP growth to the price of electricity might be surprising. However, once one decomposes GDP growth, one observes that the decrease in electricity prices allows for an increase in the Domestic Income Multiplier (DIM, see section 4.2.1) with +0.4%, which is a consequence of on the one hand import substitution (the volume of Y+M over Y decreases 0.2%, item 2 in Table 5.14), and on the other hand an increase in the average value of goods and services supplied to the South African economy (+0.3%, see item 3 in Table 5.14) – representing structural change and growth in exports. In parallel, to maintain equilibrium on the Balance of Payments with the 1.7% additional GDP growth, the REER decreases 0.7% (recall the mechanism through which the REER adjusts with GDP growth in IMACLIM-ZA scenarios described in Box 5 in Chapter 4).

Table 5.14 Decomposition of GDP growth for Ct300 RTSC and its variant with reduced CFC costs for ELC

Item	1	2	3	4	5	6	7	8	9	10
Values are relative to BY	Per worker output volume (Y) ⁽¹⁾	Supply volume (Y+M) over Y / worker ⁽²⁾	Value of resources per unit of supply ⁽³⁾	Value of supply per worker ⁽⁴⁾	Decrease of costs per unit of GDP ⁽⁵⁾	GDP per worker ⁽⁶⁾	Active population ⁽⁷⁾	Employment rate ⁽⁸⁾	GDP ⁽⁹⁾	DIM
Ct300 RTSC	1.230	0.993	1.027	1.255	1.049	1.316	1.341	1.113	1.965	1.084
... & with CFC ELC -12%	1.230	0.992	1.030	1.256	1.048	1.317	1.341	1.132	1.999	1.089
Difference	+0.0%	-0.2%	+0.3%	+0.1%	-0.0%	+0.1%	id.	+1.6%	+1.7%	+0.4%

Comments: (1) Per worker output volume is calculated as the geometric mean of BY and projected GDP share weighted sectoral changes in labour output productivity vs BY; (2) Supply volume per worker is calculated in the same way as output volume per worker, but for Y+M now, and divided by output per worker; (3) Value of resources per unit of supply per worker is obtained by dividing the change in GDP deflated value of total resources by the total change in workers, it is divided by the change in supply per worker to obtain the change in value of resources per worker vs BY; (4) Value of supply per worker is the GDP deflated value of resources per worker and is equal to the multiplication of the previous three items; (5) The decrease of costs per unit of GDP is the reduction of the value of total resources relative to primary income (GDP); (6) GDP per worker is the multiplication of the previous two items; (7) The change in active population is assumed exogenously and the same for RP and all scenarios; (8) The employment rate is the change in employed population relative to the change in active population; (9) GDP (vs BY) is a RP and scenario result, and can be obtained by multiplying the previous three items; (10) The DIM is calculated by dividing the product of items 3 and 5 by item 2.

As explained in section 2.1.4, under the conditions of a constant trade balance and current account over GDP, the real source for growth is a decrease of primary factor prices relative to international prices. This is expressed by the decrease in the REER, and can also be seen from the change in the average price of labour. While the latter increases by 0.46% (deflated by the GDP price index), compared to the vector of international prices, it decreases by 0.36%. The latter can be explained from

the indexation of wages on the consumer price index, which decreases relative to most other prices thanks to the decrease of the electricity price.

That devaluation is one of the signs of GDP growth thanks to a decrease in electricity prices does not mean that changes in international trade fully explain the scenario results of this section. In fact, the decrease of the electricity price also leads to increased domestic purchasing power, and the volume of final consumption (FC) grows faster than exports (X) in all sectors, while intermediate consumption (IC) tends to have an in-between position, except for energy products, intermediary consumption of which grows faster than exports and FC. The latter is due to the decrease in electricity prices (energy carriers form a Leontief aggregate in IC, see section 3.2.1) and for COA the increase in electricity output (Table 5.15).

Table 5.15 Change in volume of FC, IC and X due to 12% lower CFC in ELC for the Ct300 RTSC scenario

	COA	OIL	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
Change in X	+1.2%	-	-	+0.6%	+1.5%	+1.8%	+0.9%	+1.0%	+0.9%	+0.6%
Change in FC	id.	-	-	+1.8%	+1.9%	+2.8%	+2.0%	+2.3%	+2.2%	+1.1%
Change in IC	+2.4%	+1.7%	+2.3%	+1.9%	+2.9%	+1.9%	+1.8%	+1.8%	+1.7%	+1.8%

Limitations and conclusion

It must be added that the result for CO₂ emission intensity is over-estimated, due to the simplified assumptions of this sensitivity analysis that only capital costs of renewable power generation change, but not the technology mix of power generation itself. As a consequence, coal use per average PJ of electricity remains the same, and the CO₂ intensity per PJ of electricity neither, while the price of electricity decreases. The latter encourages more consumption of electricity. Ideally, SATIM would be run again with the changed assumption about future costs of solar PV installations to obtain a completely new set of technological coefficients for ELC, likely leading to a lower emission intensity of power generation. In that case, it would be possible to assess whether the rate of emission reduction is stronger than the rate of increase in electricity consumption, which is a key element for future CO₂ intensity of GDP.

In conclusion, cheaper electricity is found to have a strong impact on economic growth, and cheaper renewable power generation therefore has a strong impact in the context of policies to reduce CO₂ emissions like a carbon tax. The impact on emission reduction itself could not be studied very well in this scenario, because no reduction in coal-consumption was assumed. The main question in that case would be whether decreased investment costs for renewable power generation lead to substitution of fossil fuel-based power generation, and whether this compensates for the observed rebound effect in energy demand. The latter requires a (slightly) higher carbon tax to compensate for the increase in CO₂ emission intensity of the economy.

5.6.2. Exogenous productivity improvements

A few tests of sensitivity analysis have been performed on parameterisation for productivity. The counterfactual analysis of investments in skills (section 4.5) already provided some insights into the sensitivity of results to this parameter. The analysis in this sub-section provides a less distorted sensitivity analysis of outcomes to exogenous productivity or efficiency gains compared to the analysis in section 4.5, in which productivity gains came at the cost of lower carbon tax revenue available for recycling with the objective to reduce other costs of production.

One of the remarkable findings in the latter analysis was that labour productivity by itself is insufficient to increase GDP *and* employment, even if labour productivity gains are not accompanied by additional wage gains. This section shows that the reason for this outcome is that labour productivity gains create insufficient additional purchasing power and enhanced international competitiveness. Labour productivity gains therefore insufficiently increase demand, which also explains that there is no additional employment. In brief, under the circumstances presented here they cause production and revenue to be concentrated in fewer hands.

The sensitivity analysis tests presented here are respectively: Doubling of the growth rates for the trends in capital productivity; the same for the trend in material & services efficiency; and doubling of the growth rate of labour productivity. These changes are not equal in terms of *ex ante* productivity increases, but as there is no sign of any non-monotonic trend in results of scenarios so far, these tests at least depict the direction in which changes in output productivity take GDP growth, employment and other key economic indicators.

The results of the tests show that the net effect of capital and material output productivity improvement is higher GDP growth with lower unemployment, while higher labour output productivity lead to higher GDP growth too, but with higher unemployment (Table 5.16). The CO₂ intensity of GDP decreases in all tests, even though hardly visible in the test on higher capital output productivity, in which case it turns out 0.1% lower than without the additional productivity gain.

To give some context to these results, a few indicators have been added to Table 5.16 to analyse what happens in the labour market. These indicators show that there is no difference in *ex ante* costs of equal “productivity-labour units”, meaning that at equal CPI and unemployment, the output of labour is equally expensive in all tests as in RP. *Ex post*, there are differences in labour output productivity, and especially in real wage, and therefore in *ex post* costs of “productivity-labour” units. The combination of these indicators shows that costs of labour mainly follow from wage-unemployment elasticity, meaning that something other than labour productivity assumptions plays an important role in determining GDP growth and employment outcomes. Furthermore, the resulting gross labour income share in Value Added is found to follow the unemployment rate too (similar to real wage over labour output productivity). This casts doubt on the usefulness and therefore the realism of the assumption of increasing wage claims relative to labour output productivity improvements, as a

mechanism to improve labour income's share in value added. Recall that net wage growth follows the “median” labour productivity trend, which turns out to be 6% higher than *ex ante* labour output productivity growth, see section (3.6). (In section 5.6.3 follows a more elaborate discussion.)

Table 5.16 Key indicators for sensitivity tests on factor and input productivity parameters

Scenario	BY	RP	K prod growth x2	Mat effic. gain x2	L prod growth x2*
Assumptions					
Labour output prod. trend	1.00	1.35	1.35	1.35	1.81
Capital output prod. trend	1.00	1.08	1.16	1.08	1.08
Mat. efficiency trend	1.00	0.93	0.93	0.86	0.93
Results (for key indicators)					
GDP index (BY = 1.00)	1.00	2.25	2.29	2.80	2.63
Broad unemployment	39%	24%	23%	11%	31%
CO ₂ emissions (Mt CO ₂)	443	687	698	811	781
CO ₂ int. GDP (kg CO ₂ /USD ₁₃ GDP)	1.54	1.06	1.06	1.00	1.03
Hh5 over Hh1 per capita income	42	45	45	46	47
Indicators for analysis					
<i>Ex ante</i> avg. L output productivity	1.00	1.27	1.27	1.27	1.62
<i>Ex ante</i> wage over L output index	1.00	1.06	1.06	1.06	1.06
<i>Ex post</i> ** L output prod. index	1.00	1.26	1.27	1.24	1.62
<i>Ex post</i> ** wage over L output index	1.00	1.18	1.19	1.35	1.14
Gross labour income share in VA	49.8%	52.7%	53.2%	56.1%	52.4%

* In this scenario wage gains by skill beyond the “median” productivity-wage trend of RP follow *ex ante* average productivity growth; ** The “*ex post*” labour output productivity index is not completely *ex post*, because it is calculated as the average of sectoral labour output productivity increases weighted by BY shares in GDP of sectors. Thus, the wage over L output index is only a close approximation.

To identify this underlying mechanism, a decomposition analysis of the sensitivity test results is undertaken. This decomposition analysis shows that whereas the labour productivity case results in an increase in output productivity of labour and in supply per worker relative to RP, it does not offer an advantage in terms of a real decrease in costs per unit of supply (Table 5.17). As a result, real income per unit of supply hardly increases, whereas the supply which can be bought with this real income gain can be realised by much fewer workers. The result is a decrease in employment for the labour productivity gains case. The material efficiency gains case offers the opposite type of development, with a decrease in supply per worker, but an increase in real income per unit of supply. As a consequence, unemployment is strongly reduced relative to RP (Table 5.17).

A few explanations can be given for the differences in change in real income per unit of supply. In the test with higher Mat efficiency none of the economic agents claims additional income for these productivity gains. This productivity gain therefore leads to a cost-reduction and to reduced average prices. This in turn causes real income gains for all agents (labour, capital and government alike) plus an improvement of international competitiveness. The latter can be seen indirectly in the reduction of the volume of supply (Y+M) relative the volume of domestic output (Y) (3rd column of Table 5.17).

On the contrary, in the test with higher labour output productivity, there is no reduction of average costs of supply, because labour claims all income gains related to the improvement of its output productivity. Without cost reductions elsewhere in the cost structure of supply, this means that all income benefits of productivity gains remain within the already employed labour force, as it generates no additional demand. In fact, due to the assumption of wages following median labour productivity gains, labour can be considered to claim an even bigger part of the cake in response to its output productivity gains. This causes a net increase in average costs of supply and therefore in prices, which has negative consequences for international competitiveness and domestic demand. (See the explanation of the impact of non-optimal factor prices in section 2.1.4.) Labour productivity gains relative to the standard prospective parameterisation (section 3.6.3) thus lead to higher unemployment.

Table 5.17 Decomposition of GDP multipliers for 2035 of results of sensitivity tests on factor and input productivity

	Output per worker*	Supply over output/worker*	Supply per worker*	Structural change***	Change in unit costs of supply	Change in income per unit of supply	GDP per worker	Change in employment	Demography	Total GDP multiplier
Reference Projection	1.26	0.98	1.24	1.04	1.06	1.09	1.35	1.24	1.34	2.25
K product. growth x2	1.27	0.98	1.24	1.04	1.06	1.10	1.36	1.25	1.34	2.29
Mat effic. gains x2	1.24	0.97	1.21	1.05	1.13	1.18	1.42	1.47	1.34	2.80
L product. growth x2**	1.62	0.97	1.58	1.04	1.06	1.10	1.73	1.13	1.34	2.63
Change relative to RP:										
K product. growth x2	+0.4%	-0.2%	+0.3%	+0.1%	+0.1%	+0.2%	+0.5%	+1.2%	<i>id.</i>	+1.7%
Mat effic. gains x2	-1.3%	-1.3%	-2.6%	+1.3%	+6.8%	+8.2%	+5.3%	+18.4%	<i>id.</i>	+24.7%
L product. growth x2	+28.8%	-1.2%	+27.3%	+0.5%	+0.0%	+0.5%	+27.9%	-8.5%	<i>id.</i>	+17.1%

* Weighted by the Base Year share in GDP. ** In this scenario wage gains by skill beyond the "median" productivity-wage trend of RP follow ex ante average productivity growth. *** This is calculated as the change in real (GDP price index deflated) value per unit of supply per worker over the before calculated growth in supply per worker.

The last test, increase of capital's output productivity is found to have a positive impact on employment. The explanation in this case is that labour is in general complementary to capital. Capital productivity gains thus make both capital and labour more attractive as factors of production, while the price of the physical capital good consists of its production costs, which do not increase. Add the assumption that profit rates are fixed mark-up rates over production costs, and one obtains total capital revenue per unit of production to decrease. Cost reductions, as had been shown before, lead to higher international and domestic demand. Capital output productivity gains are therefore both good for GDP growth and employment. They are furthermore good for returns on capital, because under the fixed profit mark-up rate assumption, profits increase relative to capital amortisation costs, and as non-reinvested profits increase the returns on capital relative to cumulative assets from past borrowing and lending, the rate of interests and dividends is found to increase as well.

Finally, impacts of productivity assumptions on CO₂ intensity of GDP should be briefly discussed as well. The discussion of the impacts of structural change on CO₂ emissions in section 4 had already

shown that materials & services efficiency had a significant impact on the CO₂ emission intensity of GDP. This does not require additional comments. The positive impact of labour output productivity growth on the CO₂ emission intensity needs to be explained from an indirect mechanism. Obviously, the wage increasing mechanism described just before does not lead labour to become more attractive as a factor of production. Instead, the cause for lower CO₂ emission intensity is indirect: The labour productivity gains in this sensitivity test can be seen to increase income inequality. With the richest household class spending a lower share of its income on energy and transport services, and a higher share on high skill services this leads to on average lower energy and CO₂ emission intensity per Rand of final consumption (even though their consumption is much higher on a per capita basis).

In summary, this sensitivity analysis confirms what was already shown in the counterfactual analysis of productivity gains for an investment in skills in section 4.5. Namely that improving capital productivity has a stronger impact on GDP and employment than improving labour productivity. The fundamental mechanism is that demand does not increase as fast as labour productivity due to the assumed strong wage increases with labour output productivity growth. However, materials and services (Mat) efficiency gains were found to be a the most efficient way to increase GDP growth, because they lead to cost reductions.

5.6.3. Ex ante productivity indexation of wages

The reference projection and the main scenario results in Chapter 4 have been obtained with the assumption that real wage follows the *median* cross-sectoral trend in labour productivity, which turns out to be higher than *average* labour output productivity growth. As mentioned, the objective is to reflect the idea that wages in all sectors change at about the same rate.¹⁸⁹ This increase of the cost of labour relative to its productivity (6% on average, see Table 5.18) was largely compensated by cost decreases (almost 6% as well) resulting from efficiency gains for materials & services inputs (see RP results in Table 5.16 and Table 5.17 above). However, this assumption turns out to be unfavourable for labour as a factor of production in its trade-offs with other factors and inputs. A consequence of increased labour costs is reduced domestic purchasing power and reduced international competitiveness. Analysis in sections 4.5.2 and 5.6.2 already showed the negative impact on employment results of this assumption.

The sensitivity analysis in this sub-section studies what happens if indexation on median cross-sectoral productivity growth is replaced by a lower productivity index. It is an *ex post* evaluation of an important assumption regarding the wage curve, but it could be used for a future model update.

For productivity-indexation of the wage curve (φ_{sk} in Eq.35 on p.93) the analysis presented here uses *ex ante average* sectoral labour output productivity factors by skill ($LPF_{i,sk}$), weighted by the shares of sectors' Base Year labour force ($LL_{i,sk,0}$), per level of skill (Eq.73):

¹⁸⁹ A possible justification for such an assumption could be that labour would want to negotiate higher wages to compensate for increased inequality and the reduction of labour's share in value added in recent decades (see section 3.6.2).

$$\phi_{sk} = \frac{\sum_i(\overline{LL_{i,sk,0}L_{PF_{i,sk}}})}{\sum_i(\overline{LL_{i,sk,0}})} \quad (73)$$

Due to structural change and trade-offs in production, *ex post* average labour output productivity still differs from *ex ante* labour output productivity.

Table 5.18 Comparison labour productivity indexation of wages for RP

	Wage indexation Ch.4			Sensitivity analysis index.			Change new vs Ch.4 L.prod index
	Median cross sectoral L prod	Avg ex post L share L prod RP	Diff. ex ante vs ex post	Avg ex ante L share L prod	Avg ex post L share L prod RP	Diff. ex ante vs ex post	
High skill	1.35	1.27	+6%	1.24	1.29	-4%	-8%
Med skill	1.35	1.23	+10%	1.28	1.20	+7%	-5%
Low skill	1.35	1.32	+2%	1.27	1.31	-3%	-6%

However, the difference is found to be smaller than for RP in results presented in Chapter 4: Table 5.18 shows old and new parameter ϕ_{sk} for RP together with the differences between *ex ante* and *ex post* values.

Results (Table 5.19) show that GDP growth is very sensitive to the relative evolution of the costs of a “productive” labour unit: GDP growth is 7% to 24% higher than for RP and main Ctax scenarios of Ch. 4, while broad unemployment decreases 7 to 14 percentage points. Employment grows faster than GDP, job intensity of GDP increases about 2% in all scenarios. CO₂ intensity of GDP decreases between 1.0% and 3.5%. Inequality, finally, increases for almost all scenarios, which can be related to GDP growth and unequal distribution of income, in particular for gross operating surplus, capital rents, and high skill labour income: These types of income are earned mostly by the richest household class (class 5).

What is remarkable in the results presented in Table 5.19 is that the scenarios which obtained low GDP growth in the main Ctax scenarios of Ch. 4, now see GDP, employment, and CO₂ intensity of GDP improves faster than the other Ctax scenarios. The difference in macro-economic results between carbon tax scenarios and RP is reduced: A lower indexation of wages thus leads to a reduction of the estimated size of the economic impacts of carbon taxation. For example, in the case of Ct100 RTSC scenario, a gap of 4% of RP’s GDP in Chapter 4 is reduced to 3% in this sensitivity analysis. While for the Ct300 RDEF scenario the net negative impact on GDP of carbon taxation (and its revenue recycling) is reduced from 32% in results in Ch. 4 to 22% in the sensitivity analysis here.

The explanation is that relatively high labour costs are an obstacle for the decarbonisation of the South African economy. With a lower productivity indexation of wages, a “productive labour unit” becomes cheaper. This effect is reinforced through the impact that labour costs have on costs of production and therefore on average prices of products. CPI indexation of wages (and multiplication via the matrix of intermediate consumption) further reinforces this positive or negative impact of under- or over-indexation of wages on productivity. In scenarios that do not reduce costs of production by carbon tax revenue recycling (RDEF, RSUM, RGOV and RTIF-fix) this multiplication effect of high labour costs can be expected to be stronger than in scenarios that manage to compensate the *average* increase of production costs due to carbon taxation.

Table 5.19 Results with more precise wage-labour productivity indexation, and change vs RP and main Ctax scenarios

Scenario	Avg annual GDP growth	Total 2005 - 2035	GDP change vs Ch.4 Results	Broad unem-employment	Jobs per mn ZAR ₀₅ GDP	Job int. change vs Ch.4 Results	CO ₂ em. (Mt)	kgCO ₂ /\$ ₁₃ GDP	CO₂ int. Change vs Ch.4 Results	HH5 / HH1 income	Ineq. change vs Ch.4 Results
BY (2005)	-	-	-	39%	7.8	-	443	1.54	-	42	-
New RP	3.0%	+141%	+7%	17%	5.9	+1.9%	728	1.05	-1.0%	45	+0.5%
Ctax rate 100 ZAR₀₅/tCO₂											
RDEF	2.7%	+124%	+12%	23%	5.9	+1.8%	563	0.87	-1.8%	44	+2.1%
RVAT	2.8%	+131%	+10%	20%	5.9	+1.9%	578	0.87	-1.4%	45	+1.3%
RGOV	2.8%	+126%	+11%	22%	5.9	+1.9%	562	0.86	-1.7%	44	+1.8%
RSUM	2.7%	+125%	+12%	23%	5.9	+1.9%	565	0.87	-1.7%	32	+1.1%
RTIF-fix	2.7%	+125%	+12%	23%	5.9	+1.9%	564	0.87	-1.7%	45	+2.2%
RTIF-low	2.9%	+134%	+9%	19%	5.9	+1.9%	587	0.87	-1.2%	44	+1.0%
RtaY	2.8%	+132%	+10%	20%	5.9	+1.9%	581	0.87	-1.4%	45	+1.3%
RTSC	2.9%	+133%	+9%	19%	6.0	+1.9%	582	0.87	-1.2%	44	+1.0%
Ctax rate 300 ZAR₀₅/tCO₂											
RDEF	2.1%	+89%	+24%	35%	5.9	+2.2%	366	0.67	-3.5%	41	+7.1%
RVAT	2.6%	+114%	+16%	26%	6.0	+2.0%	408	0.66	-2.2%	44	+3.4%
RGOV	2.3%	+98%	+21%	32%	5.9	+2.2%	373	0.65	-3.3%	42	+5.6%
RSUM	2.2%	+94%	+19%	33%	5.9	+2.1%	374	0.67	-2.5%	23	-0.6%
RTIF-fix	2.2%	+93%	+23%	34%	5.9	+2.2%	371	0.67	-3.3%	43	+7.3%
RTIF-low	2.6%	+113%	+10%	26%	6.0	+1.6%	409	0.67	-1.7%	44	+2.7%
RTaY(285)*	2.6%	+116%	+16%	25%	6.0	+2.0%	417	0.67	-1.5%	44	+3.5%
RTSC	2.7%	+121%	+12%	22%	6.1	+2.0%	416	0.65	-1.7%	43	+2.1%

Comments: * RTaY could not be solved for a R300 Ctax and results shown here have been obtained with a R285 Ctax only, meaning a 5% lower Ctax than for other R300 Ctax scenarios, but with the same tech. coeff. for ELC.

These results emphasize that a correct understanding of wage setting in the labour markets, especially cross-sectoral is very important to assess the economic impacts of labour market-oriented policies. Another IMACLIM study found a similar sensitivity of macro-economic results under carbon taxation to wage-indexation with a wage curve, in this case with sectoral differentiation (Le Treut, 2017). Further analysis of the South African labour market in this direction is strongly recommended.

5.6.4. Sensitivity to other model parameters

International trade

Decomposition analysis already showed the importance of international trade for the results of economic projections. The decomposition analysis showed that in case substitution between imports and domestic products turned out (*ex ante*) more favourable for domestic products, this went in parallel with higher employment and higher GDP growth. This finding follows from the observation that Ctax scenarios which did not manage to transfer the carbon tax related energy (and energy sector product's) costs increase into a decrease of other costs of production and of non-energy sectors, had more foreign supply (imports) over domestic supply (production) (see section 4.4.1). Also, the devaluation of the South African Rand obtained in RP, often implied that there would be an increase (relative to RP) of costs of supply, and therefore less real income growth. In general, Ctax scenarios

obtained lower growth of income per unit of supply and higher supply per worker, resulting in higher unemployment.

Price-elasticities of international trade

An increase in import-elasticities for reference projection and Ctax scenarios alike can be expected to lead to finding higher GDP-losses and higher unemployment for Ctax scenarios, compared to the results of Chapter 4. This might depend on the scenario, because HSS and possibly also LSS might profit from higher import elasticities in scenarios in which labour costs are reduced thanks to Ctax revenue being recycled into reducing a sales tax (RVAT) or profit taxes (RTIF-low), or into subsidising labour (RTSC). Together HSS and LSS represent 62% of GDP and 78% of employment in BY (2005) calibration data. Whether a positive overall impact of higher import elasticities for international trade would be obtained therefore mainly depends on what happens to LSS, which is the most energy-dependent sector of the two. Lower import elasticities can evidently be expected to have the opposite effect.

An increase in export elasticities will, in general have a positive impact on exports, GDP growth and employment, because South African prices, in most scenarios decrease relative to foreign prices. Exceptions are the R300 Ctax scenarios (RDEF, RGOV, RSUM and RTIF-fix) whose main scenario results showed an increase of the Relative CPI (RCPI, a proxy for the REER) compared to BY. Subsequently, they would experience a negative impact on GDP growth and employment due to the higher export-price elasticity.

Schers *et al.* (2015) tested an increase and a decrease in both import and export elasticities in parallel. They found an 8% increase in GDP of 3 times higher elasticities for international trade, relative to their RP, and a 61% lower GDP versus their RP for 3 times lower elasticities. Their results are set in the context of a strong devaluation of the South African Rand in their RP (a 56% lower RCPI relative to BY), with 3 times lower price-elasticities of substitution leading to extremely rigid international trade, which translates under devaluation into very high import-related cost increases (GDP deflated). Actually, their case of 3 times higher elasticities for international trade significantly reduces (to only 17%) the devaluation of the South African Rand. This can be explained from the fact that in the case of high price-elasticities of international trade the trade balance surplus – which results from changes in the Balance of Payments (BoP, see Eq.55 on p.99) – can be more easily achieved, because higher elasticities mean that smaller relatively price changes achieve sufficient volume changes for the value of exports minus the value of imports to obtain the trade balance surplus percentage of South Africa's GDP that follows from the BoP.

The price-elasticities of substitution for international trade used in this thesis are similar to the high price-elasticity case of the sensitivity analysis by Schers *et al.* (2015). On the other hand, results for RP and the main Ctax scenarios presented in Chapter 4 in this thesis obtain higher REER's (RCPIs in Schers *et al.* (2015)). In this thesis the REER varies between 0.925 for RP and 1.03 for the Ct300

RSUM scenario. Under these conditions no significant impact on results can be expected of further higher elasticities for international trade, because higher elasticities reduce the required price difference to establish a trade balance surplus, meaning that the REER can be expected to approach a value of unity in all cases. In other words, the impacts of further changes in the elasticity of substitution are diminishing. In contrast, lower elasticities for international trade likely result in an economically less favourable reference projection and ditto lower GDP forecasts for main Ctax scenarios. The negative impact of carbon taxation in combination with different forms of revenue recycling will however be estimated to be smaller under a (very) rigid international trade case, as was shown by Schers *et al.* (2015). This can be understood from the fact that with lower price-elasticities for international trade, there will be less import-substitution and less of a decrease of exports relative to the baseline trend of export volume growth (compared to RP).

Trend in export volume

Another issue concerning international trade is the sensitivity of results concerns the baseline trend in the volume of exports itself. One can imagine that a higher trend and therefore stronger autonomous demand for South African exports by ROW puts pressure on the trade balance. From the point of view of model resolution, the higher trend will initially push exports and the trade balance surplus upwards (relative to GDP). The REER can be expected to increase, in order to compensate for this pressure and to maintain the trade balance at its share in GDP set by international borrowing and lending and the (endogenous) returns to capital, i.e. the Balance of Payments (BoP, see section 3.4). The increase of the RCPI will have a positive effect on GDP growth, because a higher CPI means that imports will be relatively cheaper.

Economically, this has two impacts: First of all, it makes domestic household consumption relatively cheaper, because two important components of household consumption: MAN and energy will be cheaper. Consequentially, the domestic CPI will be lower relative to prices of other factors and inputs, and labour will be cheaper, decreasing unemployment. Furthermore, energy, consumption of which is relatively rigid (as was shown in the Ctax scenario analysis in Chapter 4), will be relatively cheaper, thereby reducing costs of production compared to the lower export-trend situation and improving the position for international trade of South African products.

All in all, it will lead to not only higher foreign demand, but also higher domestic demand and therefore economic activity and GDP. A disadvantage is that the relatively lower energy costs, and the relatively higher exports (in which coal and EIN products take-up a significant share) will increase the carbon intensity of the South African economy. This higher expected reference carbon intensity will likely increase the relative size of the negative economic impact of carbon taxation (with different revenue recycling options).

Government final consumption

One assumption used to generate the “balanced” Reference Projection (RP) of Chapter 4 of this thesis

is that government final consumption over GDP increases by a factor 1.25, meaning that South Africa's governmental or public final consumption expenditure increases from about 19% in 2005 to about 24% in 2035. Whether this is an exaggerated assumption depends on the future politics in South Africa. In the present-day world a rate of government final consumption over GDP close to 25% is only seen in countries like France, Norway, the Netherlands, and Saudi Arabia, which are known for a high level of public services. A possible explanation for high public final consumption expenditure might be the relative height of public sector salaries, another one might be differences between countries in the extent to which services like health care or education are publicly or privately financed.¹⁹⁰ For both these aspects it is plausible that they lead South Africa, generally considered to be a country in which politicians find public services a priority, to increase government final consumption as part of GDP in parallel to a growing national income.

However, future political choices regarding public versus private service provision was not the motivation for the choice of the value of the growth rate of the share of government final consumption in GDP. The main motivation for this parameter choice was to obtain a balanced macro-economic projection: Under the assumption of fixed mark-up rates, RP could be expected to lead to profits that increased faster than labour income. The reason for such an outcome would be that the fixed mark-up rates are partly raised over import costs and partly over domestic labour costs. Labour costs tend to decrease relative to import costs in case of a decrease of the REER, meaning that the share of profits in GDP would increase. Furthermore, physical capital intensity of production decreases due to the assumption of increased physical capital output productivity. Gross Fixed Capital Formation (GFCF) would, as a consequence, not need to increase, which would mechanically lead the model to translate higher profits into a higher interest and dividends rate, as Firms would not need to reinvest their higher profits. The trade balance would also increase, to compensate for the bigger flow of returns on capital to ROW. In other words, without higher government expenditure the expected result for RP would have been devaluation plus very high interest rates and dividends and a high share of the trade balance in GDP. The increase in government final consumption helps control these variables, because an increase in the target rate of public expenditure over GDP causes the model to raise revenue and property income tax rates for households and firms alike to achieve its budget deficit target.¹⁹¹

A change in this assumption about the rate of future government expenditure over GDP would therefore either cause the rate of interests and dividends, meaning of returns on capital, to change as

¹⁹⁰ In the case of private finance of health care or education one can think of private health insurances, or private study loans. This does not exclude the possibility in these countries that income transfers (via taxation and social security benefits) allow for the affordability of these services for the poor. But, income transfers (or financial social security benefits) are not included in the government final consumption expenditure measure, but social transfers in-kind are. World Bank uses the following definition: "General government final consumption expenditure (formerly general government consumption) includes all government current expenditures for purchases of goods and services (including compensation of employees). It also includes most expenditures on national defense and security, but excludes government military expenditures that are part of government capital formation."

Source: <https://data.worldbank.org/indicator/NE.CON.GOV.T.ZS> (accessed 8 December 2017)

¹⁹¹ Another possible justification for such a response could be that high profits and high interests-&-dividends largely go to the richest household class. It could thus be logical for a government to raise taxes to finance the provision of more public services in a response to an increase in income inequality.

well: The rate of returns would for instance decrease if government expenditure would increase even further. This could lead to a decrease of the trade balance as percentage of GDP and to a decrease of income inequality and therefore likely to higher CO₂ emission intensity, because relative to GDP more fuels would be consumed domestically (it has been mentioned before that higher income inequality leads to lower CO₂ intensity of GDP because the rich spent less on energy and transport per Rand of revenue, and more on high skill services (HSS) (though they spent much more on energy and transport on a *per capita* basis). In the case of a decrease in the rate of government expenditure over GDP the impacts would of course have the opposite sign. A less CO₂ intensive economy would of course be less sensitive to carbon taxation, but I expect this effect to be relatively small considering that the differences in energy intensity of household consumption between household classes are only a few percentage points, and similarly I expect changes in the rates of returns on capital (caused by changes in government expenditure and tax rates) to only cause minor changes on the trade balance surplus and on the composition of exports. It should therefore not alter the findings of scenario analysis much.

Aspects not considered

One way of performing sensitivity analysis is testing the impact of each model parameter on the results of scenario analysis. Such an analysis would have been very elaborate, and requires certainty about the uncertainty in many model parameters. Without such information available, and without a reflection on uncertainty around more fundamental modelling assumptions such an approach might offer a false impression of certainty or a lack of guidance for policy making. The discussion of the sensitivity of modelling results to model parameterisation and other assumptions looked into aspects that were theoretically expected to play an important role in determining the size of estimated economic impacts of carbon tax revenue recycling scenarios. Nevertheless, also within that analysis some aspects could not be covered within the scope of this thesis. Here follows a short discussion about their possible role for modelling outcomes.

A first aspect relevant for modelling left out of consideration in this section was the choice of sectoral disaggregation: Average behaviour is different from total disaggregate behaviour. The PhD thesis of Gaëlle Le Treut, using a similar IMACLIM model for the French economy, showed that sectoral disaggregation matters for the estimation of the sensitivity of GDP growth to carbon taxation (Le Treut, 2017).

From the labour market it is a quick step towards the treatment of labour in production functions. In that sense, this thesis only tested one production function structure for Capital-Labour substitution, whereas the analysis by Krusell *et al.* (2000) has already shown that other structures can be plausible too, depending on the circumstances, e.g. a the context of a specific country. Moreover, the entire production function structure could be different, with a similar likeliness to represent historically found trade-offs in production (Okagawa and Ban, 2008; Van der Werf, 2008).

On the demand side, besides intermediate consumption, exports and government final consumption,

household final consumption plays an important role in structuring the future of the South African economy. This has to be admitted as a weak aspect of the current IMACLIM-ZA model, because no up-to-date (more recent than the 1990'ies) estimations of household consumption behaviour were available at the moment of model development. The model for household consumption has thus been based on an *ad hoc* model to represent rigidity in energy consumption under the prospect of rising energy prices. Two recent econometric studies of South African household consumption behaviour have come available (Bagilet, 2017; Burger et al., 2015). As part of future work, these estimates of household consumption's income and price elasticity could be integrated into IMACLIM-ZA. Ideally, as far as energy consumption is concerned, the SATIM model will be used to capture expectations about technological change and micro-economically founded household behaviour.

6. Discussion

This chapter offers a discussion of the modelling results. It particularly reflects on the limitations of the methodology used in this thesis (in section 6.1) and on how results compare to those of other studies (in section 6.2). Finally, it takes a step back and compares how results compare to theoretical predictions regarding growth and development under environmental constraints (section 6.3). All these considerations will be used in the next chapter (Ch.7), which resumes the results and their limitations to answer the research questions, to make recommendations for national and international policy making, and to give advice on directions for future research.

6.1. Reflections on the methodology

This first section assesses to what extent results of IMACLIM-ZA could be inclined in a certain direction due to choices in model structure, or assumptions in model calibration and forward-looking parameterisation. The main question is what limitations these assumptions and choices pose for the interpretation of results of IMACLIM-ZA. For instance, could they lead to an over- or underestimation of the impacts of carbon taxation and its revenue recycling, or could they favour or disfavour certain revenue recycling schemes? To treat these questions, main aspects of the IMACLIM-ZA model will be discussed one by one. First, choices in modelling of production and consumption will be scrutinized (6.1.1), then the focus will be moved to the modelling of international trade (6.1.2), to the modelling of the labour and capital markets (6.1.3), to model calibration (6.1.4), to compatibility with SATIM (6.1.5), and finally to the impact of strategic choices made in the modelling for this study (6.1.6).

6.1.1. Modelling of production and consumption

Using nested CES production functions

A first limitation to the modelling outcomes is the use of CES functions to model trade-offs between factors and inputs for all sectors except the electricity sector. Three criticisms of the use of CES functions in IMACLIM-ZA are that the CES production functions do not rely on estimates for South Africa, that the structures used (as estimated by others) represent a specific historic development which does not necessarily reflect how trade-offs take place in the envisioned future time period under envisioned (strong, exogenous) price changes, and finally CES production functions have been found to represent technological change rather imperfectly compared to Bottom-Up modelling. The IMACLIM framework's methodology is even partly motivated by the idea that econometrically estimated elasticities of substitution cannot represent the irregular behaviour of technological change. For instance, Ghersi and Hourcade showed that for one of the two Bottom-Up (BU) models¹⁹² which they analysed, behaviour for substitution between energy and capital did not resemble a CES function. Instead, the technological change of the BU model showed a decreasing elasticity of substitution with

¹⁹² The ALTER energy system model.

the increase of a carbon tax rate (Gherzi and Hourcade, 2006). Also the finding that marginal abatement costs curves are path-dependent (Kesicki, 2012) implies that elasticity of substitution cannot be constant.¹⁹³ What is true for the substitution between capital and energy in the given examples is likely also be true for other substitution behaviour, for instance, why would substitution between labour and capital or energy in the steel industry or in agriculture exhibit constant elasticity of substitution behaviour?

In brief, the use of nested CES is not the ideal way to represent expectable technological change. Still, it is one of the best available approximations for technological change – a strategy on which had to be relied given that it was out of scope for this thesis to integrate BU information on technological change for many economic sectors in the IMACLIM-ZA model and its scenarios. To compensate for this lack of integration of BU modelling or engineering information, technological coefficients of productive sectors, which result from model runs, could be compared *ex post* to theoretical estimates about potential productivity or efficiency gains. This has for instance been done in this study for energy efficiency (see section 5.5).

The structure of nested CES production functions

Another potential limitation due to the use of CES production functions concerns the structure of the nested CES production functions. Two alternatives exist, for two different parts of the nested CES structure. Together they can be expected to change the results of IMACLIM-ZA in opposite directions, thereby indicating that there is an uncertainty margin around the obtained results, rather than that results would be biased by choices in the nested CES structure (disregarding the criticism on CES functions as just expressed above).

First of all, for the KLEM part of the production function only one nested CES structure has been tested, whereas alternative structures are possible too (Van der Werf, 2008). For instance, aggregating capital (K) and energy (E) instead of capital (K) and labour (L), before aggregating with the remaining factor in a KLE aggregate (see section 3.2.1). Also, a more “usual” structure for the substitution between capital and different skills of labour could have been used: assuming all three skill levels of labour to be each others substitutes, and modelling one labour aggregate at the same level as the capital good. Both alternatives for (parts of) the nested CES structure can be expected to lead to opposite outcomes:

- Changing from a KL sub-aggregate of the KLE aggregate to a KE sub-aggregate would reduce the extent to which higher energy prices lead to higher labour intensity, because the higher energy prices would be absorbed to some extent through substitution of energy by capital¹⁹⁴. It

¹⁹³ One might argue that MAC curves do not capture the reality in which multiple actors will implement different measures for technological change at different moments, with different net present values, and that due to this overlap in the implementation of measures, experimental MAC curves might resemble a CES curve more. But, this does not change the fundamental issue, which is that the elasticity of substitution depends on the context, and cannot be constant. The more detailed the sectoral level of analysis, the less likely it seems that MAC curves can be turned into smooth CES curves (see for instance the MAC curves in: DEA, 2014).

¹⁹⁴ This, of course, also depends on the elasticities of substitution chosen for these alternative CES structures.

can therefore be expected to increase unemployment in both reference projection and Ctax scenarios;

- The second option – modelling all skills of labour at the same level as K or KE – likely leads to a lower projection for future unemployment: The reason is that the high skill labour shortage would not be felt as strongly if medium and low skill labour can substitute for high skill labour (in the interaction with a K or KE aggregate).

In brief, changing the structure of the nested CES production function would change the substitution between energy and labour, and therefore the relative impact of different carbon tax rates with different revenue recycling schemes. The proposed alternatives would have opposite impacts. Rather than suggesting a bias in results of the present structure, the alternatives to the nested CES structure of IMACLIM-ZA likely only provide an uncertainty-range about potential impacts of a carbon tax (with different revenue recycling schemes) on employment and GDP.¹⁹⁵ Unfortunately, the estimation of this uncertainty range could not be performed anymore within the time set for this thesis.

The choice of elasticities of substitution

Elasticities of substitution in CES production functions are important determinants of macro-economic results in CGE models (Koesler and Schymura, 2012). Without a solid basis for the choice of elasticities of substitution in production functions, a sensitivity analysis would have been at its place to assess how the values of these elasticities affect the size of the impacts of carbon taxation on GDP, CO₂ emissions, and unemployment, and to get a feeling for the uncertainty around the results of IMACLIM-ZA.¹⁹⁶

It can be argued though that the alternative values for elasticities of substitution in production functions (instead of the values used in the present study) lead, on average, to similar results as obtained in this thesis: Suppose the chosen values of elasticities of substitution in IMACLIM-ZA for the nested CES production functions reflect a valid range of values (typically between 0 and 1.3, see Koesler and Schymura, 2012), alternative values for elasticities would then in most cases be higher for some sectors (for TRA and EIN), and lower for other sectors (for HSS, MAN and LSS). These opposing changes can be expected, on average, to also change the impacts of carbon taxation on GDP growth and employment in opposing directions, leading only to small changes in aggregate results.

Modelling household consumption

Modelling of household final consumption in IMACLIM-ZA still requires improvement. Because of a lack of recent macro-economic descriptions of household consumption behaviour for South Africa, an *ad hoc* model of nested CES consumption functions had been constructed (see section 3.2.3). Two criticisms can be applied: First of all, a weakness of the model is that it depends on an assumed

¹⁹⁵ It would be hard though, to attach a probability to the likeliness of modelling outcomes of such alternative CES structures.

¹⁹⁶ On the other hand, such a sensitivity analysis might also create a false image of certainty, because the *probability* by which the combination of elasticities of substitution and nested CES structure represents future trade-offs between factors and inputs for South Africa would remain unknown.

context of exogenously increasing energy prices. Would this context be missing, then the model's price-inelastic floors of consumption – which pull a part of consumption out of the reach of the nested CES structure – reduce the potential for price-elastic increases of energy consumption, because it causes the price-elastic reference volume for energy consumption to be very small. Secondly, there is little basis to justify the assumption of an elasticity of substitution >1 between non-energy goods in the COMP aggregate. By consequence, household final consumption might shift away from energy-intensive products too easily, and IMACLIM-ZA might under-estimate the South African economy's "attachment" to energy-intensive goods, and thereby the negative economic impacts of a carbon tax.

Luckily, recently two econometric studies of South African household consumption behaviour have recently been published (Bagilet, 2017; Burger et al., 2015). These studies provide another model for the description of household consumption with their estimations of income elasticities and own price elasticities of consumption of (baskets of) goods than the nested CES function of IMACLIM-ZA. Despite this difference one can still evaluate whether the findings of these studies are in agreement with IMACLIM-ZA's model for household consumption. A comparison leads to the conclusion that main macro-economic results of IMACLIM-ZA would probably not be strongly affected if their models would be copied, but results for poverty and energy poverty are under-estimated, and at best just very uncertain.

To explain this I first summarize the findings of these studies: Burger *et al.* and Bagilet find that income elasticities for certain products decrease with household class average *per capita* income (or expenditure), whereas for other products it increases. Products for which it decreases are food products, fuels and furniture in Burger *et al.* (2015), and food and domestic energy use in Bagilet (2017), who performs a more long-term analysis using pseudo-panels. Products for which income elasticities increase with *per capita* income or expenditure are office machinery and rent in Burger *et al.*, and transport expenditure and to a lesser extent "other products" in Bagilet. Results for own price elasticities of products show more or less a mirror image of the results for income elasticities: Goods with low income elasticities for specific household classes also have lower own price elasticities for the same household classes (quartiles or deciles). Bagilet (2017) furthermore finds absolute values of expenditure and own price elasticities of food, domestic energy and transport to be lower than those for other goods.

One can conclude on the basis of these findings that a correct model for household final consumption for South Africa should treat agriculture and food items as a separate category. Also, following Bagilet's (2017) findings about the height of expenditure elasticity by product category, IMACLIM-ZA's nested CES model for household final consumption should have higher price inelastic shares of consumption of domestic energy use for richer households than for poorer ones, whereas it should be lower for richer households compared to poorer households for transport services. This is the opposite of what is the case of this thesis. As a consequence one might conclude that the model for household

consumption in this thesis ...:

- neglects the importance of food expenditure, which might be substituted by other products too easily as a part of LSS within the COMP aggregate, thereby in theory not showing the impacts energy prices would have on the poorest household classes when translated to food prices, but also hiding poverty-reducing impacts of labour subsidies revenue recycling scheme (RTSC) by e.g. reducing production costs in notably agriculture, food processing, or food, retail & distribution;
- might over-estimate rigidities in domestic energy use for the poor, and thereby underestimate the reduction in energy consumption by poor households (it must be said, compared to already low *per capita* energy consumption (see results in section 4));
- might over-estimate rigidities in the use of transport services by the rich, and thereby underestimate impacts of a carbon tax via the CO₂ emissions of transport-services.

Future improvement of the description of household final consumption in IMACLIM-ZA would therefore be welcome, for instance on the basis of findings of one of the two mentioned studies of household final consumption in South Africa (Bagilet, 2017; Burger et al., 2015).

6.1.2. International trade

An evaluation of assumptions made in modelling of international trade leads to the conclusion that there is an unknown uncertainty around their impact on the results of the analysis of carbon taxation, but that for now there is no reason to expect a bias towards over- or underestimating the impacts of carbon taxation or different revenue recycling scenarios. The parameters which cause uncertainty are the elasticities of substitution, the evolution of foreign prices (relative to South African prices), and the price-inelastic trend in volume of world trade by product.

Changed assumptions about price elasticities for international trade will certainly change the estimated economic costs of carbon taxation relative to the (unsustainable) reference projection: The limitation that the use of price elasticities poses to the interpretation of results resembles the limitation which their use has in CES production functions, namely that they represent certain historically calibrated values which reflect a specific historic development (for a specific geographic region or level of aggregation). It is uncertain whether these values are still valid in the face of the strong price changes as observed under carbon taxation or as exogenously assumed for energy imports in reference parameterisation. Other developments could be imagined: For instance, if trade is less flexible due to rigid global value chains, South African products which have become more expensive under international carbon taxation might be less easily substituted, or on the other hand, the economic benefits of revenue recycling of a domestic carbon tax could be lower, because it might not prove so easy to develop new industries and products and gain a place in international markets. This type of considerations is typical for global value chains analysis, but out of scope for this thesis.

Other assumptions on international trade are likely also being significant for the evaluation of a carbon tax. One of the most important aspects is the assumption about growth in world trade volume, which is applied homothetically to all sectors. No information is available to assess whether international markets for raw and main materials, manufactured goods, agricultural products, transport services, and other services would grow at an equal pace. Were growth in world trade (international demand for South African exports) to be concentrated in mining and energy-intensive sectors' products, then these sectors would increase their share in the South African economy and the relative economic impact (on GDP and employment) of a domestic carbon tax in South Africa would be bigger. Were, on the other hand, growth in world trade to be concentrated in manufacturing and services, then the opposite would be the case and the relative impact of a carbon tax on the South African economy would be smaller.

Also, the analyses of an international carbon tax regimes presented in sections 5.3 and 5.4 would obtain different results if changes in the trend in the volume of world trade by product would have been taken into account. The reason for raising this point is that a foreign or international carbon tax likely leads to a sharp decline in coal exports, compared to RP. This would lead to a devaluation of the South African Rand (relative to RP) to maintain the trade balance surplus required for an equilibrium in the Balance of Payments. In theory, a domestic carbon tax that recycles revenue in such a way that it reduces costs of domestic production elsewhere than in energy use (as it is the case in RVAT, RTaY, RTIF-low and RTSC), such a decrease in foreign demand for coal could be replaced more easily by exports of non-energy intensive industries, which would have improved their international competitiveness thanks to carbon tax revenue recycling.

However, the alternative scenario for a multilateral carbon tax regime (presented in section 5.3) actually obtains results in which South Africa's energy-intensive industries obtain a better economic outlook than in the case of a unilateral (domestic) carbon tax only. The explanation for this counter-intuitive result is that the multilateral carbon tax increases international prices for energy-intensive products and therefore reduces the loss of exports energy-intensive goods and of substitution of domestic energy-intensive goods by imports relative to RP, as it is found in results of the unilateral carbon tax regime of the Ctax scenarios in Chapter 4. Additional research is therefore necessary to evaluate how domestic and international carbon tax regimes could affect exports (and imports) by sector.

6.1.3. Modelling of technological change and factor markets

The definition of skills in labour market modelling

The labour market model proposed in this thesis has two main weaknesses, which I discuss next. First of all, the interpretation that skills of labour are purely positional is probably a position that is too extreme. Secondly, the approach in which capital is complementarity to high skill labour might not be compatible with the assumption that educational attainment is positional.

Regarding the first of the two, even though inequality in South Africa's educational system seems a

good reason to split the labour market in skill segments, it is doubtful that an increase in the average level of educational attainment causes people with only a high school degree – who, theoretically, have high skill jobs too in 2005 BY calibration data – to no longer qualify for high skill jobs by 2035. Especially since high skill labour is projected to be in shorter supply. Of course, this model had been chosen as the best choice between two evils. Were a labour market model to be found that is in-between a model which assumes skill segments to have constant levels of educational attainment (CEA) and the present model in which skill segments are defined as constant shares of the labour force (CSLF) – then, clearly, a lower skill-shortage would lead to a better prospect for GDP growth and employment both in RP and Ctax scenarios (see for instance the impact on GDP growth of a reduction of the high skill shortage in section 4.5.1). There is no reason to believe that a carbon tax would have bigger negative economic consequences in this context, relatively speaking.

However, one scenario that might turn out less positive in this context is RTSC with revenue recycling into labour subsidies. The reason is that if there would be less high skills labour shortage (and relatively less expensive labour) to begin with, then the impact of reducing these costs will be smaller too. Of course, an investment in skills that affects the amount of people available to the high skill segment will have a smaller (positive) impact on GDP growth too in these circumstances, if there is less of a high skill shortage. The investment option in which the thresholds between skills do not change, but in which productivity is improved (especially of intermediate inputs) can be expected to have about the same results.

The second criticism concerns the issue that the analysis by Krusell et al. (2000), which found proof for complementarity between equipment capital and high skill labour (and their aggregate substituting for low skill labour), calibrates his model of the US labour market on the basis of skill being equal to the level of educational attainment. Restraining the high skill category in the positional labour market model of this thesis while the average level of education increases might be pushing the interpretation of Krusell et al's findings very far. Nevertheless, in defence of the labour market model in IMACLIM-ZA I would like to recall that Krusell *et al* mainly served as an inspiration for how to model a future in which technological change is low skill labour-saving, testing also what happens if one adds the present-day common perception that the level of education which gives access to good jobs is increasing. Furthermore, a model in which skills equated to constant (fixed) levels of educational attainment (CEA) was not capable of absorbing the foreseen increase in South Africa's labour with high school degrees or higher (see Schers et al., 2015). A last reason for the choice of labour market model in this thesis was that the positional labour market model also allows defining skills of labour as fixed roles in production (meaning, as a characteristic of *demanded* labour, and not supply).¹⁹⁷ A

¹⁹⁷ The underlying assumption is that increasing demand for education per job type can be expected to take place in societies which on average become better educated and technologically more developed. For instance, it seems that many OECD countries have gone through a development in which the same types of jobs started to be fulfilled by people with increasingly higher levels of education, e.g. think of employees in supermarkets and shops, factory workers, or agricultural workers. Such a development might have partly followed on, and partly been the precursor to increasing complexity of work. Or, it might just reflect that – due to how the educational system works, or due

constant educational attainment (CEA) definition of skills would not allow for this.

Exogenous assumptions about labour productivity growth

An approach in which the average level of educational attainment of the labour force varies raises another question: What is the link between the level of educational attainment (or any measure for skill of labour) and labour's (average) output productivity by level of skill?¹⁹⁸ In IMACLIM-ZA the implicit assumption is that an increasing average level of educational attainment goes, for each of the three skill groups, in parallel to an increase in labour productivity.¹⁹⁹ The question is how much labour productivity (and maybe also that of other factors of production) should vary with the level of educational attainment. It is likely a very complicated question as labour productivity depends of more than just the workers set of skills and might face the same technological rigidity as energy use.²⁰⁰ Also, South Africa's concern is that of quality of education. The link between quality of education and labour productivity seems to have never been studied at all (see the discussion in section 3.3.1). The conclusion is that to complete the counterfactual approach used in this thesis, either requires further research, or expert- and stakeholder-based scenario development.

Related to the previous issue is the question whether, and at what speed, South Africa could develop less energy-intensive, more labour-intensive, high value added generating activities. For instance, the typical image of German manufacturing is that it produces high value-added goods, like medical equipment, whereas manufacturing in Asia produces technologically less advanced, low value-added goods. Countries like South Korea and China might try to develop their industries, especially manufacturing, into production of more advanced goods that generate higher value added. These activities likely require a better skilled labour force and probably a good "knowledge infrastructure" and regulatory environment.²⁰¹ Some development economists hold the view that this process is the consequence of a mix of policy interventions and market regulations (Amsden, 1987; Easterly, 2001; Mazzucato, 2015; Seguino, 2014). Based on their insights, one cannot take it for granted that specific industries will take root and then "take off" (grow quickly). Under IMACLIM-ZA's current high level of sectoral aggregation no distinction between "high tech" and "low tech" is possible, and it is therefore not easy to model a transition to a high-skill, high-tech economy. If new sectors cannot absorb new highly skilled labour, possibly radical exogenous assumptions about the introduction of these sectors, or about changes in labour productivity in existing sectors should be considered, including negative productivity growth for high skill labour.

to personal preferences – over time the majority of people receives an increasing number of years of education independent of whether this is required by the job market. Studying the explanations for the evolution of educational attainment with job types was unfortunately out of scope for this thesis.

¹⁹⁸ This question is also relevant (although to a lesser extent) for a constant level of educational attainment (CEA) definition of skills in a labour market model.

¹⁹⁹ Not only educational attainment, but also increasing work experience and on-the-job training - with the ageing of the labour force – but also technical learning, e.g. translating into a better organization of companies or production, could improve labour productivity.

²⁰⁰ One idea might be to use estimations of skill premia and their evolution over time as the basis for estimating this link.

²⁰¹ With knowledge infrastructure and regulatory environment one can think of academic research labs, R&D labs in companies, good patent laws and offices, good policies to support innovation and new companies, etcetera.

Dual accounting, and the interpretation of aggregated goods

Another possible criticism of the present study might be the use of aggregated goods. For energy products aggregation is relatively easy, because it concerns relatively homogenous products with clear-cut units (e.g. *kWh* of electricity, *toe* or *MJ* of energy content).²⁰² Quantities of goods of other sectors however are represented by quasi-quantities, or in other words price index-based volume indexes. This should not be a problem as working with price indexes is common practice in economics (see for instance OECD, 2001b), but it does require one to be conscious of the fact that the quality of a composite or aggregate good can change over time and between sectors and end users. That this can still make economic sense is shown by the example of a very aggregated volume index that has been proven to be economically meaningful; This is the case of the index for the volume of world trade by the Netherland's Bureau for Economic Policy Analysis shows (CPB, 2016; The Economist, 2015). The latter index is capable of separating in a meaningful way price and volume developments in international trade at an aggregate level, demonstrating market under- and oversupply effects.

A different question is that of dual accounting of the capital good, which might be less straightforward than that of sectoral goods and services.²⁰³ In a model with only one sector outside energy sectors the capital good can only be the one homogenous composite good, and thus equals the average product of the composite, non-energy good of the economy (see Ghersi and Hourcade (2006)). But, in case one models multiple non-energy sectors, the capital "good" will be composed of multiple different goods (a vector of multiple non-energy goods). The latter description in theory offers the possibility to differentiate the composition of capital over time, or between sectors. This possibility has not been used in IMACLIM-ZA, because sectoral disaggregation is still very crude, and data on which basis to calibrate or assume change in the composition of the capital good was absent too.²⁰⁴ The still quite high level of aggregation at which sectors are defined in IMACLIM-ZA might be an argument to consider it still acceptable to treat physical capital as a homogenous good – namely mainly consisting of MAN (manufacturing goods) and LSS goods (construction, amongst others). Technological change then implicitly takes place within the products of each of these sectors that go into capital goods, not by replacing one by another sector.

The capital market and investment

The model for the capital market (investment, capital formation, returns on investment, net borrowing and lending) is like any model a simplification of reality with some shortcomings. One shortcoming however is that it does not assume an imperfect capital market, thereby assuming that capital write-

²⁰² Of course, one needs to be ware not to aggregate electricity and steam, whose energy content has a completely different level of entropy (or potential for "work"), neither can one readily exchange coal and gasoline as a carfuel, etcetera. But those matters are by majority dealt with by Bottom-Up energy (engineering) models.

²⁰³ In the past statistics offices tried to track the volume of physical capital, but this requires intensive data processing and analysis and has therefore been abandoned by many statistics offices: see for instance the methodology for how to measure capital stocks and productivity by OECD (2001a, 2001b).

²⁰⁴ To improve the description of the capital good in the case of capital being a vector of multiple non-energy goods, as is the case in IMACLIM-ZA, one could opt for more "disaggregation", e.g. distinguishing different types of capital goods, and differentiating them by sector. An alternative solution, used in the IMACLIM-R approach (Hourcade et al., 2010; Waisman et al., 2012), is the use of Bottom-Up *modules* that determine, based on energy prices and energy demand, the composition and price of installed capital.

offs equal capital intensity of production, excluding the possibility of under-utilisation of capital or even of stranded assets. To enable modelling of stranded assets, the model should track capital stocks by sector, e.g. as in Alton *et al.* (2014). Another element of their analysis deserves to be taken over as well, namely that technological change takes place at the pace of renewal of a sector's capital stock, though calibration of such parameters might be a problem. Furthermore, with differentiation in capital stock by sector, one could also introduce non-homogeneity of the capital good into the model, like Dai *et al.* (2016) do in their macro-economic analysis of investment in renewable energy for China.

A related issue is that investment is modelled using the *beta* vector which represents the size of investments over capital amortisation, see Eq.69 on p. 100, and especially that it is fixed at BY values. If one assumes constant average capital lifetimes (or depreciation rates), this implies that the growth rate of the capital stock is the same in the projection year as in BY, and the same in all scenarios. This is at odds with the differences in GDP growth rates between scenarios, meaning that implicitly between BY and projection year the amount of gross savings and investment have been higher or lower than in BY and projection year, depending on the result for GDP growth obtained. Were a modelling solution to be found to correct this assumption, and make beta correspond to the average annual GDP growth rate obtained, then one would obtain changing shares of investment and final consumption in GDP. In IMACLIM-ZA this would change economic structure somewhat, because investment consists primarily of MAN and LSS goods, whereas final consumption primarily consists of MAN and HSS goods, with the addition of energy consumption, and only a minor role for LSS goods. It is not clear what the consequences would be for results for energy and CO₂ emission intensity of the South African economy: Household consumption seems more energy-intensive than investment, but final demand of LSS directly creates about twice as much intermediary demand for EIN and TRA (two energy-intensive sectors) than final demand for HSS.

The use of the *beta* vector for modelling investment furthermore means that IMACLIM-ZA does not track capital stocks and their vintage structures. Due to this simplification of the capital market, the model cannot treat the question of stranded assets in fossil fuel-based industries or the speed with which a sector's capital stock changes. The latter should hopefully not be an issue regarding the length of the time step of the projection, namely 30 years, and the high level of sectoral aggregation.

In favour of IMACLIM-ZA's modelling of the capital market it should be remarked that the model (indirectly) represents investment more realistically than many CGE models with exogenous savings do: This is by separating physical capital and net operating surplus (profits), and by separating profits from interests and dividends: It uses Gross Fixed Capital Formation (GFCF) to represent investment, and it distinguishes between profits on one side – distributed as income to owners or retained by firms for re-investment – and returns on (financial) assets on the other side in the form of interests and

dividends (see section 3.4.2).²⁰⁵ Of course, there must be scientific literature available on which basis a better models for investment behaviour and saving could be developed, e.g. to model the part of profits that is retained for re-investment, and how households net savings or foreign investment respond to rates of returns on equity (financial assets) and changes of the real effective exchange rate. This was out of scope for this thesis, but it is a very interesting issue for future model improvement.

6.1.4. Model calibration: income distribution and hybridisation

A lack of calibration data has in several cases been solved by making assumptions. These assumptions have of course been judged to be plausible, but they remain points of uncertainty in IMACLIM-ZA's description of the South African economy. One of these sources of uncertainty or simplifications is the description of South Africa's tax system and of the country's income distribution (including different transfers between agents). Their implications for the results are discussed first. Next, this sub-section discusses potential impacts of assumptions and simplifications used for the construction of the "energy bills" Input-Output (I-O) table, and those used in the hybridisation procedure on modelling outcomes.

The tax system and informality

Simplifications of the tax system probably do not affect the results very much, with two exceptions: the lack of taking into account the informal economy might lead to overestimation of the impact of a carbon tax on price-elastic trade-offs between inputs and factors in production, or in consumption, and it might lead to an overestimation of benefits for the poor of the Ctax revenue recycling scenario with a reduction of the sales tax (RVAT). Furthermore, simplifications in the representation of the tax system lead to a limitation of the number of tax reform policies that can be analysed. The latter is not an objection for the strategic level at which this thesis analyses carbon tax revenue recycling, but is to signal that for future work, an improvement of the description of the tax system could be useful.

The representation of the South African system of taxation and subsidies is limited to the level of detail available in the SAM 2005 (StatsSA, 2010a), in the South African Supply & Use tables (SU tables) (StatsSA, 2010b) and integrated economic accounts (SARB, 2012). The efforts to retrieve more detailed data have been limited, because the ambition of this thesis was not to provide analysis of detailed measures and impacts until 2035, a time horizon which is surrounded by uncertainties about future developments in the global economy and technology. Rather, the objective was to provide a more strategical analysis for carbon tax revenue recycling for South Africa, given certain stylized developments, e.g. of productivity at an aggregated sectoral level. Still, some simplifications in the representation of the South African tax system might affect the findings of this thesis. One potential omission is leaving out informal economic activity or informal labour, which likely does not pay Value Added Tax (VAT), fuel levies and other product taxes, production taxes, profit taxes, or

²⁰⁵ The more common, neoclassical representation of the macro-economy suggests that the main goal of firms is to maximise profits, which means that they end up equalling returns on capital. These models treat saving and lending for investment as a unique feature of households. It might be more realistic to assume that the main goal of firms is to generate sufficient income for their owners and to guarantee this for a sufficiently long period of time. Remaining economically viable is then most important, and re-investing profits is in that case a corner stone of firm's economic future.

contributions to social security and pension funds as part of labour costs.

An exploration of the addition of the informal economic activity to IMACLIM-ZA has been performed (Guerard, 2014). The conclusion is that informal labour in South Africa is significant (estimates range between 18% and 36% of the labour force, depending on definitions of informality), but its weight in terms of labour income or value added are a lot smaller and smaller than in other developing and emerging economies in Africa, Latin America or Asia.²⁰⁶ The size is sufficiently significant to consider including informal economic activity in IMACLIM-ZA, but the approach explored by Guerard has not been copied for reason of limitations in data availability and requirement for data manipulation. Furthermore, the approach includes splitting a large number of economic sectors into two (formal and informal activity), creating bi-directional exchanges between formal and informal sectors. IMACLIM-ZA currently limited number of sectors and solver variables (200 maximally) was therefore another reason to exclude a separate treatment of informal activity in IMACLIM-ZA.

Indirectly the model does take into account informality. SAM data (StatsSA, 2010a), due to the way in which it is constructed²⁰⁷, likely incorporates a significant part of informal economic activity. Of course, whether this is the case depends on StatsSA's methodology for combining different statistical sources (e.g. data coming from the South African Reserve Bank) and for dealing with statistical differences. This methodology is unfortunately not reported. IMACLIM-ZA calculates tax rates or unit product taxes over aggregate values of sales or revenue, and therefore calculates average tax rates for formal and informal economic activity. Tax rates are therefore likely underestimated, but this does not need to affect the analysis of macro-economic impacts of policies. The reason is that the way in which IMACLIM-ZA's calibrates tax rates actually might lead to a correct representation of the weight of taxes on a sector's economic activity: Due to forward-linkages from informal to formal economic activity (Valodia and Devey, 2012), taxes paid by the formal part of a sector can be assumed to be levied implicitly also over the informal part of a sector's activity, at the aggregate level of sector-definitions of IMACLIM-ZA. Calibration of tax rates on the basis of SAM aggregates in theory also reduces tax rates to an average for both formal and informal activity, e.g. for household income taxation. Of course, projecting the economy into the future while holding tax rates constant implicitly means that the share of informal revenue in a household class' total revenue remains constant, which might be unlikely for a developing economy.

An exception for this way of calibrating tax rates in IMACLIM-ZA is the VAT rate, which has been set at the official rate in 2005 of 14%, but only for final consumption of non-energy sectors and ELC.

²⁰⁶ On the basis of Guerard's survey of literature, one can conclude that informal labour made up a significant part of the South African labour force from 2005 to 2007 (31% to 36%), though only a small part of labour income (8-12%) (Guerard, 2014). Other reports arrive at similar estimates (for the years 2001 and 2008) of informal employment varying between 18% and 36% of total employment, depending on the definition of informality, with the share in value added typically being smaller (Devey et al., 2003; ILO, 2013; StatsSA, 2008a; Valodia and Devey, 2012).

²⁰⁷ On the basis of Labour Force surveys, Income and Expenditure surveys and other surveys of households.

In the case of product taxes it is the category of the unit “other product taxes” which compensates for statistical differences with total product tax earnings as reported in SAM 2005 and SU tables produced through this universal application of the VAT to all final consumption (of households, by government, and for investment). This could lead to an under- or overestimation of VAT paid in final consumption depending on the household class (and to an over- or underestimation of the quantity of goods consumed). Recycling of carbon tax revenues through the reduction of a sales tax in the RVAT scenario could therefore lead to an over- or under-estimation of the effect which it has on the purchasing power and on the standard of living of different household classes. Specifically, one might assume that the poorest household classes buy more products through informal retail and therefore benefit less from this measure than currently found in IMACLIM-ZA’s results. On the other hand, also a benefit of revenue recycling through sales tax reduction might be unregistered, which is a reduction in informal retail, and therefore a higher share of formal activity and slightly higher income and profit tax receipts – therefore allowing to further reduce the sales tax or other taxes. Of course, a risk of introducing a carbon tax is that a part of trade and retail in energy products will move away from formal trade and retail to informal trade and retail. The estimation of this potential weakening-effect of informality, despite being out of scope for analysis with IMACLIM-ZA, on the effectiveness of a carbon tax should therefore be topic of further research.

Another option for future work is to develop a more nuanced treatment of income, property and property revenue taxes. These taxes are now aggregated into one single tax rate for each economic agent: For firms this rate is calibrated as the rate of the total of their revenue or profits and property income taxes paid over their total Gross Operating Surplus (GOS_F); For each of the five household classes the revenue and property income tax rate is calibrated over a households class’ total gross disposable income before taxation ($GDIBT_{Hh}$). This simplification limits the type of tax reforms which can be analysed with IMACLIM-ZA, and notably the treatment of profit taxes (a part of GOS coming from productive sectors goes to households in the form of mixed income), or of taxes on interests and dividends. Of course, also assets are aggregated into net (financial) assets, and not distinguished by type of asset (real estate, savings, government bonds, shares, stock options, etc.). This leaves little possibility to model tax reforms for their impacts on investment. On the other hand, other limitations to the current version of IMACLIM-ZA, such as the fixed profit mark-up rates and the endogenous interest rate, do not allow to model feedbacks of reforms of a more detailed tax system on investment behaviour either. In two cases, that of the two options for modelling revenue recycling through a reduction in firm’s profit taxes, this lack of endogeneity of the impacts of profit and property income taxes has been solved through a “what if” analysis, analysing both what happens if a reduction in profit taxes is accompanied by firms decreasing their net profit mark-up rates (RTIF-low) and what if profit mark-up rates stay fixed (RTIF-fix).

Income distribution, social security and other transfers

Besides for taxation, accurate data was also missing for the distribution of different types of primary

income (wages by level of skill and GOS) and of transfers between economic agents (social security and pension benefits, returns to capital, and other transfers). Especially, a disaggregation by household expenditure class was missing. With the help of several assumptions these knowledge gaps have been covered, in order to arrive at a plausible distribution of all kinds of income among household classes for BY calibration data. More on income distribution calibration data in Appendix B.4.

The importance of BY calibration data for the macro-economic projections is that in many cases values of these other types of incomes than labour income have been kept constant (see model description in Chapter 3). For example: future non-working age population is more or less constant over working age population by household class, and *per capita* unemployment benefits are kept constant over the CPI, while *per capita* pension benefits are kept constant over the average real wage. The main reason for these choices is that insights are lacking in the future dynamics that determine the distribution of income between household classes, e.g. regarding social security or GOS income. A consequence is that the model does not include much endogenous change in socio-economic characteristics of household classes. For this reason, income inequality can be considered to be quite rigid. Only the distribution of future employment and future ownership of (financial) assets among household classes really changes income inequality in IMACLIM-ZA, and even these two components are largely determined exogenously (see section 3.6.4).

In contrast to the rigidity of the way in which social security is modelled, one other parameter regarding public services changes a lot. This concerns the assumption that the quantity of government final consumption relative to South Africa's GDP grows 25% – an assumption which has justified in the light of an increased rate of returns on equity (ri_F , for interests and dividends) obtained in RP (see section 4.2.2). Possibly, both the assumptions about rigidity in social security and income distribution, and the assumption about change in government expenditure over GDP are too extreme. However, they can be considered to compensate each other in terms of the evolution of future government expenditure, meaning that the total share of government in GDP stays within a reasonable range going from 28.5% in BY calibration data to around 30 to 31% in RP and Ctax scenarios. As a part of future work a more nuanced approach could be developed, e.g. by constructing multiple scenarios for future social security policy and public services with the evolution of *per capita* GDP. For now, one must keep in mind that IMACLIM-ZA probably overestimates future income inequality and poverty due to restrictions on the growth of social security and due to rigidity in the demography, also for labour by level of skill, of household classes. This is the case in both RP and in the Ctax scenarios. The relative impact of the carbon taxation and its revenue recycling on inequality is therefore probably not much affected, and not over- or underestimated because of these assumptions on income distribution.

Construction of energy I-O tables in quantities

Assumptions have also been made in the estimation of (I-O table) energy bills to deal with lack of knowledge or to simplify certain aspects of the South African energy system. Appendix B.5 discusses

the most important assumptions one-by-one to evaluate their impact on results in a deductive manner. Here, two reasons are given for why IMACLIM-ZA potentially slightly underestimates the impact of a carbon tax on South Africa's economy due to assumptions in calibration of volumes of production, transformation and use of energy for fuels.²⁰⁸

The first reason is related to an unfortunate error in the construction of the energy I-O table in quantities regarding the quantity of exported refined fuels. The error made is that exports of refined products have been based on SATIM calibration data for these exports for 2006, and not 2005. This mistake causes IMACLIM-ZA to underestimate BY exports of refinery products (REF) by about 45%. Also, imports of crude oil (OIL) for production of exported refinery products are estimated 15% lower than should have been the case in IMACLIM-ZA's BY calibration data. Nevertheless, this error does not lead to a downward correction of oil import bills or of the export value of refinery products in comparison to the values found in SAM data and SU-tables: The oil import bill in IMACLIM-ZA equals that of the SAM 2005, and the export bill for refined fuels obtained with quantities of IMACLIM-ZA's calibration data is even more than 60% higher than the export value for refinery products obtained from SAM data and SU-tables. The latter might be because data used for this thesis overestimated for oil and refinery product prices. Else, SU and I-O tables underestimate the values of the flows of refinery products. The conclusion is that these errors need mending, but that so far information is lacking as to whether they translate into deviations from Input-Output statistics.

If, regardless of the comparison with SAM data one assumes that prices used for the estimation of the energy bills are right (see Appendix B.5), and that quantities for refinery products' exports and oil imports are indeed too low, then this would mean that IMACLIM-ZA under-estimates both the export value of refinery products and the value of crude oil imports. The consequences for the estimate of South African CO₂ emissions in BY calibration data would be small, because of the low CO₂ emission factor for oil refining relative to that of production of refinery products in CTL and GTL plants, while emissions from exported fuels are not taken into account in IMACLIM-ZA.

In contrast, IMACLIM-ZA's reference projection become more energy- and CO₂-intensive with a higher BY calibration estimate for volume and value of exports of REF products, due to the way the REF sector has been modelled. This can be understood in the following way: (1) in hybridisation, non-energy sector exports adjust to maintain the total value of exports of the SAM 2005. If REF's export value were to increase by 85%, then its share in total export value in BY calibration data would increase from 4% currently to 7%; (2) Translated to RP, the share in export value of 6% of REF in current results for RP would increase to about 10% (also due to the exogenous trend for growth of export volume); (3) This relatively higher growth of REF exports would also cause relatively higher consumption of coal and gas by the REF sector due to the Leontief structure for energy inputs (as part

²⁰⁸ The potential impacts on modelling results of assumptions made for deriving technological coefficients for electricity production from SATIM are discussed in the next sub-section.

of the “Energy aggregate”) to production, which means higher CO₂ emissions for the REF sector.²⁰⁹ As a consequence, the impact of a carbon tax on South African exports, the trade balance, and economic growth would be slightly bigger than in the results of this thesis. “Slightly” only, because analysis in section 5.4 showed that the effect of a cost increase for some exports on the rest of the economy is relatively small, due to exchange rate corrections and due to the big role that domestic demand plays in the South African economy.

A second reason why the construction of the I-O table in energy quantities potentially causes IMACLIM-ZA to underestimate the economic impacts of a carbon tax concerns the distribution of energy consumption for private transport over the five household classes. Assumptions consist of two steps: The first step allocates SATIM’s estimates for private vehicle energy use to SATIM’s three household classes; the second step distributes this energy use (together with residential energy use) to IMACLIM-ZA’s five household classes. The assumptions are such that this allocation of private vehicle energy use to household classes might result in an under-estimation of REF use for private vehicle use by the poorest household classes and in an overestimation for the richest household class (see Appendix B.5). After inclusion of residential REF consumption this translates in an under-estimation of REF consumption by the upper-middle income class (Hh4) of about 20%, and for the poorest three income classes (Hh1 to Hh3) of about 60%. This, in turn, would imply that current calibration data leads to an under-estimation of future demand for REF and future energy poverty, because the share of price-inelastic REF consumption is assumed higher in the budget of the poorest 4 household classes (about 3%) than in that of the richest household class (only 2% of their budget) in IMACLIM-ZA. If this rigid energy consumption increases on average, then the resulting bigger “attachment” to fossil energy use would mean that the economic impact of a carbon tax would be slightly bigger too.

Finally, the level of sectoral detail for the 34x34 sector I-O table which is used for hybridisation requires some assumptions on the distribution of energy end use by sector coming from SATIM, which has less economic sectors than the SAM I-O table. These assumptions are discussed in Appendix B.5, but are not expected to lead to a bias in the analysis of carbon taxation with IMACLIM-ZA. Similarly, assumptions made to obtain energy prices per user for the construction of the “energy bills” I-O table are expected to have no negative consequences for the estimation of economic and environment impacts of carbon taxation and different forms of revenue recycling. A detailed discussion of potential uncertainty due to assumptions in generating user-specific energy prices is given in Appendix B.5. Hybridisation of energy bills and SAM (and SU-table) data is performed on the basis of a 34x34 sector I-O matrix (see Appendix B.1).

Hybridisation and aggregation of the I-O table

To prepare the creation of the hybrid I-O table, some adjustments of SAM data (StatsSA, 2010a) were

²⁰⁹ In reality, the impact of a carbon tax on the South African economy with higher oil use by refineries and with a higher share of refinery products’ in export value should be limited, because of oil refining’s relatively low CO₂ emission factor.

necessary too. First of all, some SAM sectors had to be disaggregated to create the possibility to introduce energy sectors. This was done on the basis of information coming from Supply & Use (SU) tables (StatsSA, 2010b). In a next step, SAM data is made ready for hybridisation through a crude matrix multiplication which moves resources, taxes and margins between sectors along with the share in output value consisting of other sector's products. The objective is to obtain an I-O table on the basis of the principle "one sector = one product". This obviously causes differences in the cost structures of sectors, but considering that almost all sectors produce their own product in large majority, these differences are considered negligible. These adjustments of the SAM table are discussed in Appendices B.1 and B.5.

The sectors which change most due to hybridisation are – apart from energy sectors and transport services, and apart from the effect of aggregation of some sectors prior to hybridisation –: Textiles & footwear; Machinery & electronic equipment; Financial intermediation; Trade & retail; and Business activities & communication. These sectors respectively see the total value of their inputs and output change by resp. +123%, -37%, -17%, -15%, and -14%. Other sectors see their inputs or output value change by less than 10% of its pre-hybridisation value. In all these sectors except Trade & retail, more than three-quarter of the decrease in total value of inputs (resources) comes from a decrease in intermediate consumption (IC), imports, trade & transport margins and product taxes. One of the items of IC which increases for all sectors due to hybridisation is that of expenditure on transport services (TRA). For the Trade & retail sector IC of transport services increases strongly, to compensate its value added (VA) is reduced to arrive at a decrease in the sector's total output value, like for other sectors which have been designated in the hybridisation procedure to absorb changes caused by the introduction of energy bills. Many sectors who see their consumption of Transport services increase strongly, actually witness a small decrease in NOS and wages. The reason is that net operating surplus (NOS) and wages of the Transport services sector itself has grown. An exception is the coal sector, whose VA increases together with the increase in its IC. The reason is that in the hybridisation procedure the assumption is that energy sectors keep the ratio of VA over IC of their original cost structure if no other information about their cost structure has been used.

The changes caused by hybridisation of the cost structure of non-energy sectors (other than TRA) are smaller when translated to the aggregated sectoral level of IMACLIM-ZA: MAN's total output value becomes 7% lower, EIN's 1% lower, that of LSS 11% lower, and that of HSS 10% lower. In terms of gross value added (excluding product taxes minus product subsidies) the changes are comparable: MAN's gross value added decreases 11%, EIN's decreases 9%, LSS' gross value added decreases 8%, and HSS' decreases 5% due to hybridisation. The biggest part of these decreases is due to adjustments to accommodate the increase of the size of the Transport services sector, which – due to externalisation of companies internal transport activities – almost doubles in size, both in VA terms and in total resources and output (uses) value. The coal mining sector sees its value increase due to

hybridisation by a bit more than 50%, also mainly due to growth of the value of intermediate consumption (IC) of transport services. The refineries sector sees its total supply value grow by 21%, (also) mainly due to growth in the costs for IC.

The isolation of transport activities from other parts of productive activities is considered a useful change, in view of possible future work and in order to separately treat improvements in transport energy efficiency from those of industrial, manufacturing or buildings & appliances energy efficiency. Whether Transport services VA should grow as much as the sector's IC of refinery products and other energy products is questionable though, because company-internal transport might not be other industries' most VA generating activity. Better data on the cost structure of Transport services should therefore be integrated in the future.

The conclusion is that hybridisation has been moderately successful in isolating energy activity, especially electricity production, refineries and transport services, from the rest of the economy, while respecting aggregate macro-economic values as found in the SAM and without radically changing the economic structure of other sectors.

6.1.5. Compatibility with SATIM

Two different models cannot match perfectly. One must bear in mind that the two models are required to differ to some extent, because of fundamentally different approaches: SATIM assumes a “central planner” with perfect foresight and minimises the total cost of energy systems (within constraints) over the entire modelling period, but without macro-economic feedbacks. Conversely, IMACLIM-ZA has full macro-economic feedbacks but operates in a second-best setting and under myopic behaviour.²¹⁰ The approach for the evaluation of model and scenario compatibility between SATIM runs and IMACLIM-ZA scenarios is therefore to evaluate whether differences in modelling approach and assumptions (including parameterisation) explain *or* require differences in outcomes or trajectories and whether the found differences in trajectories are within reasonable margins. This is done partly quantitatively and partly qualitatively. The idea is to also assess how model and scenario differences could influence results of IMACLIM-ZA.

A comparison of in trajectories of SATIM with the change in the 2005 to 2035 one-step projection in IMACLIM-ZA shows that differences arise in 3 instances: the evolution of factor and input prices; in the resulting electricity price; and in the volumes of electricity produced and imported, and of coal

²¹⁰ Another issue for model correspondance is timing: IMACLIM-ZA is used in this Ph.D. thesis as a one-step “prospective static” comparison, whereas SATIM is a model with multiple time-steps of one to five years. Therefore, in SATIM data, like prices, are represented by year-to-year trajectories, whereas IMACLIM-ZA calculates new economic equilibrium with its resulting prices on the basis of a kind-of retrospective interpretation of what happened in the past time-period, as captured in its production and consumption functions, with for some parameters, such as import prices and factor productivities “end values” for the projection year exogenously given. In theory, IMACLIM-ZA's time-steps could be reduced, with trajectory data available for exogenous parameters, but for practical reasons such as model solving time this was abandoned. A consequence of the differences in both models dynamic characteristics is that the shape of parameter trajectories (e.g. timing of oil price increases or restraints in time of the introduction of certain technologies) in SATIM might differ from the “retrospective” 2005 to 2035 interpretation in IMACLIM-ZA. Luckily many parameters in SATIM grow almost linearly (rise of energy prices or the carbon tax) or close to exponentially (growth in demand with GDP), which resembles the “retrospective” interpretations of IMACLIM-ZA.

consumption (Table 6.1 Comparison of variables and parameters related to electricity production in SATIM runs and IMACLIM-ZA).²¹¹ For prices the observations are the following:

- The endogenous price trajectories in IMACLIM-ZA reveal some differences with the exogenous price trajectories of SATIM. (GDP deflated) coal price in IMACLIM-ZA increases from 8.1 million (mn) ZAR₀₅/PJ in BY to 14.3 mn ZAR₀₅/PJ in 2035 (w/o a Ctax). This is a faster increase than in SATIM, where it goes from 8.5 mn ZAR₀₅/PJ in BY to 12.9 mn ZAR₀₅/PJ in 2035 (w/o a Ctax). Two explanations can be given for the stronger increase of the coal price in IMACLIM-ZA: (1) prices of non-energy inputs and capital decrease relative to prices of other inputs and factors due to productivity gains, this means that the coal price increases when deflated by the GDP price index; (2) the increase of transport margins to exogenously impose a cost increase of domestic coal production might be too strong. In the case of carbon taxation the same mechanisms contribute to price increases of coal, with revenue recycling sometimes reducing the relative cost of labour and/or capital and non-energy inputs even further;
- Thanks to cost decreases with productivity gains of the elements of which the capital good consists in IMACLIM-ZA (mainly MAN and LSS) capital unit costs decrease in IMACLIM-ZA, while they are assumed constant in SATIM;
- Production of Materials & services products (Mat) in IMACLIM-ZA is on the one hand subject to higher costs of energy, but on the other hand benefits from productivity gains. The price of Mat therefore remains about constant;
- Labour costs (net wages plus charges), on the other hand, increase due to the increase of real wages with the reduction of the unemployment rate. In SATIM, labour and material costs are implicitly assumed to remain constant over time;
- Concerning the cost (for SATIM) or the producer price (for IMACLIM-ZA) of electricity production, which are modelling results in both models, the main difference is the price in BY 2005, which marks a period in South African history of underinvestment in electricity infrastructure (Baker et al., 2014; IEA, 2013): IMACLIM-ZA uses the regulated electricity price which reflect this under-investment, and which lead to almost zero net operating surplus in BY calibration data (implying zero returns to capital). SATIM, on the other hand, calculates the true cost of electricity production including levelized costs for capital rents. This way, SATIM's estimates a (societal) cost of electricity production which is higher than the (regulated) average electricity price that IMACLIM-ZA uses. Over time, this difference is eliminated. In the projection, some future differences in electricity prices between IMACLIM-ZA and SATIM runs still remain, but these originate from differences in the evolution of input

²¹¹ Intensity of power generation in terms of natural gas use and diesel use is not discussed here for reason of their negligible contribution to total power generation, see also Appendix C.8.

and factor costs which are a typical difference between a partial and a general equilibrium model.

Table 6.1 Comparison of variables and parameters related to electricity production in SATIM runs and IMACLIM-ZA

Model & Scenario Base Year (BY) or 2035 with or w/o Ctax	Unit	SATIM runs Upd.IRP-2010 (2035)				IMACLIM-ZA for RVAT (2035)*			
		BY 2006	No Ctax	R100 Ctax	R300 Ctax	BY 2005	No Ctax	R100 Ctax	R300 Ctax
Prices (in R05, & GDP PI deflated for IMACLIM)									
Avg coal price for Electricity (or ELC)	<i>mn R05/PJ</i>	8.5	12.9	17.3	29.6	8.1	14.3	24.2	43.7
Index capital (K) unit cost Electricity	<i>Index</i>	100	100	100	100	100	95.4	94.5	92.7
Index O&M unit costs of Electricity	<i>Index</i>	100	100	100	100				
Index of "Mat" unit cost ELC	<i>Index</i>					100	100.5	100.9	100.9
Index Labour (L) unit cost ELC	<i>Index</i>					100	148.4	145.3	141.3
Index KL-aggregate unit costs for ELC	<i>Index</i>					100	114.0	112.3	109.6
Electricity production cost (SATIM) or price (pY)									
Costs of ELC production (incl. Ctax)	<i>mn R05/PJ</i>	98	114	125	140	59	116	137	155
Volumes									
Electricity produced	<i>PJ</i>	904	1 791	1 731	1 690	844	1 401	1 229	1 017
Electricity imported	<i>PJ</i>	24	185	186	192	2.2	4.2	3.8	3.3
Coal consumed	<i>PJ</i>	2 663	4 392	3 285	1 916	2 541	3 569	2 419	1 199
CO ₂ emitted by power generation	<i>Mt CO₂</i>	257	424	318	186	240	338	229	114
CO ₂ intensity of electricity production	<i>Mt CO₂/PJ</i>	0.28	0.24	0.18	0.11	0.28	0.24	0.19	0.11

Comments: Results are shown for RVAT because the scenario obtains of all scenarios approximately intermediate results in terms of relative price changes, and growth in electricity demand.

In brief, the prices of inputs and factors to the electricity sector diverge especially for coal use and for the aggregate labour factor, and to a lesser extent for the (physical) capital factor. Labour costs seem less important as they only make up 16% of costs in total supply of electricity in BY, but they are a considerable part of the costs of the "KL" aggregate.²¹² The average price of the aggregate KL-factor increases 14% in RP, 12% in Ct100 RVAT, and 10% in Ct300 RVAT. Compared to the price of KL, the price of coal (relatively) can be calculated to increase by 55%, which is about the same as in SATIM. In contrast, the relative evolution of the coal price compared to that of the KL-aggregate in the Ct100 and Ct300 RVAT scenarios is respectively 31% and 41% faster than in SATIM.

The observation that the price of the KL-aggregate increases relative to the price of coal would imply that in IMACLIM-ZA the electricity sector should have replaced coal-fired power generation faster than in the results obtained from SATIM. Of course, in reality it is IMACLIM-ZA which likely overestimates the future costs of coal. But, the decrease in the costs of capital should still encourage the use of less coal-intensive electricity production, while the influence of the price of labour on technological choice might not be very big in reality. The conclusion is that the projected evolution of input and factor prices of IMACLIM-ZA does not completely correspond to results obtained from

²¹² In BY they are 42% of KL aggregate costs (physical capital plus gross labour costs), but due the exogenous increase of ELC's capital intensity with the catch up of investment in new capacity, labour's share in the KL-aggregate costs decreases to 29% in RP, despite labour's price increase and the exogenous increase in labour intensity.

SATIM. The lack of feedback in IMACLIM-ZA from relative prices on technological change in this case potentially leads to an under-estimation of the phasing out of coal-fired power generation, and therefore an over-estimation of the CO₂ intensity of electricity production. Macro-economically this could cause an over-estimation of the impacts of a carbon tax.

On the other hand, the developments in volumes of electricity production in IMACLIM-ZA should possibly have the opposite impact on coal and CO₂ intensity of electricity production: Due to lower GDP growth forecasts and the higher electricity price forecast, IMACLIM-ZA obtains a lower future electricity demand compared to SATIM. This should therefore translate into less new capacity additions for power generation. This would then probably mean that the share of coal-fired power generation remains higher.²¹³

What creates uncertainty around this evaluation of the future share of coal-fired power generation in IMACLIM-ZA is that a carbon tax is capable of pushing life-extension of old or discarded coal-fired power plants out of the electricity mix in the consulted SATIM scenarios – if electricity demand does not grow as fast, it might be possible that old coal-fired power plants are taken out of operation sooner. Depending on the carbon tax and on the extent to which this mechanism plays a role, one arrives at coal intensities and CO₂ intensities of power generation between 10% lower and 41% higher than in RP and Ctax scenarios of IMACLIM-ZA (see Appendix C.8 for details).

A last difference which stands out is the difference in electricity imports. This difference can mainly be explained through differences in calibration (Appendix C.8). Though imports are about 10% of future South African electricity supply in the results of the SATIM runs, their amount is probably mainly determined by technological capacity (international grid connections), and it is therefore considered of minor importance for the analysis of carbon taxation in IMACLIM-ZA.

Overall, the differences found in trajectories for prices and electricity demand are considered to be relatively small especially considering the strong possibility that the two main differences (capital prices and growth in demand for electricity) probably cancel each other. The use of technological coefficients from SATIM in IMACLIM-ZA is therefore considered acceptable.

6.1.6. Strategic choices

On a more strategic level there are some things that need to be kept in mind too when looking at these results. Firstly, the impacts as compared to the RP have been presented to estimate as a matter of speaking “the economic weight” of the carbon tax, but especially, to have a point of comparison to understand how the carbon tax and the recycling mechanism function. Without an RP it would not be clear how other assumptions for the projection of the South African economy to 2035 would work out. The RP should not be interpreted as a prediction of South Africa’s future under inaction in terms of climate change. Many other policy interventions and other developments in time will play a role in the

²¹³ Due to a higher share in the electricity mix of old coal-fired power generation and of under the updated IRP-2010 already planned expansion of coal-fired power generation.

real evolution of South Africa's economy, and other non-considered policies have a part in South Africa's GDP growth and joblessness problems (see the discussion in section 1.1). Also, it seems increasingly utopic to think nowadays of a future in which climate change will have no consequences for economic output. For South Africa, questions could for instance be how climate change impacts its agricultural output, or the cost of agricultural products, and their role in the cost of living and the remaining budget for non-agricultural demand. As such, the distance to RP is not the real measure for the impact of a carbon tax policy.²¹⁴ This is the reason why the adverb “unsustainable” has been added to the Reference Projection.

Criticism on the RP could also be that the growth projection is based on exogenous parameters for technological change or productivity growth and on the trend in volume of exports, which have been chosen to arrive at a balanced economic growth path, which respects normal ranges of values for several central macro-economic indicators, such as the REER, returns on investment (captured by interest rates), and the labour and capital shares of value added. Whether technological progress would really follow such a trajectory is unknown. The ideal solution would be to consult industrial and labour economics experts, and experts of production technology of major economic sectors, as well as market experts for markets of specific export and import goods for the South African economy, in order to construct a better set of assumptions about these future developments.

A remark should also be made about the suggested comparison between different recycling options: Modelling of different recycling options might be severely limited and might underestimate or overestimate economic outcomes of specific scenarios compared to what could be expected if more second-order impacts would have been taken into account. These impacts could be feedbacks on technological change, and possible benefits in terms of better public health or lower crime rates which could lead to higher productivity gains (see e.g. Cichello et al., 2011; Haarmann et al., 2009). This might lead to an underestimation of benefits of particularly the lump-sum revenue recycling scenario (RSUM). On the other hand, some for economic development disadvantageous phenomena have not been taken into account either: e.g. investment in, and exports of manufacturing and services might suffer from the volatility of South Africa's exchange rate (Hausmann, 2008).

Another strategic limitation to the study is that only a limited set of policies has been tested (mainly due to a simplified representation of the South African tax system), and that policies have only been analysed for a limited number of indicators of economic, social and environmental success. Proposals to diversify policy evaluation, e.g. as those by the Commission Sen-Stiglitz-Fitoussi (Stiglitz et al., 2009), were unfortunately out of our scope.

6.2. Comparison to other studies on carbon taxation in South Africa

This sub-section compares outcomes of basis scenario analysis with analyses by others. Chapter 1

²¹⁴ Other considerations about what a good Reference Projection could entail are for instance discussed by Rozenberg *et al.* (2014).

discussed substantial prior analysis of the impacts of a carbon tax in South Africa.

6.2.1. Alton *et al.* (2012, 2014)

Both the scenarios of the present study as their results seem closest to those of Alton *et al.* (2012, 2014): Recall that Alton *et al.* find that a carbon tax of 210 ZAR₂₀₁₀/tCO₂ (145 ZAR₂₀₀₅/tCO₂) by 2025 leads to an approximate 36% decrease in GHG emissions relative to BAU (41% when deducting net exported emissions). This means that their findings are consistent with South Africa's NDC, depending on the baseline. In the case of a domestic "production" carbon tax, GDP losses in 2025 range between 0.7% and 1.7% relative to BAU (depending on the recycling option). It must therefore be concluded that Alton *et al.* find more modest economic impacts of a carbon tax compared to the results for carbon tax revenue recycling scenarios of this thesis. The impacts on CO₂ emissions of carbon taxation that Alton *et al.* find are stronger than found in this thesis: For a carbon tax of 100 ZAR₂₀₀₅/tCO₂ this study finds reductions in CO₂ emissions of only around 20 to 25% relative to RP, assuming a 2013 update of the IRP (RSA, 2013b).

The most similar result to that of this study that Alton *et al.* find that the South African economy already significantly decarbonises for carbon tax rate that is modest from an international perspective (of 27 USD₂₀₁₃ per tonne of CO₂). The reason for this sensitivity of South African CO₂ emissions to the price of CO₂ must be sought in the fact that South Africa comes from a situation with very low energy prices, as outlined e.g. in Pauw (2007, Table 6, p.35), while the economy is very CO₂ intensive due to a high reliance on coal. The price impact of a carbon tax is therefore relatively big and has a relatively high weight in the South African economy. This is also the case in IMACLIM-ZA (e.g. compare Figure 4.11 with Figure 4.10 on p.171).

The standard carbon tax revenue recycling mechanism in e-SAGE is a reduction of a sales tax, which obtains medium outcomes compared to the two other scenarios for carbon tax revenue recycling: a social transfer to households and a reduction of corporate tax rates, respectively comparable to the lump-sum transfer scenario (RSUM) and the reduction of profit taxes with lowering of profit mark-up rates (RTIF-low) in IMACLIM-ZA. The relative preference between these scenarios for GDP growth is the same as found with IMACLIM-ZA in the present study.

The differences in outcomes between this study and Alton *et al.* (2012, 2014) should be attributed to differences in modelling, parametrisation, and scenario definition. Firstly, GDP growth might be easier to obtain in Alton *et al.*'s model and less sensitive to carbon taxation for a few reasons:

1. Alton *et al.* assume carbon-adjusted import tariffs and export-rebates to avoid the disadvantages of the price increases due to a carbon tax for international competition. Indeed, also in IMACLIM-ZA a scenario with a multilateral carbon tax regime translates into a few percent points higher GDP and lower unemployment, though the resulting impacts for GDP growth and employment of that scenario are still bigger than in Alton *et al.*

2. Secondly, the e-SAGE model is likely not capable of obtaining strong impacts on GDP growth due to the way it models the growth engine; particularly how it models factor markets, output growth and investment: (i) e-SAGE represents the South African economy already with a higher degree of flexibility to adjust to adverse circumstances than IMACLIM-ZA, because of e-SAGE's intertemporal profit maximisation which sets profit mark-ups to clear the capital market (full use of capital) and with wage-setting that clears medium and high skill labour market segments; (ii) the way investment is modelled likely has a moderating impact on prospective GDP growth.

To understand the latter, consider the following: The basis for GDP growth in e-SAGE is exogenous growth of total factor productivity (TFP), which has the same function as exogenous growth of output productivity of factors plus efficiency improvement for intermediate inputs in IMACLIM-ZA. Beyond this growth of TFP, it is factor availability that determines output growth in e-SAGE, while a CES function determines substitution between capital and aggregate labour at the sectoral level. Factor availability is determined in the following way:

- Labour supply by level of skill is exogenous and medium and high skill labour is fully employed at wages that guarantee full employment (market-clearing wage setting). In contrary, for low- and unskilled labour Alton *et al.* assume an upward-sloping labour supply (LS) curve with an elasticity of 0.1, which implies that wages can be considered very inelastic²¹⁵, but this inelasticity is rather advantageous for GDP growth, because low- and unskilled labour remain cheap in times of decreasing unemployment, which can be observed in Alton *et al.*'s result of baseline evolution of real wages: those of low-educated workers increase with less than 1% on average per year, while those of high-educated workers increase 4% per year;
- Capital availability is driven by a fixed exogenous saving rate for households, who earn all primary factor income. This is accompanied by exogenous inflow of net foreign investment, fixed at an absolute amount in foreign currency and thus variable with the exchange rate.²¹⁶ This foreign investment has a moderating impact on GDP growth: In case growth of real household income decreases because a carbon tax makes households' preferred products more expensive and therefore reduces their real income, this exogenous foreign investment pushes GDP growth upwards. It namely guarantees a steady flow of gross fixed capital formation and of demand for exports, even if household savings and demand are depressed a bit.

Furthermore, in contrast to IMACLIM-ZA, net debts and assets are not tracked in e-SAGE. The latter means that net foreign investment could be considered a gift (at least within their time horizon up to

²¹⁵ For instance, a wage curve with an elasticity of 0.1 (or 0.15) (as in IMACLIM-ZA, see section 3.3) corresponds roughly to an upward sloping labour supply curve with a (non-constant) elasticity around 0.3: see [Box 7](#).

²¹⁶ Foreign investment plus the trade balance add up to zero.

2025), because returns to capital all go to households, and firms do not pay for the “debt service” of foreign investment. Altogether this means that foreign investment compensates for possible fall-backs in growth of the capital stock if household savings plus TFP growth would turn out lower.

In contrast, in IMACLIM-ZA’s fixed profit mark-ups and rigid wages for all skills of labour are likely less optimal for GDP growth. As shown in section 4.2.2, “claims” for income by labour (wages), capital (rents) and government (indirect taxes) can affect GDP growth negatively if they increase relative to the growth of average factors’ and intermediate inputs’ output productivity. This namely increases costs and thus reduces domestic demand and international competitiveness. Furthermore, in IMACLIM South Africa there is no intertemporal optimisation, and the implicitly present capital stock follows results for GDP growth rather than driving GDP growth, and there is no exogenous source for investment. Growth in IMACLIM-ZA can therefore be concluded to be more sensitive to the excess burden of a carbon tax than in e-SAGE.

However, two additional aspects should be taken into account to explain results for GDP growth in e-SAGE, but they can be reasoned to have opposite impacts on GDP growth under carbon taxation. Their net influence therefore depends on their precise calibration in e-SAGE, which is not given in Alton *et al.* (2012, 2014). The first aspect is that Alton *et al.* assume that energy efficiency gains increase in response to the relative change in energy prices, and that they also depend on the speed at which capital stock is renewed. In this way the ratio of value added (VA, or capital and labour income), which grows relative to non-energy intermediary inputs with TFP, grows faster over intermediate inputs of energy products. However, there is no substitution of energy by capital or labour in parallel to these energy efficiency gains, and from this perspective e-SAGE’s energy efficiency gains can be considered to resemble energy efficiency improvement that is free of charge. IMACLIM-ZA does not assume autonomous energy efficiency improvement in the main scenario analysis presented in Chapter 4, and only has price-elastic reductions in energy intensity in a trade-off with capital, labour and other inputs. This means that (within sectors) energy efficiency comes at the cost of higher expenses for other factors. Of course, IMACLIM-ZA’s increase in efficiency of use of materials & services inputs indirectly has a similar impact on energy intensity of average South African output as free energy efficiency gains, but as mentioned, this efficiency gain could be considered rather equivalent to a part of TFP gains in e-SAGE. Furthermore, it is irrespective of energy prices and it is therefore the same with or without carbon taxation while e-SAGE’s free energy efficiency gains increase under carbon taxation.

The other not yet mentioned aspect that plays a role in GDP growth in e-SAGE, and which probably is the model’s only assumption that is disadvantageous for GDP growth under carbon taxation, is that e-SAGE fixes its outlook for electricity production at the Integrated Resource Plan for their (revised) baseline, which means that the energy intensity of electricity production is irresponsive to carbon taxation. This assumption however is acceptable given the time horizon of Alton *et al.*’s analysis,

running from 2010 to 2025. Nevertheless, the rigidity of electricity production in South Africa might be economically disadvantageous, as decarbonisation of the electricity sector seems one of the cheapest forms of CO₂ emission reduction for South Africa (Merven et al., 2017).

The conclusion here is that there are sufficient elements which could explain the difference in impacts on GDP growth and employment between the results of Alton *et al.* (2012, 2014) and those of the present study. Parameterisation of TFP and energy efficiency improvement in e-SAGE should furthermore explain the strong CO₂ emission reductions obtained in their analysis.

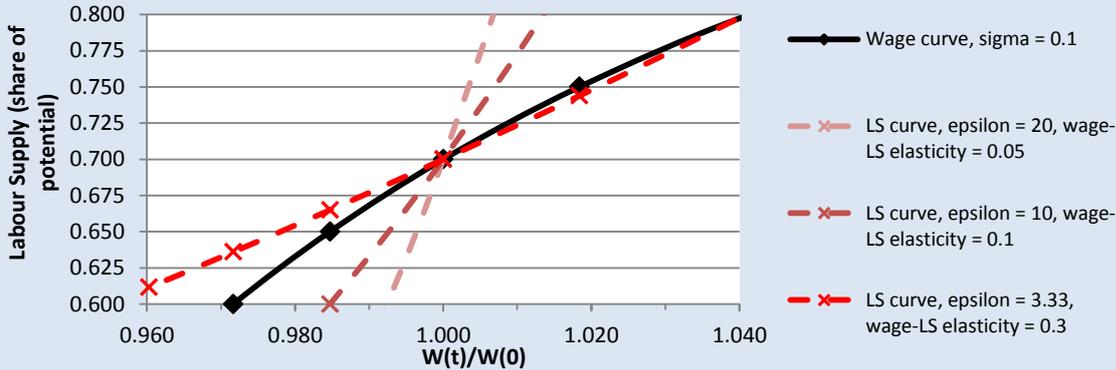
Box 7 Differences between Labour Supply curves and the wage curve

Alton *et al.* (2012, 2014) define a labour supply curve for low and unskilled labour, with equilibrium labour supply, *LS*, over base year labour supply, \bar{L}_S , related to equilibrium wage, *W*, over base year wage, \bar{w} , through supply-wage elasticity, ϵ : $LS = \bar{L}_S * \left(\frac{W}{\bar{w}}\right)^\epsilon$

For their central case this means that Alton *et al.* assume an increase in labour supply of (employed) low and unskilled workers to translate into only modest salary gains²¹⁷, which is expressed by the assumption of a real wage-labour supply elasticity of 0.1. This elasticity is the inverse of epsilon, which expresses supply-wage elasticity and whose value therefore equals 10.

In a sensitivity analysis Alton *et al.* test wage-supply elasticities of 0.05 and 0.3. A standard wage curve with a wage-unemployment elasticity of 0.1 as used in IMACLIM-ZA is closest to the latter of the two values, as can when one plots in the a wage curve in the same way as a labour supply curve (Figure 6.1). Besides, the experimentally found wage curve would resemble a labour supply curve with non-constant elasticity; hence the curve in Figure 6.1 would take the form of a polynomial equation rather than that of an exponential relation as the labour supply curves.

Figure 6.1 Labour supply with relative real wage, for different labour supply curve elasticities and a wage curve



In their sensitivity analysis Alton *et al.* find lower GDP losses, but surprisingly higher employment losses with carbon taxation for the higher ϵ value. Possibly (the details published about results and model parameterisation of Alton *et al.* are insufficient to be sure), this is caused by better educated

²¹⁷ The labour supply curve's theoretical principle actually proposes the inverse, but South Africa is marked by high involuntary unemployment, thus it would be safer to assume that it is a lack of jobs, rather than low pay, which keeps people out of work.

workers, whose wages clear their labour market segments, being capable to claim higher wage rates when low skilled labour sees their wage rate decrease quicker with an increase of unemployment. In a second step, high skill labour's final consumption *might* be disadvantageous for low skill labour intensity of production in e-SAGE, requiring more energy and high skill services goods, and as a percentage of budget less low skill services.

6.2.2. Merven et al. (2014) and Altieri et al. (2015)

As mentioned in section 1.4 Merven *et al.* (2014) and Altieri *et al.* (2015) analyse economic strategies for, and impacts of CO₂ emission reduction using a linked model which combines the e-SAGE CGE model of Alton *et al.* (2012, 2014). In the case of Merven *et al.* e-SAGE is coupled to the electricity sector version of the South Africa TIMES bottom-up energy system model (SATIM-E) to compare a business-as-usual reference scenario with the introduction of a carbon tax, and two scenarios where emission reduction is achieved by increased renewable energy. Altieri *et al.* study how two distinct socio-economic development paths for South Africa perform under a carbon budget constraint of 14Gt cumulative CO₂ emissions for the period 2015 to 2050. In their study, SATIM's full energy sector version of (SATIM-F) is used to determine the optimal CO₂ emissions trajectory for the electricity sector.²¹⁸ This trajectory is imposed on the coupled e-SAGE – SATIM-E model, which further adjusts energy demand to meet the constraint of the CO₂ emission budget. The advantages of both studies compared to Alton *et al.*'s study (2012, 2014) are that they use a linked model to consistently model the development of power generation and its CO₂ emissions in view of fuel prices, carbon prices and an electricity demand that is responsive to endogenous GDP growth.

Merven et al. (2014)

Merven *et al.*'s study only considers power sector CO₂ emissions, and therefore does not present economy-wide outcomes for CO₂ emissions (Merven et al., 2014). Under conservative assumptions for the future costs of renewable energy technology Merven *et al.*'s additional renewable power generation scenarios (RE1 and RE2) lead to negative GDP projections in comparison to achieving emission reduction through the introduction of a carbon tax (Ctax). However, the impacts of their three scenarios on GDP in 2040 remain small, between -0.7 (for a Ctax) and -1.9% (for RE2). Impacts on employment are a bit bigger, namely between -2.5% (for RE1) and -3.9% (for RE2) with the RE1 scenario leading to a positive impact on employment and the RE2 scenario to a negative impact compared to the carbon tax scenario. The reason for difference in economic outcomes is that the carbon tax is recycled into a sales tax reduction, and therefore leads to output growth in non-energy intensive sectors, such as agriculture and the food industry. The RE1 and RE2 scenarios do not have the benefit of revenue recycling, and in fact absorb a part of the rigid amount of investment (see the discussion of Alton *et al.* (2012, 2014) just before).

²¹⁸ Altieri *et al.* (2015) perform one iteration between SATIM-F and the coupled e-SAGE – SATIM-E model to adjust the former to GDP growth, and energy demand coming from the latter.

In the case of more optimistic assumptions about future cost decreases for renewable energy, Merven *et al.* find that this strongly improves the economic outlook of the RE2 program, and to a lesser extent of the RE1 program, whereas there is hardly any change in results of the carbon tax scenario, which sticks closer to the updated IRP of 2010 for South Africa's future power generation. The latter would imply that the updated IRP 2010 under-invests in renewable power generation if future costs of renewables turn out lower. Merven *et al.*'s outcomes suggest that it would be better in this case to decarbonise electricity generation than other sectors. On the other hand, it would be preferable to have a better informed model for energy use in other sectors than power generation to evaluate whether priority in decarbonisation should lie in power generation or in other economic sectors.

In IMACLIM-ZA such high renewables power generation scenarios have not been tested, and a comparison of the outcomes is therefore not really possible. The carbon tax scenario of Merven *et al.* (2014) consists of a carbon tax that is similar to the 100 ZAR/tCO₂ carbon tax scenario used in this thesis, though the 100 Rand Ctax rate in SATIM of this thesis is achieved in 2020 and not 2025 as is the case for the 120 Rand Ctax rate in Merven *et al.*'s study. In IMACLIM-ZA the carbon tax leads to a reduction of CO₂ emission intensity of electricity production of about 10% by 2025 and about 24% by 2035 (see coal intensity in section 3.1.3 – absolute changes cannot be compared, because the evolution in the total output of power generation is different between the present and Merven *et al.*'s study).

Merven *et al.* (2014) find a similar relative impact on GDP growth for their carbon tax scenario as Alton *et al.* (2012, 2014) do, but relatively bigger impacts on employment, and this despite the fact that the carbon tax they test is about 2.5 times lower than the central carbon tax scenario of Alton *et al.* (10 USD/tCO₂ instead of 25 USD/tCO₂). The reasons for this smaller difference are unknown, and might be related to other parameters (e.g. the saving rate or foreign investment), e.g. reference growth is higher in Alton *et al.* than in Merven *et al.* (2014) (respectively 3.9% and 3.1% per year). The explanations for differences of GDP sensitivity of e-SAGE to carbon taxation between Merven *et al.*'s study and this thesis are likely the same as for the differences with Alton *et al.* (2012, 2014), namely, in their case lower GDP sensitivity to carbon taxation because of: an unresponsive investment volume; intertemporal welfare optimisation; capital market-clearing profit margins and market-clearing wage setting for a large part of the labour market; and costless energy efficiency gains.

The take-away of Merven *et al.*'s analysis for IMACLIM-ZA is that, there is a possibility that the one-way integration of SATIM outcomes in IMACLIM-ZA might lead to sub-optimal decarbonisation of the electricity sector. Under optimistic assumptions about future cost of renewable power generation, the costs of electricity could turn out lower. If IMACLIM-ZA were to take the latter into account, it would find less negative consequences of a carbon tax for future South African GDP growth and unemployment. Vice versa, IMACLIM-ZA also has lessons for the study of Merven *et al.*, because analysis in IMACLIM-ZA suggests that GDP growth really only depends on future productivity and the change in average (real) costs of domestic output. In IMACLIM-ZA, there is no competition for a

rather rigid amount of investment as in e-SAGE, and the lower electricity costs of Merven *et al.* Renewable Energy investment programs would be a stimulus for growth and likely lead investment programs in renewables to turn out relatively more advantageous compared to a carbon tax scenario than found by Merven *et al.* (2014).

Altieri et al. (2015)

Altieri *et al.* (2015) do not analyse the implementation of a carbon tax, but work with a 14 Gt cumulative CO₂ emission budget, optimally divided in a budget for the power sector and one for the rest of the economy on the basis of analysis with SATIM-F. They consider two economic visions, tested by means of introducing “shocks” relative to reference assumptions of the linked e-SAGE – SATIM-E model, and analyse how both visions turn out economically in respecting the cumulative emission budget. The first vision they test is one of increased investment in low skill labour-intensive sectors, e.g. agriculture, furniture, and the “other services” sector. The second vision they test is one in which they increase strongly the number of high and medium-skill level workers entering in the job market to reduce the skill shortage. They show that South Africa achieves considerable GDP increases in both scenarios: GDP per capita is almost three times higher than in 2010, with an average annual GDP growth from 2010 to 2050 around 2.7%, and highest for the low skill investment scenario. The latter scenario also achieves the highest increase in employment, however inequality is slightly higher for this scenario than for the high skill scenario with a bit more people in the lowest income class (18%) than in the high skill labour scenario (17%).

The CO₂ emission budget of Altieri *et al.* (2015) consumed between 2010 and 2035 approximately corresponds to 10.6 Gt of cumulative CO₂ emissions (425 Mtonne of CO₂ annually on average).²¹⁹ This is about the same size of the carbon emission budget implicitly estimated for the period 2005 to 2035 for the NDC scenarios of IMACLIM-ZA (see section 5.2), though the difference is that the latter includes process emissions, whereas Altieri *et al.* only count energy-related CO₂ emissions, which should roughly equal 85% of total CO₂ emissions (see section 1.2). In other words, they assume a significantly less stringent CO₂ emission budget.²²⁰

Although Altieri *et al.* do not publish results of their scenarios in comparison to a reference scenario without a carbon budget, some comparison of their results to those of IMACLIM-ZA is still possible. First of all, GDP growth figures of Altieri *et al.* (2015) are higher than IMACLIM-ZA’s finds for the Ct300 RTSC and RTIF-low scenarios, which obtain approximately 2.3% average annual GDP growth and CO₂ emissions of about 380 Mtonne by 2035 (see section 4.3.2), which means CO₂ emissions that are less constrained than the 350 Mtonne of IMACLIM-ZA’s NDC scenario, but still more constrained than Altieri *et al.*’s energy use-only CO₂ emissions of about 400 Mtonne in 2035 (which would imply 470 Mtonne of total CO₂ emissions). Altieri *et al.*’s figures are however closer to the findings of

²¹⁹ These numbers are based on a visual interpretation of Figures 17 and 18 on p.31 of Altieri *et al.* (2015).

²²⁰ Applying the 85% ratio of energy-related CO₂ emission to the carbon budget, Altieri *et al.*’s scenarios imply a carbon budget of 12.5 Gt for the period 2010 to 2035.

IMACLIM-ZA under a more optimistic assumption about wage indexation on average productivity (see section 5.6.3) which find average GDP growth for 2005 to 2035 of 2.7% and CO₂ emissions of 416 Mtonne by 2035 – meaning that IMACLIM-ZA finds more decarbonisation by 2035 for similar GDP growth. The most striking difference likely is that of the evolution of unemployment, which in Altieri et al. increases between 2015 and 2030, to decline strongly thereafter up to 2050, but by 2035 they find an unemployment rate that is at best similar to that of 2010.²²¹

The differences between results for Altieri *et al.* (2015) and those of this thesis seem not to be justified by the difference in carbon budget. In fact, given the larger carbon budget in Altieri et al. it might actually seem surprising that they do not obtain better economic outcomes than found in the scenarios of this thesis. The relatively weaker economic outcomes of Altieri *et al.*'s analysis relative to those found in this thesis can probably be explained from model differences. First of all, Altieri *et al.* take into account the investment needs to reduce CO₂ emissions steeply after 2035, which IMACLIM-ZA does not. Furthermore, though this is a bit speculative due to insufficient model details in Altieri *et al.* (2015), their carbon budget scenarios might suffer from the same disadvantage of the way investment is modelled in e-SAGE as Merven *et al.*'s renewable energy investment scenarios – namely that these investments reduce the largely exogenously fixed sum of investment available to other sectors, and such a lack of investment reduces gains in energy efficiency in the rest of the economy. This could temporarily slow down growth. At least, this is the impression one gets from the fact that Altieri *et al.* find higher *per capita* GDP growth after 2030 than before 2030. The underlying logic is that investments for energy sector expansion are mainly required when population growth is strongest, and in advance to the use of new energy infrastructure, which is when the demographic growth of labour supply is strongest, which is until 2030 (see for instance: UN DESA, 2013).

Furthermore, even in the case of their “high skill” scenario Altieri *et al.* (2015) assume growth rates of (high) very skilled and (medium) skilled labour supply that are below the average population growth rate of 1.5%, namely respectively 0.6% and 0.5% per year. This implies a declining share of high and medium skilled labour in the total labour force (assuming that the total working age population grows at least at the rate of population growth), and therefore an increase of the skill labour shortage even compared to IMACLIM-ZA's positional approach to labour market modelling. Their assumption should translate into a strong growth of medium and high skill wages and therefore into an increase of average production costs, which should slow down GDP growth. Their assumption might be in agreement with the literature they cite about the lack of educational quality and the existence of a two-class education public system, but I personally would expect that their assumption is an exaggeration and that the percentage of population with access to good quality schools (and therefore the share of people that obtain proper labour market skills) should nevertheless have increased since the end of

²²¹ Altieri et al.'s (2015) measure for unemployment must be the official unemployment rate considering that they use an unemployment rate of 24% in 2010 (see their Figure 12 at page 27), which corresponds to the official rate found in South African labour statistics (see section 3.1.4), but this should not be an issue for the comparison of the relative evolution of the unemployment rate.

Apartheid. The exact reasons for differences with the present study however remain unclear and require further investigation in the future.

Lacking a neutral reference scenario, the impact of a higher availability of high skill labour cannot be compared between this thesis. It can therefore hard to explain why Altieri *et al.* (2015) find it to be economically less attractive than their other scenario, whereas this thesis finds an investment in skills to have a positive impact on GDP growth, employment and decarbonisation per unit of GDP compared to the other scenarios tested. Likely the combination of fully employed high skill labour segments and a labour-supply curve with rigid wages for low skill labour segments plays a role in Altieri *et al.*'s. (2015) outcomes.

6.2.3. Comparison with other studies

Van Heerden et al. (2006)

Comparison to Van Heerden *et al.* (2006) is difficult, considering that Van Heerden *et al.* do not analyse environmental taxation and its revenue recycling in an integrated analysis, making it thereby not possible to take into account interactions between different taxes. Furthermore, Van Heerden *et al.* only perform a static analysis on 1998 SAM data, for a very low carbon tax rate of 35 ZAR₁₉₉₈/tonne CO₂. The only possible comparison left is that of the relative impact of different revenue recycling mechanisms. However, due to the differences in scenarios and modelling assumptions, comparison remains indirect.

In contrary to this thesis, Van Heerden *et al.* find strong a double dividend –i.e., an increase in GDP with the carbon tax relative to baseline – when recycling carbon tax revenue through reductions of VAT. However, their analysis limits the reduction to a tax break on food, while they also do not find for a general sales tax break or a break in direct income taxes. This recycling mechanism could not be tested in IMACLIM-ZA, because no agriculture or food industry sectors exist in IMACLIM-ZA's sectoral disaggregation. A break in direct taxes has not been tested either, though a more general sales tax break has been tested in IMACLIM-ZA and did not generate a double dividend in the present study either. Concerning the food tax break, Van Heerden *et al.* (2006) explain their finding as follows: “when energy is complementary to capital [as they assume], and when tax revenue recycling can be used to increase [in practice infinitely supplied] unskilled labour demand [as the food tax break does by increasing demand for agricultural products and thus for agricultural, mostly low-skilled labour], a double dividend may materialize in South Africa as in the model of Bovenberg and van der Ploeg (1996; 1998).”

That Van Heerden *et al.* (2006) find this double dividend might be caused by the fact that they do not study the interaction of taxes, meaning that the impact of a carbon tax on production costs of for instance agriculture and the food industry is not taken into account in their estimation of marginal benefits of the reduction of the sales tax. Furthermore, capital and profit margins are fully flexible just like high skill labour, which is in inelastic supply and which has perfectly flexible wages. This means

that adjustment costs of the economy are relatively low. Only low skill labour poses a rigidity in factor markets in their model, because low skill labour supply is elastic to real wage, which is exactly the cost that is addressed by revenue recycling through a reduction of sales taxes on food. This is however a similarity with the results of this thesis, which also identifies the reduction of labour costs as an efficient way of stimulating GDP growth under carbon taxation.

Devarajan et al. (2009, 2011)

The analysis by Devarajan *et al.* (2009, 2011) does take into account interactions between taxes by modelling environmental taxes and revenue recycling in the same way. Their analysis however also is a comparative statics analysis (on the basis of SAM data for 2003). They find surprisingly low welfare impacts: Only 0.3% welfare losses when recycling revenue of a carbon tax that achieves a 15% CO₂ emission reduction through reduction of all indirect taxes (on sales of products, on production, and on imports). Of course, they also assume fully flexible capital, and wage setting is market-clearing for the majority of the labour markets which they model. Furthermore, their labour market segments are not rigid, as some career switching is possible in the household and labour supply microsimulation model that they use. Nevertheless, they (like Van Heerden *et al.* (2006)) do not take into account energy sector rigidities for electricity production as this thesis, Alton *et al.* (2012, 2014), Merven *et al.* (2014) and Altieri *et al.* (2015) do. Whether this plays a role, and what the role of energy efficiency in other sectors is, remains unclear, because Devarajan *et al.* do not report on the elasticities of their CES production functions, neither on those for international trade. Lacking these details, the only conclusion that can be drawn is that this thesis agrees with the finding by Devarajan *et al.* that labour market rigidities play a big role for the welfare impacts of environmental taxation in South Africa.

Pauw (2007)

In contrast to Van Heerden *et al.* (2006) and Devarajan *et al.* (2009, 2011), Pauw (2007) does take into account bottom up insights on technological change, by using results from a partial-equilibrium MARKAL linear optimisation model for the South African energy system. The MARKAL model generates shares for different energy technologies in electricity and refineries for Pauw's CGE model. This set-up actually looks similar to the energy part of the e-SAGE model of Alton *et al.* (2012, 2014), though there is no coupling, and results of the MARKAL model are implemented unidirectional to the CGE model (as is the case with SATIM outcomes in this thesis). Of the three scenarios analysed by Pauw, the "Use the market" scenario bears the biggest resemblance to the analysis in this thesis. Pauw's Use the market scenario seems to result in a 17% to 25% reduction in CO₂ emissions between 2000 and 2015 (Winkler (ed.), 2007). To achieve this, carbon taxes increase to about 350 Rands per tonne of CO₂, which is higher than the tax rates modelled in this thesis.

Surprisingly, the high carbon tax only leads to 2% loss in GDP relative to business-as-usual, and it even leads to higher employment for the second least skilled employment category (semi skilled labour) out of four skill categories of labour. A part of the explanation is probably again flexibility in a

large part of the labour market and in the capital market, and furthermore the beneficial impact of revenue recycling through food tax breaks (similar to Van Heerden *et al.* (2006)), because the latter reduces labour costs of unskilled and semi-skilled labour – which have rigid real wages. However, another part of the seemingly low sensitivity to carbon taxation might be the fact that energy efficiency gains for non-energy sectors are copied from the MARKAL model as “free of charge”, meaning that they do not require higher capital or labour intensity. Whether this really plays a role cannot be assessed, because little detail is provided about the energy efficiency obtained for Pauw’s different scenarios. As Pauw (2007) does not analyse other revenue recycling mechanisms, little can be learnt from the comparison between his study and the analysis of this thesis.

6.2.4. Conclusion

In conclusion, one can say that the present study finds macro-economic impacts and a CO₂ emission sensitivity to combinations of carbon taxation with certain forms of revenue recycling that are bigger than those found by Alton *et al.* (2012, 2014) and Merven *et al.* (2014), but smaller than those found by Altieri *et al.* (2015). The reasons that this study finds larger impacts on GDP and employment compared to the former two studies must be linked to a lower GDP sensitivity to carbon taxation of e-SAGE, because in e-SAGE: investment volume is less responsive to GDP growth than in IMACLIM-ZA; intertemporal welfare optimisation leads to underestimate transition costs; and higher adjustment flexibility of the economy thanks to capital market-clearing profit margins and market-clearing wage setting for a large part of the labour market; and also – and probably not unimportant - energy efficiency gains that are free of charge, meaning that do not require higher capital or labour intensity. Also, Alton *et al.* (2012, 2014) assume export rebates and carbon-BTA on imports to protect South African industries. In this thesis, a more level playing field under a multilateral carbon tax scenario also leads to a few percentage points higher GDP in 2035.

Why this thesis finds similar macro-economic impacts as Altieri *et al.* (2015), and even better outcomes for employment, despite the fact that they also use a linked SATIM-e-SAGE model, like Merven *et al.* is not really clear. Probably, Altieri *et al.* (2015) are more pessimistic concerning South Africa’s high skill shortage in the future than the IMACLIM-ZA scenarios in this thesis. Furthermore, the rather rigid investment volume of e-SAGE possibly leads the changes that Altieri *et al.* (2015) model for the sectoral allocation of investment to be detrimental to GDP growth. In IMACLIM-ZA investments follows GDP growth, and GDP growth depends on factor output productivity growth, intermediate input efficiency gains and cost reductions, and such changes in investment allocation have not been modelled. It must be admitted though that this thesis also does not yet take into account capital costs for the investments required for a steep decline in CO₂ emissions between 2030 and 2050, something Altieri *et al.* (2015) take into account given a foreseen limited carbon budget after 2030.

In terms of choice between revenue recycling mechanisms, many of the mentioned studies are more limited in scope than this thesis, and comparison is therefore difficult. Other studies discussed here

have more different revenue recycling scenarios, but comparison to these other studies is more difficult because of bigger differences in model architecture or due to the time horizon of Pauw (2007), Devarajan *et al.* (2009, 2011), and Van Heerden *et al.* (2006) being much shorter, or static (respectively 2015, 2003 and 1998). What this study has in common with these other studies is that they find that a reduction of the costs of labour provides a promising channel for carbon tax revenue recycling.

6.3. Discussion of results in the context of theory about economic development under environmental constraints

An interesting question to answer is how the findings in this thesis correspond to theory about growth and development under environmental constraints as discussed in Chapter 2.

A question to be asked about these outcomes is: *To what extent do the outcomes of main Ctax revenue recycling scenarios reflect theoretical views about a transition from “brown” to “green” growth?*

The discussion here will focus on economic growth under environmental constraints, because the specific characteristics of a developing economy were not at the centre of the modelling exercise in IMACLIM-ZA. For instance, technological change has been dealt with through (exogenous) assumptions about future factor output and input efficiency productivity growth, and not through endogenous mechanisms that could represent the process of convergence (see Chapter 2) or other theories about how economies develop. Of course, South Africa’s economic and labour market structure reflects that of a developing economy for a part, and the question of increasing educational attainment of the labour force has been dealt with in this thesis. The question to what extent results reflect or raise insights about economic development will therefore briefly be touched at the end of this section.

6.3.1. The question of a double dividend

Concerning growth under environmental constraints, the first main question is whether a strong or only a weak double dividend is possible in South Africa by the introduction of a carbon tax and a particular type of revenue recycling. The second main question is what kind of tax reform would have the lowest distortive impact on South African GDP growth and employment (while achieving sufficient CO₂ emission reduction), and why?

The answer to the first question is simple: None of IMACLIM-ZA’s scenarios analysed in this study results in a “strong” double dividend.²²² This means that the modelling of the South African economy and different tax policies in IMACLIM-ZA and its scenarios does not result in a carbon tax causing ...:

²²² A strong double dividend means that revenue recycling of an environmental tax results in economic progress in at least one economic criterium (in most cases GDP growth is the chosen criterium), next to achieving the environmental objectives that motivated the introduction of the tax reform, relative to a reference without the environmental tax reform. In case of a weak double dividend, revenue recycling of an environmental tax reduces the excess burden of the environmental tax, but insufficient to improve results compared to the no-tax reform reference case. The reduction of excess burden improves the situation compared to introduction of the environmental tax without a revenue recycling (often a lump-sum transfer to households is chosen as the reference case for a weak double dividend).

1. ... aggregate technology to be more productive than in the (unsustainable) reference projection. In other words, the combined effect of elasticities of substitution in the nested production and consumption functions is an elasticity of substitution of fossil fuel-based energy use < 1 . This means that more expensive energy products are substituted at a rate that is lower than the increase of their price relative to prices of other products or factors. The consequence is that the average price of goods increases (in real terms), and that the income share in total resources decreases. This means that international competitiveness and domestic purchasing power of (factor) income decrease, and therefore that demand and economic activity decrease relative to the reference;
2. ... no or insufficient change of for GDP growth possibly sub-optimal prices of factors and taxes – note that this is a theoretical consideration, because optimal configuration for GDP growth of factor pricing and taxation has not been studied: Meaning that *if* reference projection factor payments (gross profits and wages) or taxes levied on production or products are too high compared to international prices to have maximum GDP growth, *then* the levying of the carbon tax in combination with a reduction of other taxes or subsidy of factors in the scenarios studied apparently could not sufficiently alter these theoretically possible sub-optimality in factor payment and taxation.

Of course, the price of labour, especially of high skill labour, has been found to be very distortive to the South African economy in IMACLIM-ZA, which can be seen from the strong positive impact on GDP growth of an investment in access to high quality education and vocational training which increases high skill labour supply.²²³ Reasons why labour costs could be more distortive in IMACLIM-ZA are the steep wage curve for high skill labour whose base year unemployment is lower than for other skills, and in the reference projection even lower. It would be interesting to study whether a bigger investment could have even better outcomes for GDP growth in combination with decarbonisation of the economy. But, such an analysis requires better data and analysis of (potential) impacts on labour supply and productivity (of all factors and inputs) of an investment in education and training than currently available for South Africa.

The fact that IMACLIM-ZA is capable of finding this conclusion is thanks to the fact that it does not represent the South African economy as a set of perfectly cleared markets, like neoclassical theory assumes. Capital rents in the form of profit mark-ups, rigid wage-setting, and taxation of products and production in theory all have the potential to be sub-optimal for GDP growth and employment in IMACLIM-ZA. Also, IMACLIM-ZA's representation of the economic structure, with sectoral disaggregation, multiple labour factors and multiple household classes, is relevant for the results obtained for GDP growth and employment.²²⁴

The non-perfect representation of the South African economy explains why the best “weak” double

²²³ E.g. as the consequence of increased access to high quality education, although social networks play a role as well, see section 4.5.

²²⁴ One reason is that average or aggregate elasticities at one point in time change due to structural change, something which a single-sector model, or a single-household model cannot take into account.

dividend has been found for recycling carbon tax revenue through labour subsidies. The scenario in which carbon taxation is recycled into labour subsidies (RTSC) achieves higher GDP growth (and employment) than the RTIF-low scenario, in which carbon tax revenue is used to reduce taxes on profits and therefore indirectly on capital rents. This is a remarkable finding in the context of the double dividend debate (see for instance: Bovenberg and Ploeg, 1998; Goulder, 1995). The relatively better performance of the labour subsidies scenario is even truer when one considers the risk that a reduction of profit taxes does not translate into lower profit mark-ups, in which case GDP growth turns out significantly lower (see the results of the RTIF-fix scenario in Ch.4).

It must be noted though that labour subsidies are the most efficient option for carbon tax revenue recycling in the interaction with a carbon tax. This finding does not necessarily mean that the price of labour plus taxation of labour²²⁵ is a bigger economic distortion in South Africa than net (after tax) profit mark-ups plus taxation of profits. Whether labour or capital taxation (or another tax) creates the highest excess burden for the South African economy has not been tested independently of the introduction of a carbon tax. The reason why labour subsidies are particularly advantageous in the context of carbon tax revenue recycling is that labour subsidies reduce labour costs and thereby facilitate the kind of technological change that reduces the excess burden of the carbon tax. Effectively, it increases the aggregate economy's price-elasticity of demand for energy products by stimulating technological and structural change.

Of course, there is a real chance that labour costs could be more distortive to the South African economy than capital costs even without carbon taxation – as could be seen from the strong positive results for GDP growth of reducing the high skill constraint, as discussed above. The solution for too high labour costs could be to improve (multifactor) output productivity, e.g. by improving skills of labour, or reducing labour costs in another way. Or both could be achieved, as was suggested by the analysis of an investment in skills of labour. On the other hand, it is also likely that IMACLIM-ZA prefers reducing taxes on labour or subsidising labour over reducing profit taxes, because it assumes too much flexibility in the capital market and too much rigidity in the labour market (due to rigid skill segments) (see the discussion in section 6.1).

6.3.2. Expectations of a growth drag, increased capital intensity and higher employment

Besides the question of the double dividend two other notions on economic growth and employment discussed in Chapter 2 are:

1. A transition from a non-renewable resources-based (or natural capital exhausting) economy to a clean or renewable resources-based economy likely causes a “growth drag”;
2. The idea that cleaner technology increases employment.

²²⁵ In IMACLIM-ZA these are contributions for social security and to pension funds.

The first point connects to one of the research questions (to be verified if still correct), namely:

Do main Ctax scenario outcomes show the mechanisms for a transition to “green” growth as proposed by Huetting (1996, 2010) and by Smulders et al. (2014)?

Recall from Chapter 2 that Huetting makes his prediction with the argument that in the Netherlands (Huetting, 1996, 2010) and worldwide (Tinbergen and Huetting, 1991) growth of productivity mainly took place in the most energy-intensive and polluting industries, which he supports by empirical data. He found productivity growth to be much smaller in less polluting economic activities, such as services.²²⁶ Smulders *et al.* (2014) arrive at the same prediction, but arguing on the basis of neoclassical assumptions that presently optimal technology has been developed while it has been possible to externalise environmental costs. Internalising these costs would, with present-day technology mean more effort to generate the same output. Smulders *et al.* add that even if renewable capital is equally productive as present-day capital, then replacement of resource-exhausting capital by renewable resources-based capital will consist of investment without growth of TFP. This is even more the case when polluting capital needs to be retired early (as stranded assets).²²⁷ Also, if more capital is necessary to generate the same level of output as before, then savings need to increase to generate and maintain this larger capital stock. The conclusion is that final consumption and has to be reduced in favour of savings relative to business-as-usual.

The results of Ctax scenarios in this thesis also show lower GDP growth than for RP. And, results of Ctax scenarios show an increase in (physical) capital intensity, though these increases remain small: 0.5% to 3% in comparison to RP for Ct100 scenarios, and 1% to 7% increase for Ct300 scenarios. This means that the growth drag, with lower capital (and labour) productivity, can be found to some extent in IMACLIM-ZA. However, the projection period in this thesis does not go far enough into the future to observe growth in Ctax scenarios overtaking growth in RP at the moment that economic consequences of climate change start to be felt.

A central argument for Huetting and for Smulders et al. is that there is no environmentally better and economically more productive technology available compared to existing technology. For the majority of sectors in this thesis technology has been modelled through a nested CES specification, and except for the aspect of energy efficiency (in section 5.5), no *ex post* evolution has been performed to see whether energy- and capital intensity in scenario results corresponds to findings in technology assessment studies about future efficiency in all factors of production (primary and secondary ones). The study of energy efficiency potentials suggest that the potential for efficiency improvement is limited in a number of key energy-consuming industries (Allwood et al., 2011). Analysis of the question of future potential energy efficiency gains showed that IMACLIM-ZA models energy

²²⁶ This finding resonates Goulder’s analysis that the production of capital goods in the US tends to be energy-intensive (Goulder, 1995).

²²⁷ Furthermore, it is likely that the new energy saving capital requires more up-front investment than existing capital, as it is the case for renewable energy. In order to maintain an economy’s capacity to produce, investment must increase. Consumption therefore needs to decrease at least temporarily to make room for savings and investment.

efficiency gains in South Africa close to what can currently be expected (section 5.5).

However, the electricity sector (ELC), has exogenous technological change that varies with carbon taxation and which is Bottom-Up model-informed. This BU-model-based information shows that a carbon tax leads to higher electricity prices, meaning that it suggests that as far as electricity is concerned, no future technology is available that is more productive than reference case technology. Of course, there are indications that solar PV-based electricity production is becoming a lot cheaper and possibly even competitive with fossil-fuel based electricity production (Wright et al., 2017). In this case the findings of this thesis would be too pessimistic about technological change and GDP under carbon taxation. Sensitivity analysis showed a high sensitivity of GDP to the costs of electricity, and under carbon taxation therefore to the costs of renewable power generation (section 5.6.1).

In summary, a growth drag, relative to reference growth, is very likely. Yet, it's consequence should maybe not be exaggerated, considering that multiple Ctax scenarios find GDP growth above the average of the last 10 years.²²⁸

The second point concerns Hueting's prediction that clean technology requires more labour (or time) than existing technology, because existing technology's high labour productivity originates from substitution of labour (and time) by machines (capital) and energy use.²²⁹ With present-day technology, Hueting says (Hueting, 1996), reducing environmental pollution requires partly undoing this substitution. It thus implies decreasing labour productivity and *real* wages. The consequence of lower labour productivity, according to Hueting, would be more employment, because with more labour-intensive technology GDP can only be increased (in an absolute sense) through higher employment. Of course, Hueting's argument does not consider macro-economic feedbacks and the conditions for macro-economic equilibrium – and as the discussion of modelling GDP growth in this thesis showed, unemployment seems rather a consequence of the average price of primary factors relative to average primary factor productivity. This does not necessarily change with technological change.

Of course, as scenario analysis in this thesis showed, the right type of environmental taxation makes capital and secondary factors such as energy and materials more expensive, and labour relatively more attractive as a factor of production (see RTSC scenario results in Ch.4). However, this thesis does not assume a change in the (in IMACLIM-ZA exogenous) trend in labour productivity, like Hueting's reasoning suggests. A proper assessment of labour and capital content of clean technologies of production would be needed to find what assumptions about future factor productivity can be made.

²²⁸ According to World Bank data, average annual real GDP growth in South Africa from 2007 to 2016 was 2.1%.

²²⁹ Examples could be, airplane travel which reduces travel time, and therefore also the number of hours worked by staff in providing a transport service, in comparison to e.g. train or bus travel. The use of fertilizer and chemicals in agriculture, which replace manual work might be an example too, and yet another example is information technology, which might make more information more easily accessible, but at the same time increases the number of machines per worker. Of course, information technology could make it possible to optimise production processes and for instance reduce water, energy and material use in production processes and products. But the basic idea of environmental taxation is that these improvements will only be realised once environmental externalities will be internalised through regulation or taxation.

6.3.3. Conclusion about how results reflect theoretical predictions

In summary, the combined assumptions, hypotheses and calibration data behind IMACLIM-ZA suggest that South Africa should expect a growth drag relative to a Reference Projection for at least a period of transition in which cleaner technologies are developed in order to achieve South Africa's NDC. However, with the right revenue recycling mechanism, the economic impacts could be considered mild, and GDP growth could still be well above the growth rate of the last few years, and it could be combined with almost halving of unemployment.

Still, many uncertainties remain, especially whether IMACLIM-ZA makes correct assumptions about future technological change. Predictions and comparison with the Reference Projection concerning future (lower) employment depend very much on these assumptions about technological change and should therefore be considered very uncertain. Also, IMACLIM-ZA has a rather flexible treatment of the capital market, and might too easily assume that the investment necessary for future GDP growth will be realised, even if returns on capital might decrease in certain scenarios. From this perspective it could be possible that the growth drag is underestimated, and that additional policy would be needed to stimulate necessary savings to finance investment.

Another limitation of the present study is that no long(-er) term analysis has been performed to see whether, and for how long, a growth drag would take place, once potential negative consequences of climate change on growth (on productivity) and their timing are taken into account in the reference projection without climate change mitigation policy.²³⁰

²³⁰ Climate change repercussions for economic development are expected to be experienced after 2050 (Ref, and see section Xx), but the study in which this expectation is based might be outdated. It would be interesting to see whether developments such as increasing droughts do not affect GDP growth more negatively than engaging in a transition now.

7. Conclusion

This concluding chapter answers the research questions of this thesis (section 7.1). Findings will first be summarized in the answer to the central research question (section 7.1.1). Then more detailed conclusions follow regarding the results of specific carbon tax revenue recycling scenarios, as well as the achievement of the NDC (7.1.2). Findings regarding the potential impacts of an investment in skills get special attention (in section 7.1.3). Alternative assumptions are discussed (in section 7.1.4) first of all to evaluate the international context for a carbon tax, next concerning the role of energy efficiency, and finally for modelling of the wage curve. Attention is also paid to the explanation of the macro-economic mechanism behind the results of this thesis at the end of this section (7.1.5).

Section 7.2 translates the scientific conclusions to implications and recommendations for climate change policy in South Africa. Generalisations for the rest of the world and international climate policy will be made as well. Furthermore, the discussion in the previous section identified some methodological weaknesses and knowledge gaps. Section 7.3 formulates recommendations for future work on this basis.

7.1. Answers to the research questions

7.1.1. Main research question

How could climate policy, notably a carbon tax and the use of the public revenue that it generates, influence South Africa's economic development? What order of magnitude could be expected from such policies in terms of socio-economic impacts and environmental impacts?

The main conclusion on the basis of the scenario analysis in the previous chapters is that a carbon tax and its revenue recycling could have something in-between having almost no impact up to having a significant negative impact on South African GDP growth, depending on the choice of revenue recycling scheme and the carbon tax rate. The order of magnitude of impacts on GDP growth varies between almost a double dividend, for the 100 Rand carbon tax recycled into labour subsidies and with an investment in skills of labour that reduces the high skill shortage, and as a worst-case scenario the case of a 300 Rand carbon tax is purely recycled into reducing the public deficit, with a GDP one third smaller than reference GDP in 2035 (of 125% above GDP in 2005). In these cases CO₂ emissions vary respectively between a reduction of 20% and a reduction of 56% relative to reference CO₂ emissions, which projects a 55% growth of South African CO₂ emissions compared to base year data (for 2005).

These results depend strongly on the choice of revenue recycling mechanism, but also on the type of technological change that is foreseen. The best way to recycle carbon tax revenue for GDP growth is by doing it in such a way that costs of domestic production are reduced in other sectors than the energy and energy-intensive sectors which see their average prices increase due to carbon taxation. Revenue

recycling that stimulates technological change away from the use of energy or energy-intensive products, and that promotes the use of labour turns out to result in the best combination of economic and environmental development. This is notably the case for revenue recycling in the form of labour subsidies and in the form of a reduction of taxes on profits, assuming that companies will reduce their profit mark-up rates.

Results for broad unemployment vary in the same way as results for GDP growth, though there is some variation in the labour intensity of GDP between different revenue recycling schemes. Findings vary between hardly any impact on unemployment (measured by its “broad” definition) in the case of a R100 carbon tax recycled into labour subsidies with an investment in skills, *or* with optimal energy efficiency prospects. While on the negative end revenue recycling of a R300 carbon tax through a reduction of the public deficit leads to a doubling of the broad unemployment rate compared to that of the reference projection. It must be noted that this thesis analyses the specific expectation of a future with continued autonomous labour-saving technological change of especially low skill labour, and that this development is assumed to be the same with and without carbon taxation, except for price-elastic substitution. With price-elasticities of substitution between factors and intermediate inputs effectively being smaller than 1.0, this means that no fundamentally different pathway of technological development is foreseen under carbon taxation.

Carbon taxation does not seem to influence income inequality very much, which depends on other aspects of the economy, such as the relative size of labour and capital income, the rate of returns on capital, the growth in employment by skill, and finally social security and pensions. Only recycling of carbon tax revenue into a lump-sum transfer to households radically reduces (almost halves) income inequality. Poverty, in contrast to relative inequality, is affected by carbon taxation though. Without further assumptions about increases in social security, and with insufficient increases in low skill jobs, the lowest household income classes see little progress in their purchasing power of energy products compared to 2005, except in the lump-sum transfer scenario.

The results presented in this thesis depend on modelling and scenario assumptions (e.g. simplifications inherent to modelling), and some of these assumptions can be expected to cause over- or under-estimations of the socio-economic and environmental impacts of a carbon tax and its revenue recycling. One of the two most significant causes for bias in the results is the way in which the labour market has been modelled. This might lead to an overestimation of future cost of labour relative to labour’s productivity, and thus leads to an overestimation of economic impacts of carbon taxation. The capital market, on the other hand, might be modelled too flexible, which might lead to an under-estimation of possible (negative) consequences for GDP growth and employment.

7.1.2. Main findings for carbon tax revenue recycling schemes

In order to answer the central research question of this thesis a set of sub-questions has been defined to

structure the potential answer to the central question of this thesis. The first sub-question was:

“How do the different carbon tax revenue recycling scenarios impact key indicators for South Africa’s socio-economic development and CO₂ emission mitigation policy?”

The following key indicators were defined in Chapter 1 as relevant for evaluation of scenarios:

- CO₂ emissions;
- GDP per capita;
- Broad unemployment rate;
- CO₂ emission intensity of GDP;
- Income inequality.

To answer this research and other research questions, the IMACLIM-ZA model was developed (see Chapter 3). Scenario outcomes were compared to the Reference Projection, presented in section 4. Scenario analysis evaluated different carbon tax revenue recycling schemes for two rates of a carbon tax: 100 ZAR₀₅ per tonne of CO₂ emissions (the R100 Ctax, *or* Ct100 scenarios), and 300 ZAR₀₅ per tonne of CO₂ emissions (R300 Ctax, *or* Ct300 scenarios). The scenarios analysed were:

RDEF	Reduction of the public deficit (possibly leading to a budget surplus);
RVAT	Reduction of the sales tax on final consumption; ²³¹
RGOV	Increase of government expenditure;
RSUM	Lump-sum transfer to households on an equal <i>per capita</i> basis;
RTIF-fix	Reduction of taxes on profit or income of firms while firms do not change their profit mark-up rates;
RTIF-low	Reduction of profit or income taxes of firms who respond by reducing profit margins;
RTaY	Carbon tax revenue is used to reduce taxes on production, up to the extent that production is subsidised;
RTSC	Carbon tax revenue is used to reduce social security contributions paid as a rate over net wages, up to the extent that labour is subsidised.

The closure rule for the public budget, for comparability between revenue recycling scenarios, was that the public budget deficit should equal -3% of GDP. An exception to this rule was RDEF, in which all taxes were kept at constant rates and the public budget deficit decreased thanks to carbon tax receipts. In the RSUM scenario for a R300 carbon tax, the budget deficit rule had to be relaxed as well in order to obtain a modelling resolution.

Summary of results (including for identical CO₂ emission targets)

Big differences were found between carbon tax revenue recycling (Ctax) scenarios in terms of GDP

²³¹ South Africa has a Value Added Tax (VAT), which technically is not a sales tax, which only applies to final consumption. To simplify matters the VAT it has been modelled as a sales tax.

growth, CO₂ emissions, and employment. Differences in CO₂ intensity of GDP and income inequality, on the other hand, were not very big in most cases. Table 7.1 summarizes a comparison of Ctax scenarios with the reference projection (RP). It shows that two revenue recycling schemes result in

Table 7.1 Comparison of key results for Ctax scenarios with reference projection for 2035 (RP)

Scenario	GDP in 2035 vs RP	CO ₂ emissions, vs RP	CO ₂ emission intensity of GDP, vs RP	Employment (nr of jobs), vs RP	Hh class 5 over class 1 income gap, vs RP
Ctax rate 100 ZAR₀₅/tCO₂					
RDEF	-11%	-26%	-16%	-11%	-4%
RTIF-fix	-10%	-25%	-17%	-10%	-2%
RSUM	-10%	-25%	-16%	-10%	-29%
RGOV	-10%	-25%	-17%	-10%	-3%
RVAT	-6%	-22%	-17%	-6%	-1%
RtaY	-6%	-22%	-17%	-6%	-1%
RTIF-low	-4%	-20%	-17%	-4%	-1%
RTSC	-5%	-21%	-17%	-3%	-2%
Ctax rate 300 ZAR₀₅/tCO₂					
RDEF	-32%	-56%	-34%	-33%	-13%
RTIF-fix	-30%	-54%	-35%	-30%	-9%
RSUM	-28%	-53%	-35%	-28%	-48%
RGOV	-27%	-54%	-36%	-27%	-11%
RVAT	-18%	-47%	-36%	-17%	-5%
RTaY	-17%	-47%	-36%	-16%	-5%
RTIF-low	-14%	-45%	-36%	-13%	-4%
RTSC	-13%	-45%	-37%	-10%	-5%

lower GDP and employment losses than other scenarios, while they obtain higher reductions in CO₂ emission intensity of GDP. It concerns the scenarios with revenue recycling into a reduction of profit taxes if followed by a reduction of profit mark-up rates (RTIF-low) and with revenue recycling into labour subsidies (RTSC). But, because the reduction in CO₂ emission intensity of GDP is weaker than GDP growth itself, their CO₂ emissions are still higher than in other scenarios. Income inequality of the richest over the poorest household class, finally, only changes in the RSUM scenario, which sees the *per capita*

income difference between the richest 10% of population and the poorest 20% being almost halved.

A separate analysis of four selected scenarios in Table 7.2 shows that results for GDP growth and employment of the RTSC scenario remain the best, even if the carbon tax rate is increased to such an extent that South Africa's NDC is achieved: translated to IMACLIM-ZA as 350 Mt of CO₂ emissions in 2035. This analysis also shows that the carbon tax required to achieve South Africa's NDC lies above 300 Rand₂₀₀₅ per tonne of CO₂, or well above the currently planned carbon tax rate (at 120 Rand₂₀₁₉ per tonne of CO₂, excluding exemptions).

Labour subsidies work well because they stimulate, more than the other forms of revenue recycling, technological and structural change away from energy-intensive production and consumption (and towards higher labour intensity). A co-benefit is that it promotes an increase in labour participation, and RTSC thereby improves the weight of social security and pension system contributions, which rests on the shoulders of the working. It thereby reinforces its own mechanism which makes labour a cheaper factor of production. Other revenue recycling mechanisms do not manage to promote a similarly strong “detachment” of the South African economy from its energy-intensity.

Table 7.2 Comparison of key results for NDC objective vs reference projection for 2035 (RP)

Scenario	Carbon tax rate (ZAR ₀₅ /tCO ₂)	Total '05-'35 GDP growth	CO ₂ emissions	CO ₂ emission intens. of GDP	Employment (nr of jobs)	Hh class 5 over class 1 income gap
RSUM	255	-27%	-49%	-30%	-27%	-46%
RVAT	314	-19%	-49%	-37%	-18%	-5%
RTIF-low	325	-18%	-49%	-38%	-17%	-5%
RTSC	339	-15%	-49%	-40%	-12%	-6%

Other scenarios than RTSC often still promote energy-use to some extent, in one or another way. In the case of carbon tax revenue recycling through a reduction of profit taxes (RTIF-low), the reduction is universal, and

therefore also benefits energy sectors and energy-intensive sectors. An advantage of this scenario is that it reduces South African costs of domestic production in such a way that the amount of income per unit supplied to South African markets or South Africa's export markets is relatively high. (More on this below, where the mechanism behind IMACLIM-ZA's results is summarized.) Minimizing the average cost increase due to carbon taxation, as is done by carbon tax revenue recycling into labour subsidies or into a reduction of profit taxes if this motivates companies to reduce their profit mark-up rates, means that products remain relatively cheap, and therefore low labour costs too, because wages are assumed to be indexed on the consumer price index (CPI).

Revenue recycling through the reduction of taxes on production of non-energy sectors – up to the extent that taxes on production become subsidies –, the RTaY scenario, has a similar effect as revenue recycling in RTIF-low, but it does not manage to avoid import substitution as much as the RTIF-low or RTSC scenarios. The biggest reason most likely is that it turns out to subsidize sectors with relatively high rates of imports, like manufacturing (MAN) and energy-intensive industries (EIN). With higher import dependency, South Africa's REER has to increase in order to be able to afford these imports, which comes at the expense of domestic production, and employment.

In theory, the RVAT scenario's carbon tax revenue recycling mechanism benefits the South African economy in a comparable way as the labour subsidies scenario, by making labour cheaper through a relatively lower CPI index compared to the prices of capital and other input prices. But, in contrast to RTSC and RTIF-low and RTaY, there is no compensation of the disadvantageous effect of carbon taxes on the trade-off between domestic and foreign goods. It therefore ends up indirectly subsidising foreign producers and it is therefore less effective than labour subsidies to promote South Africa's economic activity.

The remaining four of the main carbon tax revenue recycling schemes that were analysed in this thesis do not obtain a good outlook for GDP growth or reduction of unemployment. These four revenue recycling mechanisms in fact do not recycle carbon tax revenue within the tax system. Three scenarios are a transfer to one of the different economic agents: the RGOV scenario transfers carbon tax revenues to government, which increases expenditure; the RSUM scenario is a lump-sum transfer to all households on a *per capita* basis; and the RTIF-fix scenario (firm profit tax reduction not followed

by a reduction in profit mark-ups rates) translates into a transfer to company owners and (financial) asset holders, in practise mainly rich households. The RDEF scenario is slightly different, because it reduces South Africa's exogenously assumed budget deficit – up to the point that it becomes a budget surplus. In this scenario South Africa becomes a net lender to ROW and reduces its net foreign debts. These scenarios therefore offer no advantage for the average affordability of South Africa's domestic production, in terms of domestic purchasing power of wage and other forms of income, and in terms of international competitiveness.

Limitations

It must thus be concluded that this thesis finds that reducing labour costs is the most efficient way to reduce the excess burden of a carbon tax to the South African economy. These results therefore underline one of the conclusions by Devarajan et al. (2011), namely that “labour market distortions such as labour market segmentation or unemployment will likely dominate the welfare and equity implications of a carbon tax for South Africa”. There is a clear logic behind this mechanism, which is that in a country that suffers from excessive labour costs, subsidising labour helps in reducing an obstacle to less energy-intensive technologies of production. Below, this conclusion will be extended to include investment in reducing the skill's shortage as an efficient way to reduce labour costs (relative to multifactor productivity).

Nevertheless, this conclusion has to be treated with caution, as several simplifications in the modelling approach mean that advantages of other revenue recycling mechanisms might have been neglected. First of all, indirect benefits have not been taken into account. For instance, increased government expenditure in RGOV could lead to better public services and infrastructure and in this way possibly to higher productivity. RSUM could lead to better living standards, and therefore benefits for public health, a reduction in crime rates, and e.g. private investment in education, thereby potentially also indirectly creating productivity improvements.

Secondly, investment has been modelled relatively insensitive to the rate of returns on capital, and this could lead to an underestimation of the benefits of revenue recycling mechanisms that promote returns on investment like RTIF-low and RTaY, or trust of international lenders, like in the RDEF scenario. Also, the simplification of the capital market in IMACLIM-ZA could lead to an overestimation of GDP growth in scenarios in which the rates of interests and dividends decrease. The latter is somewhat the case in RTSC, though the difference with RTIF-low and RTaY remains relatively small, and rates of interests and dividends are similar as in RTIF-fix and RVAT and much higher than in RGOV, RDEF and RSUM. Furthermore, these rates are also influenced by the assumption that the government expenditure on public services as a percentage of GDP grows at the same rate in all scenarios, irrespective of GDP growth. This means that in order to respect the budget deficit, the total weight of taxes on GDP is relatively heavier in scenarios with lower GDP growth.

A last omission is that, with the exception of the scenario option for investment in skills that is

discussed below, no revenue recycling scenarios have been tested for investment in technological progress (e.g. energy efficiency) or in the creation of low carbon infrastructure. Certain infrastructural investments could be expected to improve the cost efficiency of ways to reduce CO₂ emissions, thereby lowering the carbon tax rate and the carbon tax's excess burden required to achieve a certain CO₂ emission objective.

Nevertheless, these limitations do not alter the reason why the scenario with labour subsidies works out well for South Africa, which is that it reduces excessive labour costs, and that it promotes the type of technological change that reduces energy dependency of the South African economy, replacing it by higher labour intensity, a factor amply available in South Africa. These limitations are only reason to think that other scenarios likely work out better than shown in the results of this thesis, and that there is uncertainty as to whether RTSC or RTIF-low and RTaY would be the most efficient channels of revenue recycling. It might not be possible to lift such uncertainty entirely through a modelling exercise, and one might need to consider "betting on multiple horses" as a robust strategy for economic development under carbon taxation. Some of the biggest uncertainties of the present modelling exercise though, lie in the unknown nature of future technological change, as will be discussed next.

7.1.3. Investment in skills

The one investment policy as a means of carbon tax revenue recycling that has been tested concerns an evaluation of potential impacts of an investment in skills of labour. The research question to be answered was: *Can a reduction of South Africa's observed skill shortage provide a pathway for an economic development that is low in its carbon content? Is investment in skills an interesting option as a way to use carbon tax revenue?* Here, the "partial equilibrium" answer would intuitively be that, *of course*, if labour could become more productive, one increases the value of labour as an input, and labour would partly substitute for other inputs, like energy. But, investments need to be financed, and thus draw funds away elsewhere – in this case from carbon tax revenue recycling. The question was therefore reformulated into: *How big should the impact (on growth, employment and income equality) of a certain investment in skills of labour be to be more beneficial than other ways of carbon tax revenue recycling, without raising CO₂ emissions?*

To analyse the potential for growth of an investment in skills, scenario analysis focussed on a large investment in education or training estimated at 7.5 billion ZAR₀₅ (almost 1.4 billion USD₁₃; see section 4.5). This would be equivalent to about 1.0% of South Africa's governmental final consumption, or 0.6 to 0.8% of the total budget of government and public services. It equals 7 to 15% of expected 2035 carbon tax revenues, depending on the carbon tax rate. Two types of analyses have been performed: One approach (variant A) for the investment in skills-option assumes that the investment aims at bridging the quality gap in South African education, and thereby increases the pool of high skilled labour in 2035 by 0.75 million people, or 11%. The other approach (B) assumes that

the positional character of the labour market remains unchanged. In this case, better or more education leads to improvements of multifactor productivity, meaning that more skilled labour can produce more output over the amount of capital or intermediate inputs. In this approach the objective was to find the combination of impacts on productivity of labour and capital that would make recycling of carbon tax revenue through an investment in education or training more interesting than to recycle this part of carbon tax revenue through one of the (main scenario) carbon tax revenue recycling schemes.

Variant A was analysed for the scenario with carbon tax revenue recycling through labour subsidies (RTSC), for a R100 and a R300 Ctax rate, and for revenue recycling through a reduction of a sales tax (RVAT). In variant A the investment turns out to lead to a significant increase of GDP (of 4 to 6% depending on the scenario), while the CO₂ emission intensity of GDP decreases (about 1%). Results also show a decrease of broad unemployment (1 to 2 percentage points) and even a slight decrease of income inequality (about 2%). The bigger supply of skilled labour means that there is less upward pressure on high skill wages and that they do not increase as fast as foreseen, while a decrease of unemployment of low skill labour means relatively higher wages for that skill segment. The increased attractiveness of labour as a factor of production thereby encourages substitution of energy by the capital-labour (KL) composite input to production. A disadvantage of this variant of investment in skills is that CO₂ emissions increase (3 to 5%) compared to scenarios without the investment in skills-option due to higher GDP growth. This means that with an investment in skills, a higher carbon tax rate would be required to force an economy that would show stronger growth to decarbonise more, in order to obtain the same level of CO₂ emissions as for scenarios without such an investment.

Variant B has been analysed in application to carbon tax with revenue recycling into reduction of a sales tax for a carbon tax of 100 ZAR₀₅/tCO₂ (Ct100 RVAT). This was chosen for reason of comparability with Schers et al. (2015). Furthermore, because RVAT resulted in medium macro-economic outcomes also serves to estimate an average break-even point for revenue recycling through this variant of investment in skills. Results of variant B showed that already small improvements in output productivity – in the range of 0.6 to 2.1% by 2035 when it concerns factor neutral productivity growth – lead to better economic outcomes than not investing 7.5 billion Rand of Ctax revenue in productivity improvement. The biggest question is what the wage-demands of better skilled labour will be: If wages of skilled workers remain high, then the beneficial impact of the investment on GDP growth, employment and decarbonisation of GDP will be smaller than when wage increases will be more moderate relative to output productivity. In the latter case, investment quickly turns into higher GDP growth. In the former case, a lack of cost reduction can be compensated by increased efficiency in the use of materials & services as inputs to production. GDP growth and employment have proven to be very sensitive to intermediate input efficiency, and even only a small increase of these efficiencies was found to lead to considerable GDP growth, e.g. an increase of 0.7% in efficiency of production in materials and services inputs led to 2.8% higher GDP, 1.7 percentage points lower broad

unemployment, and 0.8% lower CO₂ intensity of GDP.

In conclusion, a significant, though in terms of relative to current government budget and relative to carbon tax revenues small investment of 7.5 billion Rand₂₀₀₅ (by 2035) in education and training, has a strong potential to lead to economic benefits. Increasing access to high quality education in order to reduce a general lack of high skilled labour turns out to have a very positive impact on South African GDP growth, while leading to a lower CO₂ intensity of GDP as well. Also, if the investment would translate into higher output productivity, small improvements already turn out to lead to positive macro-economic results. Though, this depends on how better skilled labour would translate its improved productivity into salary demands. Achieving higher efficiency in the use of materials and other inputs, finally, has been found one of the most promising channels for GDP growth, increased employment and a reduction of CO₂ intensity of GDP. These findings are therefore a motivation to study how an investment in education and training could be realised, with more detailed analysis of the impacts on the labour market and on multifactor productivity.

7.1.4. Alternative scenario assumptions

A South African carbon tax in an international context

Another important question regarding the results of Ctax scenarios under different hypotheses was: *How would different international climate policy regimes affect the impacts of South Africa's carbon taxation and Ctax revenue recycling options?*

The majority of main Ctax revenue recycling scenarios have therefore also been analysed for the case in which the assumption is added that other countries implement a similar type of carbon tax. The assumption was made that that such a carbon tax would have a similar relative impact on prices between sectors relative to the price of the high skill services sector (HSS) as found in main Ctax scenarios for domestic prices. As a result, per capita GDP turned out 1 to 4 percent higher for respectively R100 and R300 Ctax scenarios, while unemployment turned out between 0.5 and 3.0 percentage points lower. A disadvantage of an international carbon tax is that South Africa can no longer “outsource” its CO₂ emissions: there will be less energy-intensive activity that will be substituted by imports, and CO₂ intensity of GDP therefore turns out higher than in the main, unilateral carbon tax scenarios presented in the beginning.

Turning the international carbon tax scenario assumptions upside down, and assuming that the Rest of the World (ROW) would want to coerce South Africa into a carbon tax regime turns out to require very high CO₂ emission-based Border Tax Adjustments (BTA) for this scenario to become less attractive than joining a multilateral carbon tax regime. The reason is that export price increases in the case of a R300-equivalent BTA on South African exports by ROW remain relatively small: For instance, max 8% for EIN products, and only 1 to 3% for products of other sectors. This means small compared to the movement of the Real Effective Exchange Rate (REER) (-5% in RP) – which adjusts in all scenarios to reduce import dependency of an above world-average growing economy. In other

words, though international competitiveness is an important aspect of GDP growth, and foreign BTA does hurt South African GDP growth, and employment even more, domestic productivity gains and cost reductions can continue to fuel GDP growth, and movements of the Real Effective Exchange Rate for still quite some time. Only an aggressive BTA, equivalent to price changes of a domestic carbon tax of 200 USD₂₀₁₃ per tonne of CO₂ (1,000 ZAR₂₀₀₅ per tonne of CO₂) is estimated more disadvantageous than implementing a 300 ZAR₂₀₀₅ per tonne of CO₂ in a multilateral context.

Of course, if domestic carbon tax impacts would be estimated lower (for instance because of the lower wage-average labour output productivity indexation discussed just before), the impacts of foreign BTA might sooner turn out more negative than participating in a multilateral carbon tax regime. Also, this analysis assumes regular price-elasticities of international trade, and possibly higher values should be considered for long term price-elasticities or price-elasticities of lasting disadvantages for international trade. Another critical remark about alternative scenarios with international carbon tax regimes is that the resulting projections still represent a South African economy which continues to export coal and other mineral non-renewable resources at the same rate. I have not explored whether such exports could continue if the ROW reduces its dependency on fossil fuels, and especially coal.

More energy efficiency versus a higher carbon tax?

Another question asked in Chapter 1 was: *What happens if industries achieve different levels of energy efficiency?* In this *ex post* analysis the energy efficiency gains found in IMACLIM-ZA were compared with values found in scientific and grey literature. On the basis of a report published by the Department of Environmental Affairs²³² an inventory was made of the potential for CO₂ emission reducing energy efficiency gains by sector. In general, energy efficiency gains by sector found are on the high side in IMACLIM-ZA, but lower for the energy-intensive EIN sector. Alternative assumptions about future energy efficiency potentials were modelled through exogenous energy efficiency improvements. These new energy efficiency estimates increased GDP growth in selected carbon tax scenarios. However, to realistically model industrial sector's energy efficiency gains for South Africa corresponding to engineering insights, there is a lack of technology assessment studies.

Alternative assumptions for labour market modelling and technological change

Modelling is a question of simplifying reality, and dealing with a lack of data, sometimes. For this reason, IMACLIM-ZA, like other models, makes use of several assumptions. Specifically, IMACLIM-ZA's growth engine rests on assumptions about technological change. Specifically, assumptions about trends in physical intensity of inputs and factors of production, and about trade-offs in production, like price-elasticities. A justified question, asked in Chapter 1, therefore is: *How do assumptions about technological change (productivity and trade-offs in production) impact model outcomes?*

Sensitivity analysis found that results were very sensitive to the assumption about input efficiency gains for materials & services (Mat) inputs, which not only increases GDP growth strongly, but also

²³² DEA (2014): "South Africa's Greenhouse Gas (GHG) Mitigation Potential Analysis"

reduces the CO₂ intensity of GDP significantly. Employment normally decreases with GDP growth, except when it was based on assumptions about increased labour' output productivity: The latter result is caused by another assumption, namely that the change in average wage is indexed (all other things equal) on median inter-sectoral change in labour output productivity. This median change turns out to be higher than average labour output productivity growth. Notably the low skill sectors (LSS) and the high skill services' sector (HSS) are assumed to have below average labour output productivity growth, while they employ more than half of South Africa's labour force and represent more than half of the country's value added.

The scenario analysis was therefore repeated under the alternative assumption that wage would be indexed on *ex ante* by calibration year labour force-weighted average inter-sectoral labour output productivity. In this case GDP growth and employment are higher in the reference projection and carbon tax scenarios, and the relative impact of carbon taxation on growth and employment turns out to be smaller than in the main scenario results presented above. Table 7.3 summarizes the outcomes:

Table 7.3 Comparison of results for R300 Ctax scenarios vs RP with alternative assumption for wage indexation with labour productivity

Scenario	Total '05-'35 GDP growth	CO ₂ emissions	CO ₂ emission intens. of GDP	Employment (nr of jobs)	Hh class 5 over class 1 income gap
RDEF	-22%	-50%	-36%	-22%	-8%
RTIF-fix	-20%	-49%	-36%	-20%	-3%
RSUM	-19%	-49%	-36%	-20%	-49%
RGOV	-18%	-49%	-38%	-18%	-6%
RVAT	-11%	-44%	-37%	-10%	-2%
RTaY-285*	-10%	-43%	-36%	-9%	-2%
RTIF-low	-11%	-44%	-37%	-11%	-2%
RTSC	-8%	-43%	-38%	-6%	-3%

Comments: RTaY scenario could only be solved up to a carbon tax of 285 Rand₂₀₀₅ per tonne CO₂ and not 300 Rand like the other scenarios presented in the table.

GDP and employment in the scenario with the worst macro-economic outcomes, RDEF, are only 22% below those of RP instead of one-third as is the case of higher wage-with-productivity indexation. CO₂ intensity of GDP turns out one or two percentage points lower than previously, due to labour being relatively more attractive as a factor of production, whereas CO₂ emissions turn out 2 to 5 percentage points of RP's CO₂ emissions higher. These

results show that there is a considerable uncertainty margin around scenario outcomes, but conclusion of comparison between scenarios stays the same.

7.1.5. Principle mechanism for growth and employment under carbon taxation

Just showing results of a quantitative analysis is not enough, what matters is understanding the economic mechanisms that lead to good results or not. For this purpose, the following research question was asked in Chapter 1: *How do the outcomes on key indicators follow from structural change, and through which mechanism do the main policy scenarios cause structural change?*

Connected to this question I address the question: *How does the IMACLIM approach impact the outcomes? What has been the added value of the inclusion of second-best economies?*

In brief, the mechanism which explains the results of the different carbon tax revenue recycling

schemes is the following: A carbon tax makes fossil energy use more costly. IMACLIM-ZA assumes that the carbon tax does not suddenly unlock a hidden potential of zero- to negative-cost options for more energy efficiency which would lead to abandoning fossil fuel-based energy use in production and consumption. Without negative to zero cost alternatives for fossil fuel-based energy use, carbon taxation makes production more expensive.²³³ This “attachment” to fossil fuel-based energy use manifests itself in limited substitution of energy by other factors (capital and/or labour) or inputs to production. Technically speaking, this equals a price elasticity of substitution lower than 1.0. The consequence is higher production costs per unit than before the introduction of a carbon tax. A second way in which the South African economy is “attached” to energy use is in final demand, where exports and household final consumption do not easily replace energy products or products of energy-intensive sectors by energy-extensive & labour intensive products. In view of this “attachment” to energy, a decrease in real income (purchasing power of factor payments) can only be limited if carbon tax revenue recycling leads to cost reductions for labour or capital, or to price reductions of other products than energy or energy-intensive products. These price reductions promote decarbonisation of production and help maintain real income and international competitiveness high.

This result also follows from standard applied neoclassical Computable General Equilibrium (CGE) models that use common (historic) price-elasticities of substitution between energy and capital and labour, or between energy and other products in household consumption.²³⁴ The difference between the results from more standard models and the results presented here is that IMACLIM-ZA does not assume perfect markets, and allows capital and labour payments to be non-optimal in terms of welfare or GDP also for other reasons than taxation. What counts in IMACLIM-ZA, next to multifactor productivity, is how the total of factor payments evolves relative to output productivity. If aggregate wage and/or profit mark-ups, and/or indirect taxes (like the sales tax or a carbon tax) increase faster than output productivity, this reduces total real income (the domestic purchasing power of factor payments and tax revenue), and it reduces international competitiveness. Furthermore, average real wage is assumed rigid through an unemployment-wage curve with a low though common value of elasticity (0.1).²³⁵ A carbon tax therefore quickly increases the cost of labour, which is by definition the most “domestic” of all inputs (capital requires materials which require imports), and which is at the same time the least carbon-intensive of all factors and inputs. Labour subsidies are therefore found to be an efficient way to reduce the excess burden of a carbon tax.

A similar impact could not be found for a reduction in taxes on profits²³⁶, because profit mark-ups are

²³³ Recall, prices changes in the present study are expressed relative to the the GDP price index (GDP deflator), in other words: relative to unit GDP primary (or factor) income.

²³⁴ See for instance Goulder (1995), or Bovenberg and Van der Ploeg (1998).

²³⁵ This value is found in several studies (Blanchflower and Oswald, 2005), and has been found to be valid for broad unemployment in South Africa (Kingdon and Knight, 2006).

²³⁶ In IMACLIM-ZA, a reduction of profit taxes with a reduction of the profit mark-up rates can be considered indirectly as a way to represent a reduction of taxes on capital comparable to market-clearing models. Although it does not affect savings or investment directly, it does affect GDP growth strongly. Not reducing the profit mark-up rate would result in lower GDP growth, as the RTIF-fix scenario results show, but in this case a higher share of after tax Gross Operating Surplus of firms is transferred to asset-holders.

modelled rigid, and independent of the productivity of capital. They do not necessarily respond to changes in the tax system, except when assumed so, as in the RTIF-low scenario. Profit-enhancing changes in the tax system therefore do not translate into changes in production costs and average prices through profit mark-ups, and therefore do not enhance competitiveness, domestic demand and GDP growth. Instead, a reduction of taxes on profits without further assumptions (e.g. as it is the case in the RTIF-fix scenario) translate into changes in the endogenous rate of interests and dividends (returns on investment) and therefore into changes in income distribution and in transfer to the rest of the world. Also, investment and the (implicit) capital stock are modelled rather flexible in IMACLIM-ZA with investment assumed to follow GDP growth relatively independent of the return on capital. This represents a world in which there is a big latent potential for savings and investment and in which the choice between final consumption, non-productive investment and productive investment is easily changed. The only link between investment and returns on investment is indirect, because low GDP growth goes in parallel to a low rate of interests and dividends in IMACLIM-ZA (without changes in the tax system). Physical output productivity of (physical) capital does not directly translate into higher rates of returns either, but it positively influences cost reductions in production and therefore GDP growth.

Finally, circumstances for international trade, in particular assumptions about the evolution of the current account (the balance of payments), lead to an almost fixed trade balance.²³⁷ With average price elasticity of international trade above 1.0, the South African economy has to substitute imports by domestic production and decrease the value of its exports to grow faster than the volume of world trade (which strongly determines South African exports). South Africa's REER therefore decreases to balance South Africa's GDP growth with the growth of the volume of world trade. This reinforces the link between decarbonisation and GDP growth, because energy products like crude oil, natural gas, and refinery products are imported for a large part.

The added value of the IMACLIM approach

The IMACLIM approach has an added value for the analysis of carbon taxation presented in this thesis in several ways. First of all, the data hybridisation approach, which combines macro-economic data with energy statistics, allows for a more detailed representation of energy use in the South African economy. This furthermore allows for the integration of insights from experts, engineering, or *bottom-up* modelling, which is notably useful when it comes to modelling future technological change. In IMACLIM South Africa this has been applied to the electricity sector, for which future technology of production (physical capital intensity and fuel intensity of electricity production) were derived from the South Africa TIMES energy system model of the Energy Research Centre of the University of Cape Town. This is an improvement when there is reason to believe that future technological change is not well represented by price-elasticities based on historic evolutions of prices and intensities of

²³⁷ Only the endogenous interest rate changes the ratio of the trade balance over GDP.

production in terms of the use of factors and inputs.

The hybrid approach, the dual accounting of values and quantities of economic flows, also leads to a more explicit treatment of productivity gains. This more explicit treatment changes the question of the “black box” of the growth engine into a plain question of growth accounting. Instead of using historic trends in growth of Total Factor Productivity to govern the relation between income and for instance intermediate inputs, IMACLIM-ZA uses physical intensities of production, which allows defining precisely the trends in the evolution of the volume of output over volumes of inputs and factors. These physical intensities are separated from value creation, which depends on wage-setting, profit mark-ups, tax rates, and also on macro-economic circumstances, such as the real effective exchange rate (REER) and the value of domestic products relative to foreign products. In this way it could be shown that growth of real income in the high skill services sector was partly caused by cost reductions in other sectors and not entirely by productivity gains of factors in this sector.

Furthermore, thanks to this approach, the analysis in this thesis could for instance assume GDP growth partly on the basis of efficiency gains in the use of materials and services in production. Another advantage application was that the question of realistic energy efficiency gains in production of non-energy sectors could be treated more explicitly.

Thirdly, the IMACLIM approach does not assume market-clearing wage setting or profit maximisation neither does it assume perfect foresight as in models with intertemporal optimisation. This is necessary to allow the model to have “imperfect” wages and profit margins, with possible negative consequences for GDP growth. IMACLIM-ZA does not claim to be the perfect model for labour or capital markets, but what is important is that avoiding intertemporal welfare maximisation and perfect market-clearing in factor markets, allows to model rigidities that could be lifted by recycling of carbon tax revenue. This is not possible in case pre-existing economic equilibrium assumes factor payments to correspond exactly to the marginal product of factors (minus tax receipts). For analysis of the labour market, the approach with segmented labour markets by level of skill, modelled through rigid wage setting, allows to identify investment in skills as one of the most beneficial ways of carbon tax revenue recycling.

In brief, thanks to the IMACLIM approach, this thesis is capable of an improved representation of technological change in the electricity sector, of evaluating future technology in regard to energy efficiency improvements, and to capture the impact on GDP growth of rigid profit mark-up rates and labour market rigidities, and the benefits of addressing carbon tax revenue recycling in such a way that these rigidities can be overcome. In this way the results of this thesis are a perfect example of the point made by Guivarch et al (2011) that including market imperfections in a model is necessary to measure not only costs, but also benefits from the introduction of the market distorting “additional cost” of a carbon tax.²³⁸

²³⁸ In this case, in disregard of environmental externalities, as is the case in the reference projection, which therefore could be branded “unsustainable”.

7.2. Policy implications

7.2.1. Achieving South Africa's NDC and NDP

One can draw several conclusions for South Africa's policies for climate change mitigation and economic development on the basis of this thesis. Two acronyms are important in defining South Africa's policy goals for combining climate change and economic development: NDC and NDP. The NDC is South Africa's Nationally Determined Commitment (NDC) to the 2015 Paris Agreement of the UNFCCC²³⁹ (UNFCCC, 2015a). The NDP is South Africa's National Development Plan (National Planning Commission, 2011).²⁴⁰

Concerning South Africa's NDC this thesis finds that its objective is achievable at a carbon tax rate of about 300 ZAR₂₀₀₅ per tonne of CO₂, meaning well above the currently scheduled carbon tax rate of 120 ZAR₂₀₁₈ per tonne of CO₂. Whether the NDC objective can be achieved strongly depends on a few elements: Firstly, it depends on the decarbonisation of electricity production through replacement of coal-fired thermal power plants by renewable power generation. Secondly, it depends on efforts to realise maximal increase of energy efficiency – especially in heavy industry, mining and transport. Besides energy efficiency, efficiency gains for input of other resources, materials and services in all economic sectors are important as well. The analysis in this thesis suggest that a strategy of increasing efficiency in intermediate inputs to production offers a promising route for combining the achievement of climate change objectives with economic development.

It matters a lot for South Africa's economic development *how* carbon tax revenue is recycled. This thesis finds that a mix of four economically promising channels for recycling carbon tax revenue would be the best way to achieve South Africa's multiple policy objectives for climate change mitigation and socio-economic development. This thesis did not test combinations of revenue recycling mechanisms and did not test what would be the most optimal mix, but this question of optimality also depends on political preferences to be defined in democratic political procedures. The "mix" that I advise on the basis of this thesis comes forth from the insight that the different political objectives of economic growth, employment and equity in combination with the environmental objective of reduced CO₂ emissions cannot be realized with one revenue recycling scheme only. Different channels of revenue recycling should be combined, in yet unknown proportions.

The first channel is recycling carbon tax revenue into a labour subsidy: Out of all revenue recycling schemes analysed this option provides the strongest stimulus for technological change towards less energy- and materials-intensive production. It therefore leads to the lowest CO₂ intensity and the highest employment intensity of South African GDP. However, a disadvantage of this revenue recycling scheme and that of the majority of other revenue recycling schemes is that it does not reduce relative and absolute poverty of the poorest households, which face increasing energy prices. Another

²³⁹ UNFCCC = United Nations Framework Convention on Climate Change.

²⁴⁰ Section 3.6.2 motivates why the growth objectives of the NDP seem too ambitious nowadays.

disadvantage is that the combination of carbon taxation with revenue recycling in labour subsidies comes at the cost of reduced returns on capital, and the analysis of this thesis possibly underestimates the sensitivity of investment and therefore GDP growth to the rate of returns on capital.

To overcome these two disadvantages, two other revenue recycling schemes should be considered in parallel: A policy similar to revenue recycling through a *per capita* lump-sum transfer to households – this strongly reduces poverty; however it is expected to come at a serious macro-economic costs to the rest of the society. Better targeted anti-poverty interventions involving smaller budgets than recycling 100% of carbon tax revenue into a lump-sum transfer should be considered instead. Examples are measures to reduce energy dependency of households²⁴¹, or a version of labour subsidies that is pro-low income households. Disadvantageous consequences of a carbon tax for profits should be counteracted by recycling a part of carbon tax revenue into a reduction of taxes on profits. This option comes at the risk that, if market configurations do not lead to a decrease in profit mark-up rates or if it would not lead to investment in productive capital, the macro-economic impacts could be equally disadvantageous for South Africa as in the case of recycling 100% of carbon tax revenue into deficit reduction or a lump-sum transfer to households, resulting in weak GDP growth and increasing unemployment.

The fourth, but certainly not the economically least interesting channel for recycling of carbon tax revenue is the case of an investment in skills of labour. The analysis in this thesis assumes that South Africa's labour market will be marked for a long time to come by strong present-day and past disparities in inequality in access to high quality education, while technological change is assumed to continue to develop in a low-skill labour saving direction, as has been witnessed in recent decades. In such a context, South Africa's high skill labour market segment will be marked by an increasing shortage, causing further increases of in international comparison already elevated costs for high skill labour, thereby effectively reducing the affordability of South African products. This has negative repercussions for GDP growth: The investment in skills scenario shows that under these circumstances, additional availability of 0.75 million high skill workers by 2035 could decrease broad unemployment by 1 to 2 percent points or by 0.25 to 0.5 million jobs, especially for medium and low skill labour. It would furthermore add 4 to 5% to 2005 - 2035 GDP growth, representing a value many times larger than the annual sum of carbon tax revenue spend on education and training investment in this scenario, which was estimated at 7.5 billion Rand₂₀₀₅ by 2035. Lastly, an investment in skills can be expected to reduce the CO₂ emission intensity of South Africa's GDP by 1%, by increasing labour's attractiveness as a factor of production.

That being said, three other revenue recycling schemes analysed in this thesis came out as being very disadvantageous for the South African economy. However, several secondary benefits of these

²⁴¹ Winkler (2017) suggest a few measures, which could be realised for 30 to 40 billion Rand₂₀₁₆ or about 15 to 20 billion Rand₂₀₀₅, which is about one fifth of the 92 to 117 billion Rand₂₀₀₅ of carbon tax revenue estimated to be collected in the 300 Rand/tonne CO₂ carbon tax scenarios of IMACLIM-ZA.

measures, or more tailored versions of these revenue recycling schemes for a small part of carbon tax revenue, can be imagined to lead to specific economic benefits and therefore deserve further attention in future research. This concerns the following recycling schemes, for the following reasons:

- Revenue recycling by reduction of a Value Added Tax (VAT) turns out to have an economic performance that is a bit weaker than that of revenue recycling through the reduction of profit taxes or via labour subsidies, but this should not disqualify it as a potential channel for revenue recycling. The reason for its weaker economical results was that revenue recycling through the reduction of sales taxes partly benefits foreign producers and does not compensate average domestic production for loss of international competitiveness due to costs of carbon taxation as much as the latter two recycling schemes. However, the major benefit of revenue recycling through a sales tax reduction is that it reduces the Consumer Price Index (CPI) relative to other prices in the economy, which makes costs of making a living and labour relatively cheaper. A more limited application, e.g. in the form of a food tax break (as proposed by other studies on carbon taxation in South Africa), could therefore still be economically beneficial and might have the potential to reduce poverty;²⁴²
- Secondly, the impacts of carbon tax revenue recycling into increased governmental expenditure on public services could not be fully analysed with IMACLIM-ZA, because indirect effects on productivity, for instance through improved health care or a reduction of crime, could not be evaluated. However the just mentioned case of investment in skills-option showed that such impacts could be significant. More elaborate future analysis of the impacts of this revenue recycling option is therefore required;
- Thirdly and lastly, carbon tax revenue recycling through production subsidies only resulted in medium outcomes for GDP growth and employment too, but this option could also have a better economic outlook if it would be targeted in a clever ways, for instance in ways that would also increase the energy and materials efficiency that leads to better GDP growth, as mentioned before.

However, these caveats do not diminish the central finding that reducing the cost of South African labour is an efficient way to achieve low carbon economic development, as it directly favours the cleaner alternatives in production and consumption over the energy intensive ones. Two types of revenue recycling are in theory available: Firstly, using carbon tax revenue to subsidize employment, and secondly, by investing in large scale programs that reduce the high skill labour shortage. This thesis, however, only studied the latter of the two options in a counterfactual way, and further study is therefore required to identify possible programs and verify the investment need for such programs.

²⁴² See the study by Van Heerden et al (2006). Targeting taxes on food could also be a way to mitigate disadvantageous impacts of climate change, e.g. if food prices increase at the consequence of loss of agricultural productivity.

7.2.2. The role of international trade and climate policy

The extent of the macro-economic impacts of a South African carbon tax and its revenue recycling depends on the international context. The most important international dimensions of South African carbon taxation and its revenue recycling that are highlighted by the analysis and the results of this thesis and which are discussed here are: The existence of foreign carbon taxation; the role of foreign BTA; the role of a trade balance surplus and the composition of international trade, and connected to the question of the trade balance: foreign investment and the evolution of the REER; and, last but not least, the conditionality of South Africa's NDC, e.g. on technology transfer.

All main carbon tax (Ctax) scenarios and the Reference Projection (RP) are modelled assuming that the Rest of the World does not implement carbon taxation. In both cases, this might not be very realistic: Considering the (revived) discussion in many countries about the implementation of carbon taxation a future with carbon taxation in the rest of the world is very probable. However, considering the current lack of foreign carbon taxation, it might also have been more reasonable to analyse the main Ctax scenarios of this thesis with a carbon tax rebate for South African exports, and/or a carbon-based Border Tax Adjustment (carbon-BTA) to protect domestic products in domestic markets against unequal competition from foreign untaxed products. Alternative scenario analysis has been used to fill this gap in the main scenario analysis by analysing the case of international carbon taxation, and the case of a foreign BTA might South Africa not implement sufficient carbon taxation of its own.

Multilateral carbon taxation with an international carbon tax rate equivalent²⁴³ to the South African one has a beneficial impact on South Africa's economy in comparison to unilateral implementation for a carbon tax of 300 ZAR₂₀₀₅/tonne CO₂ (55 USD₂₀₁₃/tonne CO₂). Scenario analysis in this thesis finds about 4% higher South African GDP in 2035 and a 3 percentage point's lower broad unemployment rate. It lies in the line of expectation that Ctax rebates for South African exports and domestic carbon-BTA in case of a unilateral carbon tax could have the same impact. However, due to a reduction of economic carbon leakage, South Africa's economy's CO₂ intensity increases, which means that a similar CO₂ emission reduction will require a slightly higher carbon tax than originally foreseen, which likely reduces a part of the economic benefits of multilateral carbon taxation again.

On the contrary, a carbon-BTA imposed by ROW has a negative impact on South Africa's GDP, but is expected to be economically less significant for GDP growth than implementing an equivalent carbon tax domestically. The reason is that a foreign carbon-BTA only hits the international component of South Africa's GDP growth and leaves important domestic drivers of GDP growth, such as productivity gains, mostly untouched. For a foreign carbon-BTA to be "punitive" if South Africa decides not to act on climate change it needs to represent a carbon-tax rate of more than 3 times the envisioned equivalent international carbon tax rate. Another reason for the minor impact of foreign BTA is that the exchange rate adjusts and partly compensates for the new economic circumstances. Of

²⁴³ Equivalent is defined as having a similar relative price-impact on average sectoral prices.

course, this analysis has been performed with the use of simple price elasticities for international trade only, and structural price-competitive disadvantages or exclusion of certain international supply chains on ethical grounds might have bigger negative impacts than those expected by foreign BTA in the analysis in this thesis.

Nevertheless, South Africa's motivation for climate policy should come from within, and a sense of responsibility for the future. South Africa has a lot to lose due to climate change. Agriculture, for instance, provides more jobs than coal mining and coal-fired power plants. Also, were climate change to increase droughts, then lack of water has the potential to paralyse more services and industries in South Africa than just agriculture – e.g. think of tourism, food industry, and industries that require cooling.

Results for RP and Ctax scenarios have also been realised assuming that South Africa as a whole reduces its deficit with the rest of the world (ROW), meaning that it starts borrowing less from ROW. This is mainly achieved through South African companies and households saving more. Due to past net borrowing from the rest of the world, returns on assets (financial capital) to ROW still make-up about 1.7% of South Africa's GDP. Add another flow of 1.7% of foreign assistance and money transfers from South Africa to ROW, and this explains the projected trade balance surplus of about 3.4% of GDP in all scenarios. These constant international money flows and the trade balance surplus impose a change in the REER, meaning a devaluation of the South African Rand when GDP growth and imports are high, and revaluation when the opposite is the true. These real currency movements represent South Africa's international competitiveness, but can also be considered to reinforce South African GDP growth or a lack thereof.

However, in relation to movements of the REER of the South African Rand it is important to realise that impacts of changes in returns on assets under carbon taxation on international borrowing and lending have not been studied, because description of such economic behaviour was out of scope for this thesis. More conclusive remarks about impacts on international borrowing and lending, financial flows and therefore the real effective exchange rate of the South African Rand can therefore not be made on the basis of this thesis. In view of the significant macro-economic role of these international financial flows, further study of the role of the REER and foreign investment, and also of savings and consumption behaviour under carbon taxation is therefore recommended.

Another finding of this thesis is that relatively standard expectations about price elasticities of final consumption and international trade do not allow a major economic re-structuring of the South African economy towards economic sectors with a relatively low CO₂ intensity, e.g. many services and high-end manufacturing. If such a re-structuring is not achievable for the South African economy, then South Africa should envision reducing the environmental impact of its existing industries. However, for the energy- and transport-intensive sectors (metals, chemicals, and mining) that make up a large share of South Africa's economy the amount of cheap alternative technologies seems limited for the

time being.

This finding underlines the need to differentiate carbon pricing across countries, as also argued by Bataille et al. (2018). The argument that this thesis provides is as follows: If not all economies have the same capability to re-structure or transform to low carbon economies, then a carbon tax will have a different economic weight in different national economies. Typically middle-income countries like South Africa have high CO₂ intensities, but not necessarily the most advanced technological and educational profile. Rather than negotiating international redistribution of carbon tax funds, it might be more realistic to allow countries to have different carbon tax rates for reasons of equity. Another in theory interesting idea would be to implement differentiated consumer carbon tax rates for reasons of equity. This means, levying a higher carbon tax rate over luxury goods like holiday air travels and red meat, and a lower carbon tax rate over the construction of the necessary new environmentally sustainable economic infrastructure, e.g. the construction of energy-efficient and public transport systems, energy efficient housing, and power generation.

This thesis finds that the conditionality of South Africa's NDC on foreign assistance is very reasonable. A transformation to a low carbon economy requires the availability of new technology, and the development of new economic activity and even sectors (e.g. domestic production of machinery and equipment for renewable energy and clean production processes). It also requires a lot of upfront investment, in training of employees and education, but also in more energy- and materials-efficient production processes, which are likely more capital-intensive. South Africa's currently low credit rating makes such investments expensive.

7.2.3. The importance of technological change

The conclusion of this thesis strongly emphasizes improved efficiency materials & services use in all industries. The reason for this emphasis is that it has been found to be a crucial element to achieve economic development and climate change mitigation objectives at the same time. If the economy is to achieve higher GDP growth without creating higher CO₂ emissions, it will have to increase the efficiency by which it uses the products of fossil-fuel based industries and accompanying transport processes. Studies about the technological potential for energy efficiency gains in energy-intensive industries, mining and transport however show that the technological potential for such energy efficiency gains is limited in some of the industries that depend most on energy and fossil-fuel use like the iron & steel and cement industries, the paper industry, and the petrochemical industry. This limited technological potential concerns the potential competitive with fossil-fuel based energy against additional costs equivalent to a 300 Rand₂₀₀₅ carbon tax for current fossil fuel-based technologies of production. (This expectation is based on current foresight of state-of-the-art technological progress.)²⁴⁴ To further reduce the CO₂ emission intensity of GDP, increased efficiency of aggregate

²⁴⁴ It has been based on Allwood et al (2011), and a study by DEA (2014).

production in terms of these material inputs would be very desirable.

A few alternatives remain however, if one would want to achieve economic development that respects climate change mitigation objectives without making use of further efficiency gains in production in terms of materials and services inputs. In theory, a lack of energy efficiency gains in energy-intensive industries and transport could (partly) be compensated by further decarbonising electricity production and electrifying transport. Further decarbonisation of the electricity sector would mean decarbonisation relative to what has been considered in the bottom-up energy system model SATIM, which has been used to inform scenarios of this thesis. The SATIM runs consulted for this thesis explore the economically least-cost path to develop power generation assuming that the build plan of the Updated IRP of 2010 will be realised and that a 300 Rand carbon tax will be introduced.²⁴⁵ This thesis does not perform additional analysis to study stronger decarbonisation of the electricity sector, but there is a considerable chance that such deeper decarbonisation of the electricity sector is an economically efficient way to reduce South Africa's CO₂ emissions in the context of 300 Rand carbon tax. It depends on how abandoning plans of the Updated IRP 2010 for life extension of old coal-fired thermal power plants and for building new thermal power plants would work out. Considering possible techno-economic limitations for energy efficiency gains in industry, this option deserves exploration.²⁴⁶ A similarly interesting option to explore in this context is that of strongly electrifying transport.

The question of investment in power generation points at a weakness of the present study, which is that it did not consider early infrastructural and other technological investments as channels for carbon tax revenue recycling. The model used in this thesis does provide a framework to consider such investments, as this thesis shows that future GDP growth depends largely on how future physical capital, labour, and energy, material and services intensity of production in South Africa's economic sectors looks like. It should therefore be possible to analyse infrastructural and other technological investments could therefore be evaluated for their impact on production costs. The relevance of evaluating such investments (and their timing) is that the world does not stop once South Africa would have achieved its NDC in 2025 or 2035. The total of NDC's in the world is expected to significantly fall short of achieving the goal of limiting global warming to 2°C compared to pre-industrial era's earth surface temperature, and NDC's are far away of achieving the ambition of limiting global warming to 1.5°C (Rogelj et al., 2016). If these global targets were to be translated into carbon budgets by nation, then the emission trajectory of the 300 Rand carbon tax scenarios explored in this thesis results in only a very small carbon budget left for South Africa to use after 2035. This implies that by 2035 a series of major technological investments should be in the pipeline so South African CO₂ emissions can be brought to zero within a few years time after 2035: This thesis expects that after

²⁴⁵ The updated version of the Department of Energy's Integrated Resource Plan of 2010 (RSA, 2013b). Since 2016, there is a new IRP.

²⁴⁶ This would be possible by developing new runs (scenarios) in the South Africa TIMES model of the Energy Research Centre of the University of Cape Town (ERC, 2013).

2035 the reduction in annual South African CO₂ emissions should be about 350 Megatonne of CO₂, while the net reduction of annual CO₂ emissions between 2005 and 2035 is found to be less than 100 Megatonne of CO₂ if one follows South Africa's NDC. The latter suggests that additional policies that aim at greening infrastructural and technological investment should be considered, in parallel to a gradual increase till 2035 of the carbon tax to a rate of around 300 Rand₂₀₀₅ per tonne of CO₂.

7.2.4. Future labour productivity, wages, rent-taking and employment

This thesis finds that South Africa's economic future depends on currently unknown costs of future renewables-based production, on the costs of energy and material and energy efficiency measures, and on currently unknown future labour intensity and required skills profiles of these future technologies. These questions should therefore be central to future economic research. The analysis in this thesis assumes that future more environmentally sustainable technologies will on average be somewhat more expensive than present-day technologies. If these technologies will be labour-*extensive* at the same time, meaning that they have high labour output productivity, then the problem to be faced is that South Africa cannot simply grow its way out of unemployment. In this case, more radical measures would be required to reduce unemployment and reduce economic inequality: Redistribution of labour (e.g. shorter working weeks, or more time for training & education throughout one's career) and different forms of labour subsidies could be considered, but also policies that aim at lowering profit mark-up rates or at a more equitable distribution of capital rents.

Connected to the last point this thesis shows that what is most important for an increase in employment is that the total of income (rents, taxes and wage) – expressed in purchasing power of foreign products earned per unit of output – is reduced relative to average factors' and intermediate inputs' output productivity. Increasing productivity without increases of rents and with below average output productivity gains for labour would be the best guarantee for a reduction of unemployment. Such a decrease of rents or income over productivity is achieved in policies like the investment in skills-option, because this option reduces exaggerated high skill labour's "wage rent". Policies that increase competition and that reduce possibly excessive profit mark-up rates could be another way to increase domestic demand and employment.

7.2.5. Universal recommendations concerning carbon taxation

What is true for South Africa is to some extent also true for the world as a whole. Of course, South Africa faces some unique economic challenges, like that it is one of the most carbon (CO₂ emission) intensive economies of the world and that it has one of the highest levels of income & property inequality in the world. Also, crime, HIV, and educational and geographical inequalities inherited from the Apartheid era frustrate the country's economic development. This thesis does not analyse solutions for these problems, but does show that given reasonable (albeit uncertain) expectations about future technological progress, South Africa can achieve its NDC in combination with reasonable GDP

growth.

However, the findings of this thesis also put the NDC-approach itself, as adopted with the Paris Agreement on Climate Change of 2015 (UNFCCC, 2015b). This thesis shows that the economic outlook for countries is significantly different with or without an international climate policy regime, notably carbon pricing. This thesis shows furthermore that the economic costs of decarbonisation might be higher for some countries than for others, considering differences in the capacity of countries to finance and develop low-carbon modes of production. Other studies suggest that especially energy intensive industries like those producing basic materials such as concrete, metals, and chemicals have less, *or* only more costly possibilities to substitute the use of fossil energy and resources by more energy efficiency or low carbon sources of energy. A coherent vision on what an equitable development of the global economy would look like and on the role of each national economy in the global economy should be part of an international climate regime if such a regime is to obtain the support of people in developing and emerging countries like South Africa. Furthermore, differences in economic potential to develop low carbon economies also suggest that there is a need for international policies that organise finance for technological and economic transformation and that facilitate the adaptation of low carbon technologies in developing and emerging countries.

Let us however disregard the need for more international climate policy, and consider what the findings of this thesis could mean for other countries individually: The first steps of decarbonisation might be smaller and easier to realize for other countries than for South Africa, given that a transition to a cleaner and more labour-intensive economy will be less frustrated by a high skill shortage that makes further economic development expensive. But, on the other hand, the rest of the world might not have an equally big unharvested economic potential for economic growth from lifting this skill shortage like South Africa has. This potential concerns the reduction of the excess burden of a carbon tax by reducing labour costs or by investing in the skills of labour, or the investment in improving general productivity by better skills for the active population. This implies that a strong double dividend might not necessarily be easier to achieve by the Rest of the World than for South Africa.

Another universal conclusion on the basis of the findings of this thesis is that *if* the current expectation that future costs of clean, renewables-based technologies of production will be more expensive is true, *and if* consumer preferences remain relatively attached to energy- or greenhouse gas intensive products or services²⁴⁷, then this could lead to a reduction in the global rate of GDP growth compared to past GDP growth rates. Limitations in the potential for future GDP growth mean that the question of the future evolution of labour's output productivity has relevance for the rest of the world as shown for South Africa in this thesis. If technological change continues to improve labour's output productivity as observed in recent decades, and if it increases faster than GDP growth, then a political question will be *who* will have the chance to get educated and participate in the highly productive economic system

²⁴⁷ Typical examples are holidays by airplane, meat consumption, and bigger well-heated or -cooled houses.

to make a living as an employee, entrepreneur or owner of productive or natural capital (or assets).

However, results of this thesis contain hope as well, considering that several scenarios which achieve South Africa's NDC also obtain annual growth rates of around 2.5% per year or higher. This is well above average South African GDP growth of the recent decade. Finding solutions to South Africa's other economic problems for GDP growth therefore remains as important as finding the right way to introduce a carbon tax and use its revenue.

One ethical implication for the equity of future economic development of the outlook for technological progress and GDP growth as presented in this thesis remains to be discussed. This concerns a question of geographical and intergenerational justice, namely of who will have the right to use current cheap and polluting technology for their material welfare – assuming that clean sustainable technology of production will remain less productive and therefore more expensive than present-day resources and the environmental exhausting technology for still some time to come. For example: Should a tonne of CO₂ for intercontinental air travel today be equally expensive as the tonne of CO₂ emitted in producing the steel for a railway or the plastics and electronics for medical machines in developing countries tomorrow? Taking a shot ahead on the discussion of recommendations for future research next, I think that anybody concerned with this question should also be concerned with the following three issues: First of all, knowing and developing the cheaper renewables-based technologies to fulfil peoples material needs; Secondly, changing the way we define our needs; And thirdly, improving the global social fabric so questions of global equity can be solved in a peaceful manner.

For the field of macro-economics the issues and key elements encountered for growth under environmental constraints mean that it should be concerned with the realistic estimation and integration in economic models of future technological coefficients for production, of household preferences, and of rent- and wage-setting behaviour by factor or economic agent or sector.

7.3. Future research

The policy recommendations identify a few knowledge gaps limiting the certainty about the most optimal future path of action. In other instances, limitations are related to modelling choices in IMACLIM South Africa. In some cases, limitations in modelling are not only true for IMACLIM-ZA, but for the wider community of energy-economic models, e.g. when it concerns labour market modelling. This section summarizes important knowledge gaps, and lays out routes for future research.

7.3.1. Research to improve the analysis of South African climate change policies

Technological change is generally considered as the fundamental driver behind GDP growth and is also pivotal in the prospects for GDP growth in IMACLIM South Africa, albeit in combination with how wages and profit mark-ups are defined. The main question is whether future technology leads to more affordable products than present-day technology? In this sense, an important question is how costs of clean or renewable technologies and infrastructure compare to those of existing technology

and infrastructure? Furthermore, the question is what are realistic trajectories for future technological coefficients of production by sector for South Africa? These questions are especially important for modelling of energy efficiency of production.

More methodological questions are what historic changes in efficiency of use of intermediate inputs are (over output volume)? And the same question for the intensity of physical capital use in production? To what extent can technological change be represented by price-elastic substitution, and to what extent are changes in these coefficients autonomous? And are these changes of technological coefficients irreversible?

There is a strong chance that the future value of technological coefficients cannot be derived from historic econometric estimates, at least not with the sectoral precision wanted for a multisector model like IMACLIM-ZA. A possibility is to estimate envelopes of technological change under the evolution of different parameters on the basis of bottom-up or partial equilibrium engineering models like Ghersi and Hourcade do (2006), but if this option is not available it should be considered to quantify expert views. A good question is therefore what other methodology could be used to identify them on the basis of expert feedback?

Early investments in infrastructure, such as those foreseen for the electricity sector in South Africa's updated IRP plans and modelled in the SATIM energy system model are identified as an unexplored channel for carbon tax revenue recycling. It is therefore important to list how costs, meaning: the evolution of technological coefficients of sectors is affected by investments – notably those in infrastructure, education & training, and for instance R&D.

Heading in the other direction, a question is how a reference projection should look like if the impacts of climate change on costs of production would be taken into account. Technological coefficients of physical productivity or intensities of production would be an ideal way to take climate change impacts into account, e.g. on the output of agriculture, relative to the use of factors and intermediate inputs. One should for this reason, also consider extended time horizons, possibly in a more stylized version, so that the time horizon at which climate change impacts are felt can be taken into account.

Finally, a for South Africa strategic question in relation to climate policy is how international climate policy would affect South Africa's coal exports, and what the consequences would be for South Africa's economy? Another strategic question is whether it would be possible to quantify co-benefits, for instance on productivity, of anti-poverty policies and e.g. of increased public services?

7.3.2. Suggestions to improve labour market modelling

In developing IMACLIM South Africa's labour market model a conceptual problem was identified, namely that skill can be considered a characteristic of a job as a function in production, and as a characteristic of the worker that has or seeks employment. A question is therefore how the level of educational attainment (or of degrees) historically evolved by job type? To what extent is there a

question of labour supply-driven increases in the level of educational attainment of the employed, and to what extent did technological change require higher levels of education per job type? Or, vice versa, to what extent did higher levels of educational attainment lead to technological change? The latter two questions might be hard to analyse, but for a start it would be already interesting to know the evolution of the level of educational attainment by job type, e.g. relative to the level of educational attainment in the active population.

More likely is the chance to define and estimate a link between years of education, wage premiums, labour productivity and labour's output (volume) productivity. A related question is how wage evolves with productivity at the level of sectors.

A last suggestion for improvement of modelling supply and demand for skills would be to model include income elasticities of consumption in the consumption functions, which could turn out positive towards high skill goods. BY calibration data shows that the richest households spend an above average share of their consumption budget on HSS goods and a below average share on LSS goods. Allowing poorer household classes to develop similar expenditure patterns with growing income could lead to a greater absorption of higher educated labour in a non-positional labour market model.

7.3.3. Improvement of IMACLIM South Africa

There are furthermore some points that could be important for improvement of modelling in general, but are specifically relevant for IMACLIM South Africa. These points first of all concern further improvement of the integration of Bottom-Up modelling insights: An already mentioned idea is to estimate envelopes (reduced forms) of technological change under the evolution of different parameters like Gherzi and Hourcade do for (2006) on the basis of SATIM. Furthermore, South Africa's Integrated Resource Plan for 2016 could be taken into account as an update to more recent policy. Also, recent insights suggest that the outlook for costs of solar PV power generation has changed. These changes could be evaluated for their impacts on the expected economic impacts of CO₂ emission reduction. In connection to the discussion about early investment, a further exploration of the economic impacts of stronger decarbonisation of the electricity sector would be interesting.

Another point for improvement of IMACLIM-ZA concerns the modelling of the capital market? What would happen if it would be modelled more rigidly, e.g. if past investment depends on the rate of interests and dividends? Methodological questions would be whether there is literature or data on which basis the behaviour of profit mark-up rates could be modelled? Furthermore, a question is how the relation between gross saving, net borrowing and lending, and investment could be modelled? How does it respond to rates of return on capital? Related to the model of international trade, is the question how margins should be defined for exports? And, what the relation is between profit mark-ups and margins for domestic production and import prices?

Household final consumption has been modelled rather ad hoc in IMACLIM-ZA, and better estimates

for household behaviour for final consumption are available. It would be interesting to apply these to IMACLIM South Africa. Related to modelling household final consumption, an idea would be to model a sector for agriculture and the food & beverages industry – given that it takes an important place in household final consumption, and turns out to have priority in consumption of poor households over energy and other expenditure. Related to this last point is the question how specific investments that could reduce household’s energy-dependency could be modelled. It would be interesting to analyse these as a more nuanced form of carbon tax revenue recycling than the per capita lump-sum transfer.

7.3.4. Improvement of the IMACLIM methodology

Besides more general mentioned points about modelling GDP growth and modelling of labour and capital markets, some specific questions were encountered regarding the application of the IMACLIM approach to South Africa. Some of these problems might be relatively easy to overcome: First of all, there were issues with data quality and statistical discrepancies for South Africa, despite that the country often has good statistical data. Also, the years 2000 to 2017 have proven to show strong fluctuations for South Africa’s economy, whether due to resource prices, the oil price, or changes in foreign direct investment. These fluctuations and statistical discrepancies lead to caution in using only data for one year for model calibration. Considering the relatively long time horizon of IMACLIM, a multi-year average might be more robust for model calibration.

A second encountered issue was that IMACLIM South Africa, possibly more than other IMACLIM models focused on the behaviour of non-energy sectors in an economy. To have a choice in the level of non-energy sector disaggregation, the hybridisation procedure of economic data with energy statistics and energy price data was performed at a relatively disaggregate level. The changes caused by energy statistics were sometimes rather large, and retrospectively, it would have been better to have designated one large sector for the absorption of adjustments necessary for hybridisation. Alternatively, a procedure could be designed to aggregate non-energy sectors before hybridisation and to re-disaggregate them afterwards, respecting a certain distribution of intermediate inputs, value added and taxes from before hybridisation.

Future potential improvements of dual accounting of physical volumes and economic values are that ultimately the objective is to link economic development to the resource base of the economy, be it solid resources like metal ores, salts and other chemicals extracted from the earth, energy resources like coal, oil and gas, or (sweet) water, or more qualitative resources and sink capacities, for instance the quality of forests to purify the air. If this could be established, the connection to environmental indicators could be modelled dynamically, and it would be possible to make the connection between potentials for technological change, policies, and the time left to act on environmental overexploitation.

Finally, IMACLIM models should try to take into account a wider set of determinants for technological coefficients and future productivity growth (or reduction), such as the impact of public services, infrastructure, but also living standards, education, and poverty on e.g. labour and capital productivity. In the same line of reasoning it would be logical to try to take into account the impacts of climate change on physical factor and input productivities to have a more equilibrated comparison between scenarios. Connected to the latter would be the requirement to introduce physical accounts (and limits) for the use of land as a factor for agricultural production would be important too, to take into account the costs of food, as one of the most elementary needs and budget items of households.

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Résumé significative

L’Afrique du Sud est une économie aux revenus moyens avec un système énergétique basé sur l’utilisation du charbon fort émetteur de gaz à effet de serre, à un niveau comparable à celui des pays aux économies les plus riches du monde. Le pays a promis de réduire significativement ces émissions (de 34% en 2020, et de 42% en 2025 par rapport à un développement « business as usual » (BAU), sous condition d'aide financière et technique de la communauté internationale). Le pays connaît d'intenses débats sur les politiques pour atteindre ces objectifs, et parmi les sujets discutés figure une taxe carbone.

L'atténuation du changement climatique n'est pas le seul défi de l’Afrique du Sud. Malgré les forts progrès dans la lutte contre les inégalités (héritage de l’époque de l’Apartheid), et dans l’amélioration de la qualité de vie depuis le début de la gouvernance démocratique en 1994, la croissance économique a ralenti ces dernières années, le montant de pauvreté reste élevé, ainsi que les fortes inégalités. De plus, l’économie de l’Afrique du Sud fait face à un niveau de chômage très élevé, qui touche principalement les personnes à bas niveau de qualifications (skills) alors qu’il manque de la main d’œuvre à haut niveau de qualification.

Le rapport présenté ici souhaite fournir de nouvelles perspectives sur l’articulation entre les objectifs de l’Afrique du Sud pour l'atténuation du changement climatique et pour le développement. En particulier, le rapport se concentre sur les questions de croissance économique et de chômage, avec des réflexions sur les inégalités sociales et économiques et sur l’éducation.

Pour cette analyse, le modèle IMACLIM-ZA est utilisé; un modèle récursif des équilibres de comptabilité générale de l’économie de l’Afrique du Sud. Le modèle représente l’économie du pays comme une petite économie ouverte avec 10 productions (5 en énergie, et 5 non-énergétique), et avec 5 classes de revenus des ménages. Pour la calibrer ce modèle, l'année de référence est 2005 (l’année avec les données disponibles les plus-récentes au moment de la construction du modèle) et à partir de celle-ci, une projection est réalisée pour 2035 d'une économie équilibrée, basée sur les hypothèses de l'évolution des paramètres centraux (notamment la démographie, la productivité du travail et du capital, les prix internationaux, etcétera). La représentation de l'équilibre pour 2035 est calculée avec (dans la projection de référence), et sans politique d'atténuation du changement climatique. Les résultats pour 2035 sont analysés par rapport aux questions de la croissance économique, l'emploi et la distribution des revenus.

La calibration de l’année de base, 2005, est réalisée sur la base d’une matrice de comptabilité sociale ajustée, qui harmonise de façon consistante les flux monétaires des statistiques macro-économiques et les flux de matières énergétiques estimés sur la base des statistiques et données énergétiques. Les

différences dans les prix des biens et des services (notamment les produits énergétiques) pour les différents consommateurs (entreprises, ménages, secteur public et exports) sont également pris en compte. Pour prendre en compte des changements dans la production de l'électricité entre 2005 et 2035, le modèle se fonde aussi sur des runs du modèle TIMES Afrique du Sud du Centre de Recherche sur l'Énergie de l'Université du Cap. Au final, le modèle contient une description détaillée du marché du travail dans les perspectives de l'offre, de la demande et du fonctionnement concernant trois degrés des qualifications.

Dans la projection de référence, dans le contexte de nos hypothèses, on voit le PIB croître de 2.7% en moyenne par année, avec une augmentation du PIB par tête de 80%. Pour obtenir une telle croissance économique on augmente la productivité du travail et du capital, et des inputs intermédiaires (biens et services). Malgré une baisse significative du niveau du chômage en 2035 par rapport à 2005, on observe que le niveau de chômage reste élevé et que le manque des travailleurs qualifiés perdure. En prenant aussi en compte le plan d'investissement à long terme pour le secteur électrique de 2011, les émissions de gaz CO₂ augmentent beaucoup dans cette projection de référence.

7 scénarios de recyclage de revenus de la taxe carbone sont analysés, avec différentes utilisations des revenus de la taxe. On observe qu'une taxe carbone de 100 Rands par tonne de CO₂-équivalence (100 ZAR₂₀₀₅/tCO₂) est déjà une taxe importante par rapport aux prix de l'énergie domestique, malgré sa faiblesse par rapport aux standards internationaux, mais aura des conséquences faibles pour la croissance du PIB et l'emploi.

Une taxe encore plus élevée, à 300 ZAR₂₀₀₅/tCO₂ sera nécessaire pour obtenir les objectifs d'atténuation des changements climatiques de l'Afrique du Sud. Les conséquences pour la croissance du PIB et pour l'emploi de cette taxe carbone pourraient être significatifs. Toutefois, ces conséquences dépendent fortement du choix du mécanisme de recyclage des revenus de la taxe. Dans le meilleur scénario, qui est celui de la subvention du travail, le PIB serait moins élevé de 15 points en 2035 par rapport au BAU. Ce même scénario propose l'utilisation des revenus pour réduire les cotisations et charges (impôts) sur le travail (RTSC), créant une subvention. Il obtient les meilleurs résultats économiques, proches de ceux de la projection de référence pour une taxe à 100 ZAR₂₀₀₅/tCO₂, mais avec une forte réduction des émissions de gaz à effet de serre.

Parmi les autres options de recyclage analysés, le recyclage via un transfert des revenus de la taxe vers l'ensemble des ménages a un impact significativement négatif sur le PIB par rapport à la projection de référence. Toutefois, ce scénario a pour avantage d'être le seul à avoir un impact positif sur la distribution des revenus et la lutte contre la pauvreté.

Enfin, l'option de recyclage d'une partie des revenus de la taxe carbone ciblée sur la subvention du travail vers les investissements dans l'éducation et la formation est analysée. Ce scénario se traduit par une croissance économique accélérée par rapport aux autres scénarios.

Appendices

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A. Model description IMACLIM-ZA

A.1. System of equations IMACLIM-ZA

A.1.1. Introduction

From a mathematical point of view IMACLIM-ZA is a comparative statics model which boils down to a set of simultaneous equations (Combet, 2013):

$$\left\{ \begin{array}{l} f_1(x_1, \dots, x_n, z_1, \dots, z_m) = 0 \\ f_2(x_1, \dots, x_n, z_1, \dots, z_m) = 0 \\ \dots \\ f_n(x_1, \dots, x_n, z_1, \dots, z_m) = 0 \end{array} \right.$$

with:

- $x_i, i \in [1, v]$, a set of variables (as many as equations),
- $z_i, i \in [1, p]$, a set of parameters,
- $f_i, i \in [1, v]$, a set of functions, some of which are non-linear in x_i .

The f_i constraints are of two quite different natures: one subset of equations describes accounting constraints that are necessarily verified to ensure that the accounting system is properly balanced; the other subset specifies various behavioural extensions of these accounting constraints. Some f_i are written in a simple linear manner (*e.g.* households consume a fixed proportion of their income) others in a more complex non-linear way (*e.g.* the trade-offs in production and consumption). It is these behavioural constraints that ultimately reflect, in the flexible architecture of IMACLIM-ZA, a certain economic ‘worldview’. Model variables, constraints, and parameterisation are given in sections 3.5 and 3.1 and 3.6.

Any variable name indexed with a ‘0’ designates the specific value taken by the variable in the 2005 equilibrium (*i.e.* the value calibrated on the 2005 hybrid I-O table or the harmonised current and financial accounts of agents described). If a parameter has a flat accent, *e.g.*: \bar{x} , this indicates a calibrated parameter (not necessarily based on BY values), as opposed to a model variable (or intermediate model variable).

A.1.2. Producer & Consumer price setting

Producer price

The producer price of good i , $p_{Y,i}$, is built-up like the cost structure of production of good i , meaning: as the sum of: intermediate consumption, $p_{C|ji} \alpha_{ji}$ of goods $j = 1$ to 10 – for the 10 sectors described in report section 3.1; labour costs for skill $sk = 1$ (low) to 3 (high); capital costs, $p_K k_i$; a tax on production, $\bar{\tau}_{Yi}$ (kept at BY value in all but one scenario); and a mark-up rate, $\bar{\tau}_{NOS,i}$ (corresponding to the Net

Operating Surplus):

$$p_{Yi} = \sum_{j=1}^{10} p_{Clij} \alpha_{ji} + \sum_{sk=1}^3 p_{Lsk,i} l_{sk,i} + p_K k_i + \bar{\tau}_{Yi} p_{Yi} + \tau_{NOSi} p_{Yi}. \quad (1)$$

Import prices

The price of imported good i , $p_{M,i}$, is good-specific, for which the divergence of international prices assumed in this PhD has been discussed in report section 3.6.3. Only one price is kept constant as the *numéraire* of the model, namely the international price of HSS (High Skill Services sector), $\bar{p}_{M,HSS}$:

$$\bar{p}_{M,HSS} = p_{M,HSS,0}. \quad (2)$$

Average domestic, or: resource, price

The average price of the resource of good i , p_i , is the weighted average of domestic and import prices of good i :

$$p_i = \frac{p_{Yi} Y_i + p_{Mi} M_i}{Y_i + M_i}. \quad (3)$$

The domestic and foreign varieties of goods are assumed homogeneous in the sense that they can be exchanged, but as pointed out in the discussion about the terms of trade (report section 3.2.2), there is no perfect substitutability between the two goods. The alternative assumption of product differentiation, adopted by many CGEMs through their use of an Armington specification for international trade (Armington, 1969), has the disadvantage of creating ‘hybrid’ good varieties, whose volume unit is independent from that of the foreign and national varieties they hybridise; this complicates maintaining explicit accountability of physical (energy) flows and also an energy balance. For the sake of simplicity, non-energy goods are treated similarly to the energy ones.

Average domestic, or: resource, price

The price of good i consumed in the production of good j , p_{Clij} , is equal to the resource price of good i plus trade and transport margins, agent-specific margins, a domestic excise on oil products (t_{TIPPci}),¹ an aggregate of other excise taxes (t_{AIPi}) and a carbon tax (t_{CI}) calculated over the CO₂ emission factor (kg CO₂ per PJ) of the use of a quantity input i (a fuel, measured in PJ) in the production of a unit of good j ($\overline{\gamma_{Clij}}$).

$$p_{Clij} = p_i (1 + \tau_{Mci} + \tau_{MTi} + \tau_{MSCij}) + t_{TIPPci} + t_{AIPi} + t_{CI} \overline{\gamma_{Clij}}. \quad (4)$$

The consumer price of good i for household h (p_{Chi}), public administrations (p_{Gi}) and investment (p_{Ii}), and the export price of good i (p_{Xi}), are constructed similarly and only differ on whether they are

¹ The TIPP levied on the intermediate and the final fuel consumptions is differentiated to take account of the underlying fuel mixes.

subject to the sales tax ($\overline{\tau_{TVAi}}$; the same rate is applied to all consumptions of one good) and the carbon tax ($t_{CF} \overline{\gamma_{CFi}}$) or not. The latter tax applies to household prices only, as national accounting makes households the only final consumer of energy goods.²

$$P_{Chi} = \left[p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSChi}} \right) + t_{TIPPCFi} + t_{AIPi} + \overline{t_{CF}} \gamma_{CFi} \right] \left(1 + \overline{\tau_{TVAi}} \right). \quad (5)$$

$$P_{Gi} = \left[p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSGi}} \right) + t_{TIPPCFi} + t_{AIPi} \right] \left(1 + \overline{\tau_{TVAi}} \right). \quad (6)$$

$$P_{Li} = \left[p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSLi}} \right) + t_{TIPPCFi} + t_{AIPi} \right] \left(1 + \overline{\tau_{TVAi}} \right). \quad (7)$$

$$P_{Xi} = p_i \left(1 + \tau_{MCi} + \tau_{MTi} + \overline{\tau_{MSXi}} \right) + t_{TIPPCFi} + t_{AIPi}. \quad (8)$$

The general mark-up rate τ_{NOSi} and the agent-specific margins τ_{MS^*i} is fixed at BY values, unless changed by a scenario setting.

$$\tau_{NOS \text{ or } MS^*} = \overline{\tau_{NOS \text{ or } MS^*}}, \quad (9)$$

with $\overline{\tau_{NOS \text{ or } MS^*}}$ the base year (calibrated) mark-up rate or specific margin (for consumer *).

Trade margins τ_{MCi} and transport margins τ_{MTi} , identical for all intermediate and final consumptions of good i , are calibrated on the base year (2005) equilibrium and kept constant, with the exception of those on the productions aggregating transport and trade activities—respectively the TRA and LSS goods, which are simply adjusted, in the projected equilibrium, to have the two types of margins sum up to zero:

$$\begin{aligned} & \sum_{j=1}^n \tau_{MCLSS} P_{LSS} \alpha_{LSSj} Y_j + \tau_{MCLSS} P_{LSS} (C_{LSS} + G_{LSS} + I_{LSS} + X_{LSS}) \\ & + \sum_{i \neq LSS} \sum_j \overline{\tau_{MCi}} p_i \alpha_{ij} Y_j + \sum_{i \neq LSS} \overline{\tau_{MCi}} p_i (C_i + G_i + I_i + X_i) = 0 \end{aligned} \quad (10)$$

and similarly:

$$\begin{aligned} & \sum_{j=1}^n \tau_{MTTRA} P_{TRA} \alpha_{TRAj} Y_j + \tau_{MTTRA} P_{TRA} (C_{TRA} + G_{TRA} + I_{TRA} + X_{TRA}) \\ & + \sum_{i \neq TRA} \sum_j \overline{\tau_{MTi}} p_i \alpha_{ij} Y_j + \sum_{i \neq TRA} \overline{\tau_{MTi}} p_i (C_i + G_i + I_i + X_i) = 0. \end{aligned} \quad (11)$$

² Public administrations consume a ‘public service’, whose energy content appears in the energy consumption of the production in which it is aggregated—and is taxed for its carbon content at this level.

Labour costs of skill sk in sector i , $p_{Lsk,i}$, are equal to the prevailing net wage $w_{sk,i}$ plus payroll taxes (both employers' and employees' social contributions), which are levied following a skill-specific rate $\tau_{CS,sk}$ common to all sectors, and pension contributions (both public and employees' private pension contributions) $\tau_{ACS,sk}$ also following a uniform rate by skill level sk calibrated on the hybrid I-O table (harmonised with current and financial accounts data) for 2005:

$$p_{Lsk,i} = (1 + \tau_{CSsk} + \tau_{ACSsk})w_{sk,i}. \quad (12)$$

The average wage of skill sk in production i , $w_{sk,i}$, varies as the average wage of skill sk across all sectors w_{sk} :

$$w_{sk,i} = \frac{w_{sk}}{w_{sk0}} w_{sk,i0}, \quad (13)$$

which is subject to variations linked to unemployment following the wage curves (see below).

The cost of capital p_K is understood as the cost of the 'machine' capital. It is obtained as the average price of investment goods:

$$p_K = \frac{\sum_{i=1}^n p_{Ii} I_i}{\sum_{i=1}^n I_i}. \quad (14)$$

CPI the consumer price index is computed following Fisher, *i.e.* as the geometric mean of a Laspeyres index (variation of the cost of the BY basket of goods from the BY to the future set of relative prices) and a Paasche index (variation of the cost of the future basket of goods from the BY to the future set of relative prices):³

$$CPI = \sqrt{\frac{\sum_{i=1}^n p_{Ci} C_{i0} \sum_{i=1}^n p_{Ci} C_i}{\sum_{i=1}^n p_{Ci0} C_{i0} \sum_{i=1}^n p_{Ci0} C_i}}. \quad (15)$$

A.1.3. Households' income, savings & investment

$GDI_{BT,h}$ the gross domestic income of class h before taxation is defined as the addition and the subtraction of the following terms:

³ Class-specific indexes can similarly be constructed using class-specific prices (differentiated thanks to specific margins) and consumptions and applied to *e.g.* the computation of class-specific real gross disposable income variations.

- A share $\omega_{Lh,sk}$ of the sum of aggregate endogenous net wage income by skill level of labour sk for all sectors i , $\sum_{i=1}^n w_{sk,i} l_{sk,i} Y_i$. This share of net wage is calculated over the share in a “reference revenue” on the basis of the previous average net wage by skill level and household class and the new number of actives by skill level in each household class.
- A share $\omega_{GOS,h}$ of the total gross operating surplus accruing to households GOS_H , which responds to the share of gross operating surplus accruing to companies, $\omega_{GOS,S}$. This share could also be considered as a part of ‘ownership income’ (the gross operating surplus of national accounting) that goes to households, GOS_H , which are based on the SAM 2005 (StatsSA, 2010b) and normally in the System of National Accounts they should correspond to the real and imputed rents that accrue to households, but it is not excluded that income from direct ownership of enterprises by households is part of GOS in the South African SAM as well, as it also includes mixed income. The ω_{Kh} (the distribution of GOS_H across household classes) are endogenous.
- Social transfers, in 3 aggregate payments (pensions $\rho_{Ph} N_{Ph}$, unemployment benefits $\rho_{Uh} N_{Uh}$, other social transfers $\rho_{Ah} N_{Ah}$), the calculation of which is similarly based on the product of a *per capita* income ρ and a target population N .
- An exogenous share ω_{ATH} of (small) residual transfers A_{TH} .
- A ‘debt service’ $i_H D_h$, which corresponds to property income (interests, dividends, real estate revenues, *etc.*).

Hence:

$$\begin{aligned}
GDI_{BT,h} = & \sum_{sk=1}^3 (\omega_{Lh,sk} \sum_{i=1}^n w_{sk,i} l_{sk,i} Y_i) + \omega_{GOS,H} GOS_H \\
& + \rho_{Ph} N_{Ph} + \rho_{Uh} N_{Uh} + \rho_{Ah} N_{Ah} + \overline{\omega_{ATH} A_{TH}} - i_h D_h
\end{aligned} \tag{16}$$

with A_{TH} a constant share ω_{ATH} of A_T (see Equation 76):

$$A_{TH} = \overline{\omega_{ATH} A_T} \tag{17}$$

The gross disposable income of class h GDI_h is obtained by subtracting from $GDI_{BT,h}$ the income tax T_{IRh} levied at a constant average rate (Equation ...), and other direct taxes T_h that are indexed on the *CPI* (Equation 60). R_h , the consumption budget of class h , is inferred from disposable income by subtracting savings. The savings rate τ_{sh} is exogenous (calibrated to accommodate the values of GDI_h and R_h in the BY equilibrium). On top of the GDI before taxes minus tax levies we also account for the build-up of pension equity, PEQ , which we define as the net difference between pension contributions

and pension benefits, though in reality it should be corrected for gains or losses in pension equity value. This is equity that is managed by financial corporations (pension funds, be they private or public) (see below), but which is counted by the SAM 2005 (StatsSA, 2010b) as part of household gross disposable income.

$$GDI_h = GDI_{BT,h} - T_{IRh} - T_h + PEQ \quad (18)$$

$$R_h = \left(1 - \overline{\tau_{Sh}}\right) GDI_h \quad (19)$$

A further exploration of the data available in the current and financial accounts gives households' investment $GFCF_h$ (Gross Fixed Capital Formation) as distinct from their savings; $GFCF_h$ is assumed to follow the simple rule of a fixed ratio to gross disposable income (Equation 20). The difference between savings and investment gives the auto-financing capacity (AFC) of class h , AFC_h .

$$\frac{GFCF_h}{GDI_h} = \frac{GFCF_{h0}}{GDI_{h0}} \quad (20)$$

$$AFC_h = \overline{\tau_{Sh}} GDI_h - GFCF_h \quad (21)$$

Pension contributions and benefits

Total change in pension equity of household class Hh, PEQ_{Hh} , adds to households' financial assets, and is calculated as the difference between pension contributions and pension benefits:

$$PEQ_{Hh} = (PC - PB) * ShPFund_{Hh} \quad (22)$$

, with:

ρ_{PHh} average per capita retired person pension benefits of Household class Hh, which are calculated through indexing BY per capita pension benefits by household class on national average wage growth;

$ShPFund_{Hh}$ the share of a household class in total pension funds, calculated on the basis of a kind of quasi household class pension equity growth indexed on a household class' wage growth, relative to BY ($\sum_{sk}(w_{sk,Hh} * LL_{sk,Hh}) / \sum_{sk}(\overline{w_{sk,Hh,0}} * \overline{LL_{sk,Hh,0}})$):

$$ShPFund_{Hh} = \frac{\overline{PEQ_{Hh,0}} * \sum_{sk}(w_{sk,Hh} * LL_{sk,Hh}) / \sum_{sk}(\overline{w_{sk,Hh,0}} * \overline{LL_{sk,Hh,0}})}{\sum_{Hh}(\overline{PEQ_{Hh,0}} * \sum_{sk}(w_{sk,Hh} * LL_{sk,Hh}) / \sum_{sk}(\overline{w_{sk,Hh,0}} * \overline{LL_{sk,Hh,0}}))} \quad (23)$$

PC Total pension contributions, calculated as:

$$PC = \sum_{sk,j}(\tau OCS_{sk,j} * w_{sk,j} * LL_{sk,j}) \quad (24)$$

PB total pension benefits, PB , are calculated as:

$$PB = \sum_{Hh} (\rho_{PHh} * N_{PHh}) \quad (25)$$

, with for PC and PB :

$\tau OCS_{sk,j}$ adjusts as a variable so that in 2035 $PEQ = 0$.

ρ_{PHh} average per capita retired person pension benefits of Household class Hh , which are calculated as a national average wage growth indexation of BY per capita pension benefits in a household class;

N_{PHh} household class Hh 's number of persons of retired age (65+) that is based on a share in total projected retired people and which is calculated on the of growth of the active population by household class;

Unemployment and other social benefits

Social benefits, SB_{Hh} , consisting of unemployment benefits and other social benefits, are calculated as (Eq.42):

$$SB_{Hh} = rU_{Hh} * NU_{Hh} + \overline{rOSB_{Hh,0}} * N_{Hh} \quad (26)$$

, with:

rU_{Hh} household class Hh 's average unemployment benefits per unemployed person, which equal CPI indexed Base Year (BY , 2005) household class Hh 's average unemployment benefits per unemployed person;

NU_{Hh} household class Hh 's number of unemployed persons (see section 3.6), which equal a household class' BY share in unemployed by level of skill times the new total number of unemployed per level of skill of labour;

$\overline{rOSB_{Hh,0}}$ household class Hh 's average fixed on BY data calibrated average *per capita* other social benefits, which equal nil, as all BY social security has been allocated to unemployment benefits or other transfers (see Appendix B.4), however it is used to model the per capita lump sum transfer to households in the $RSUM$ scenario;

N_{Hh} household class Hh 's population (see section 3.6);

Household class shares in wages by skill

The share of a household class in wages by level of skill is calculated as a household class' share in skill-specific net wage with new labour distribution by skill and class, but with old wages per skill and class. More precisely, it is calculated as a household class' "quasi" share in total revenue by skill, were average wage per worker of a household class to remain at its BY rate (calculated with: $\overline{\omega_{Hh,sk,0}}$ *

$\sum_j (\overline{w_{sk,j,0}} * \overline{LL_{sk,j,0}}) / \overline{LL_{sk,Hh,0}}$), but using new (endogenous) numbers of workers by household class (and skill: $\sum_j LL_{sk,Hh}$) and its sum per level of skill ($\sum_{Hh} \sum_j LL_{sk,Hh}$, in the calculation of total “quasi” wage by level of skill), see Eq.27:

$$\omega W_{Hh,sk} = \frac{\overline{\omega_{Hh,sk,0}} * \sum_j (\overline{w_{sk,j,0}} * \overline{LL_{sk,j,0}}) / \overline{LL_{sk,Hh,0}} * \sum_j LL_{sk,Hh}}{\sum_{Hh} (\overline{\omega_{Hh,sk,0}} * \sum_j (\overline{w_{sk,j,0}} * \overline{LL_{sk,j,0}}) / \overline{LL_{sk,Hh,0}} * \sum_j LL_{sk,Hh})} \quad (27)$$

A.1.4. Trade-offs in consumption

Trade-offs in consumption are defined per household class and at the level of *per capita* volumes of consumption. They are modelled through nested CES specifications (Figure 3.4 in section 3.2). However, considering the strong inertia in the consumption of energy and transport by households – e.g. rigid housing location choices determining households’ demand for energy for private transport –, CES flexibility is allowed only beyond basic needs, i.e., exogenously set floors of volume of consumption for ELC, REF and COA. Floors of consumption and price elasticities of substitution are given along with the model’s parameterisation in section 3.6.

Above the exogenously set floors of quantities of volume of consumption mathematical expression of the consumption functions for *per capita* consumption by household class is similar to that of production function by sector and is as follows:

Per capita volume of consumption of aggregate non-constrained consumption CONS for household class *Hh* is a model solution variable, constrained by households consumption budget constraint. *Per capita* volume of the energy aggregate good EAG and of the composite good COMP for household class *Hh* are given by similar CES specifications (Eqs.18 and 19):

$$\begin{aligned} EAGpc_{Hh} = & \\ & \left(\frac{\overline{a_{CONS_{Hh}}}}{\overline{pEAG_H}} \right)^{\sigma_{CONS_{Hh}}} * \\ & \left(\overline{a_{CONS_{Hh}}}^{\sigma_{CONS_{Hh}}} * \overline{pEAG_H}^{(1-\sigma_{CONS_{Hh}})} + \overline{b_{CONS_{Hh}}} * \overline{pCONS_H}^{(1-\sigma_{CONS_{Hh}})} \right)^{-1/\rho_{CONS_{Hh}}} * \overline{CONSpc_{Hh}} \end{aligned} \quad (28)$$

$$\begin{aligned} COMPpc_{Hh} = & \\ & \left(\frac{\overline{b_{CONS_{Hh}}}}{\overline{pCOMP_H}} \right)^{\sigma_{CONS_{Hh}}} * \\ & \left(\overline{a_{CONS_{Hh}}}^{\sigma_{CONS_{Hh}}} * \overline{pEAG_H}^{(1-\sigma_{CONS_{Hh}})} + \overline{b_{CONS_{Hh}}} * \overline{pCONS_H}^{(1-\sigma_{CONS_{Hh}})} \right)^{-1/\rho_{CONS_{Hh}}} * \overline{CONSpc_{Hh}} \end{aligned} \quad (29)$$

, with:

$\overline{EAGpc_{Hh}}$ and $\overline{COMPpc_{Hh}}$ household class *Hh*’s *per capita* volume of consumption of the EAG and COMP aggregates;

$\overline{a_{CONS_{Hh}}}$ and $\overline{b_{CONS_{Hh}}}$

CES coefficients for the substitution between EAG and COMP for household class Hh calibrated on BY data;

$\sigma_{CONS_{Hh}}$

elasticity of substitution between EAG and COMP;

$pEAG_H$ and $pCONS_H$

prices of the consumption aggregates EAG and COMP for household final consumption (Eq.24-25 below);

and $\rho_{CONS_{Hh}}$ (Eq.20):

$$\rho_{CONS_{Hh}} = \frac{(\sigma_{CONS_{Hh}} - 1)}{\sigma_{CONS_{Hh}}} \quad (30)$$

On the basis per capita volume of final consumption of the EAG and COMP aggregates by household class the model calculates the per capita volume of final consumption of the individual goods. Eqs.21 and 22 illustrate this for EIN and MAN.

$$\begin{aligned} FC_EINpc_{Hh} = & \\ & \left(\frac{\overline{a_{COMP_{Hh}}}}{pEIN_H} \right)^{\sigma_{COMP_{Hh}}} * \left(\overline{a_{COMP_{Hh}}}^{\sigma_{COMP_{Hh}}} * pEIN_H^{(1-\sigma_{COMP_{Hh}})} + \overline{b_{COMP_{Hh}}} * pMAN_H^{(1-\sigma_{COMP_{Hh}})} + \right. \\ & \left. \overline{c_{COMP_{Hh}}} * pLSS_H^{(1-\sigma_{COMP_{Hh}})} + \overline{d_{COMP_{Hh}}} * pHSS_H^{(1-\sigma_{COMP_{Hh}})} + \overline{e_{COMP_{Hh}}} * \right. \\ & \left. pTRA_H^{(1-\sigma_{COMP_{Hh}})} \right)^{-1/\rho_{COMP_{Hh}}} * COMPpc_{Hh} \end{aligned} \quad (31)$$

$$\begin{aligned} FC_MANpc_{Hh} = & \left(\frac{\overline{b_{COMP_{Hh}}}}{pMAN_H} \right)^{\sigma_{COMP_{Hh}}} * \left(\overline{a_{COMP_{Hh}}}^{\sigma_{COMP_{Hh}}} * pEIN_H^{(1-\sigma_{COMP_{Hh}})} + \overline{b_{COMP_{Hh}}} * \right. \\ & \left. pMAN_H^{(1-\sigma_{COMP_{Hh}})} + \overline{c_{COMP_{Hh}}} * pLSS_H^{(1-\sigma_{COMP_{Hh}})} + \overline{d_{COMP_{Hh}}} * pHSS_H^{(1-\sigma_{COMP_{Hh}})} + \overline{e_{COMP_{Hh}}} * \right. \\ & \left. pTRA_H^{(1-\sigma_{COMP_{Hh}})} \right)^{-1/\rho_{COMP_{Hh}}} * COMPpc_{Hh} \end{aligned} \quad (32)$$

, with:

FC_EINpc_{Hh} and FC_MANpc_{Hh} household class Hh 's per capita volume of FC of EIN and MAN;

$\overline{a_{COMP_{Hh}}}$ to $\overline{e_{COMP_{Hh}}}$

CES coefficients for the substitution between non-energy goods for household class Hh calibrated on BY data;

$\sigma_{COMP_{Hh}}$

elasticity of substitution between the elements of COMP (EIN, MAN, LSS, HSS, TRA) for household class Hh ;

$pEIN_H$, $pMAN_H$, etc.

prices of household final consumption of EIN, MAN, LSS, HSS, and TRA;

and $\rho_{COMP_{Hh}}$ (Eq.34):

$$\rho_{COMP_{Hh}} = \frac{(\sigma_{COMP_{Hh}} - 1)}{\sigma_{COMP_{Hh}}} \quad (33)$$

The equations for LSS, HSS and TRA are similar, but of course with the first term of the equation referring to their CES coefficients (respectively: $c_{COMP_Hh}/pLSS_H$, $d_{COMP_Hh}/pHSS_H$ and $e_{COMP_Hh}/pHSS_H$) and these products prices for household final consumption. For REF and ELC, as sub-items of the EAG aggregate good the price-elastic substitution is defined in a similar manner as that between EIN and MAN in Eqs.21 and 22, but with only two goods in the CES function.

The price of the aggregate goods for household final consumption is calculated in a for a nested CES framework standard way, as the weighted average of its components, which is (Eq.24-26):

$$pCOMP_H = \left(\overline{a_{COMP_Hh}}^{\sigma_{COMP_Hh}} * pEIN_H^{(1-\sigma_{COMP_Hh})} + \overline{b_{COMP_Hh}} * pMAN_H^{(1-\sigma_{COMP_Hh})} + \overline{c_{COMP_Hh}} * pLSS_H^{(1-\sigma_{COMP_Hh})} + \overline{d_{COMP_Hh}} * pHSS_H^{(1-\sigma_{COMP_Hh})} + \overline{e_{COMP_Hh}} * pTRA_H^{(1-\sigma_{COMP_Hh})} \right)^{(1-\rho_{COMP_Hh}^{-1})} \quad (34)$$

$$pEAG_H = \left(\overline{a_{EAG_Hh}}^{\sigma_{EAG_Hh}} * pREF_H^{(1-\sigma_{EAG_Hh})} + \overline{b_{EAG_Hh}} * pELC_H^{(1-\sigma_{EAG_Hh})} \right)^{(1-\rho_{EAG_Hh}^{-1})} \quad (35)$$

$$pCONS_{Hh} = \left(\overline{a_{CONS_Hh}}^{\sigma_{CONS_Hh}} * pEAG_{Hh}^{(1-\sigma_{CONS_Hh})} + \overline{b_{CONS_Hh}} * pCOMP_{Hh}^{(1-\sigma_{CONS_Hh})} \right)^{(1-\rho_{CONS_Hh}^{-1})} \quad (36)$$

A.1.5. Firms

Gross Disposable Income and investment (decision making)

Similar to that of households, the firms' disposable income GDI_S is defined as the addition and subtraction of:

- An endogenous share (explained below) $\omega_{GOS,S}$ of Gross Operating Surplus *i.e.* GOS (see Eq 27),
- A 'debt service' (interests, dividends) $i_S D_S$, which is strongly positive in the Base Year equilibrium (firms are net indebted in 2005), and served at a fixed interest rate $i_S = i_{S,0}$,
- Corporate tax payments T_{IS} , on the basis of corporate tax rate τ_{IS} and calculated over their GDI before taxation,
- And an exogenous share ω_{OTS} of other transfers O_T , which are assumed to be a constant share of GDP:

$$GDI_S = \omega_{GOS,S} GOS - i_S D_S - T_{IS} - \rho_{Ph} N_{Ph} - P_{EQ} + R_P + \overline{\omega_{OTS}} O_T. \quad (37)$$

Additionally PEQ and R_P refer to the build-up of pension fund value by households. South Africa has a mixed pension system. There is a state pension which is completely independent from social

contributions to reduce poverty at old age. There also are employees' contributions to employee pension funds, and people are free to make use of private pension funds. As pension funds fall under financial corporations, thus firms, and pension equity is registered as a debt of firms to households in the SAM 2005 (StatsSA, 2010b), we decided to make pension contributions add to company income, and to subtract pension benefits paid to pensioners, and the change in pension equity (to lift it from taxation).

The ratio of the gross fix capital formation of firms $GFCF_S$ to their disposable income GDI_S is assumed constant; similar to households and in accordance with national accounting their self-financing capacity SFC_S then arises from the difference between GDI_S and $GFCF_S$. The net debt of firms D_S is then calculated from their AFC_S following the same specification as that applied to households.

$$\frac{GFCF_S}{GDI_S} = \frac{GFCF_{S0}}{GDI_{S0}}. \quad (38)$$

$$AFC_S = GDI_S - GFCF_S. \quad (39)$$

Trade-offs in production

The trade-offs between production factors follow the nested-CES structure described section 3.2.1 and its Figure 3.3, except for the electricity (ELC) sector, whose coefficients we derive from the South African TIMES model of the Energy Research Centre of the University of Cape Town, as described section 3.1. The CES trade-offs can be expressed, in a general form, as an intensity of an input or factor A_j over output Y_j of productive sector j , in a trade-off with factor B_j and with the overarching composite factor or input AB_j (Eq.6):

$$\frac{A_j}{Y_j} = APF_j^{-1} * \left(\overline{a_{AB_j}} * \left(\frac{p_{A_j}}{APF_j} \right)^{-1} \right)^{\sigma_{AB_j}} * \left(\overline{a_{AB_j}}^{\sigma_{AB_j}} * \left(\frac{p_{A_j}}{APF_j} \right)^{(1-\sigma_{AB_j})} + \overline{b_{AB_j}}^{\sigma_{AB_j}} * \left(\frac{p_{B_j}}{BPF_j} \right)^{(1-\sigma_{AB_j})} \right)^{-\rho_{AB_j}^{-1}} * \frac{AB_j}{Y_j} \quad (40)$$

, with:

APF_j and BPF_j	productivity growth multipliers of inputs or factors A_j, B_j ;
$\overline{a_{AB_j}}$ and $\overline{b_{AB_j}}$	CES coefficients calibrated on BY data;
p_{A_j} and p_{B_j}	prices of input or factor A_j and B_j ;
σ_{AB_j}	elasticity of substitution between A_j and B_j (see Appendix C.3 for values);
$\frac{AB_j}{Y_j}$	ratio of the aggregate of A_j and B_j, AB_j , over Y_j ;

$$\text{and } \rho_{AB_j} \quad \rho_{AB_j} = \frac{(\sigma_{AB_j} - 1)}{\sigma_{AB_j}} \quad (41)$$

As an example, Eq.8 and Eq.9 give respectively the equations for the intensity of capital over Y , κ_j , and of low skill labour $L_{sk1,j}$ over Y , $\lambda_{sk1,j}$:

$$\kappa_j = \frac{K_j}{Y_j} =$$

$$\frac{1}{KPF_j} * \left(\frac{\overline{b_{KL3,j}}}{\overline{pK_j/KPF_j}} \right)^{\sigma_{KL3,j}} * \left(\overline{b_{KL3,j}}^{\sigma_{KL3,j}} * \left(\frac{pK}{KPF_j} \right)^{(1-\sigma_{KL3,j})} + \overline{a_{KL3,j}}^{\sigma_{KL3,j}} * \left(\frac{pL_{sk3,j}}{LPF_{sk3,j}} \right)^{(1-\sigma_{KL3,j})} \right)^{(-1/\rho_{KL3,j})} * \frac{KL3_j}{Y_j} \quad (42)$$

$$\lambda_{sk1,j} = \frac{L_{sk1,j}}{Y_j} =$$

$$\frac{1}{LPF_{sk1,j}} * \left(\frac{\overline{b_{KL,j}}}{\overline{pL_{sk1,j}/LPF_{sk1,j}}} \right)^{\sigma_{KL,j}} * \left(\overline{b_{KL,j}}^{\sigma_{KL,j}} * \left(\frac{pL_{sk1,j}}{LPF_{sk1,j}} \right)^{(1-\sigma_{KL,j})} + \overline{a_{KL,j}}^{\sigma_{KL,j}} * pKL23_j^{(1-\sigma_{KL,j})} \right)^{(-1/\rho_{KL,j})} * \frac{KL_j}{Y_j} \quad (43)$$

with:

$LPF_{sk,j}$, and KPF_j Respectively the labour and capital productivity factors, which give relative growth in productivity (their values are defined in Appendix C.1).

The Leontief parts of the production function, for intermediate consumption (IC) of energy products and materials & services products, are calculated as the BY calibrated ratio of each good over its aggregate good E (Eq.10) or Mat (Eq.11). The prices pE and $pMat$, relevant for the CES trade offs in the production function, are calculated as the weighted average of the prices of the goods out of which they are composed (Eq.12 to 13). The prices of the individual products for IC, in turn, are determined on the basis of pY and pM as explained above.

$$\alpha_{ij} \equiv \frac{IC_{ij}}{Y_j} = \frac{\overline{IC_{ij,0}}}{\overline{E_{j,0}}} * \frac{E_j}{Y_j}, \text{ for } i = \text{COA, OIL, GAS, REF, ELC} \quad (44)$$

$$\alpha_{ij} \equiv \frac{IC_{ij}}{Y_j} = \frac{\overline{IC_{ij,0}}}{\overline{Mat_{j,0}}} * \frac{Mat_j}{Y_j}, \text{ for } i = \text{EIN, MAN, LSS, HSS, TRA} \quad (45)$$

$$pE_j = \frac{\sum_i (IC_{ij} pIC_{ij})}{E_j}, \text{ for } i = \text{COA, OIL, GAS, REF, ELC} \quad (46)$$

$$pMat_j = \frac{\sum_i (IC_{ij} pIC_{ij})}{Mat_j}, \text{ for } i = \text{EIN, MAN, LSS, HSS, TRA} \quad (47)$$

For the model to achieve equilibrium at all levels of the nested CES tree with the help of only a few variables: Each sector's Y_j (for OIL its imports M) and producer's price pY_j ; plus the prices of the non-aggregate labour inputs $pL1$, $pL2$, $pL3$ (constrained by wage curves, see section 3.3.2); and the price of

capital (which follows from the solution of the capital market, see section 3.4). Intensities of non-aggregated variables: $\lambda_{skl,i}$ to $\lambda_{sk3,i}$ and κ_i are also model variables. The prices of intermediate inputs are endogenous, their calculation is the topic of section 3.2.5. Prices of CES aggregates (KLE to KL3 down the nested CES tree in section 3.2.1) are calculated according to CES specifications, for which the general description is given by Eq.14, similar to Eq.6 before, describes the quantity of primary factors or intermediate inputs:

$$pAB_j = \left(\overline{a_{AB_j}}^{\sigma_{AB_j}} * pA_j^{(1-\sigma_{AB_j})} + \overline{b_{AB_j}} * pB_j^{(1-\sigma_{AB_j})} \right)^{(1-\rho_{AB_j}^{-1})} \quad (48)$$

As an example, which is also one of the model's closure rules (see section 3.5), Eq.15 gives the calculation of pY_j :

$$pY_j = \left(\overline{a_{KLEM_j}}^{\sigma_{KLEM_j}} * pKLE_j^{(1-\sigma_{KLEM_j})} + \overline{b_{KLEM_j}} * (pMat_j AMEI)^{(1-\sigma_{KLEM_j})} \right)^{(1-\rho_{KLEM_j}^{-1})} \quad (49)$$

, with:

$\overline{a_{AB_j}}$ and $\overline{b_{AB_j}}$	CES coefficients for the substitution in production of sector j between the KLE aggregate and the Mat aggregate calibrated on BY data;
$pKLE_j$ and $pMat_j$	prices of inputs KLE_j and Mat_j for IC by sector j ;
AMEI	exogenous material efficiency improvement which reduces the perceived cost of Mat relative to BY – equivalent to APF_j ; ⁴
σ_{KLEM_j}	elasticity of substitution between KLE_j and Mat_j (see section 3.6);
ρ_{KLEM_j}	calculated on the basis of σ_{KLEM_j} .

Gross Operating Surpluss

Capital consumption, constant rates of operating margin π_i and specific margins M_S (see below) determine the gross operating surplus (GOS). This GOS , which corresponds to capital income, is split between agents according to shares calibrated on Base Year data:

$$GOS = \sum_{i=1}^n \left(p_{K_i} k_i Y_i + \overline{\pi}_i p_{Y_i} Y_i \right) + M_S \quad (50)$$

By construction, the specific margins on the different sales M_S sum to zero in the Base Year equilibrium (this is a constraint of the hybridization process). However, they do not sum in the projection equilibrium, in which their constant rates are applied to varying prices:

⁴ Note that "efficiency" of usage is the inverse of productivity of an input or factor, and that $pMat_j$ is therefore multiplied with AMEI, unlike pK and pL in Eq. 8 and 9, which are divided by the sector-specific productivity trend to reduce their "perceived" cost.

$$M_S = \sum_i \left(\sum_j \overline{\tau_{MSCI_{ij}}} p_i \alpha_{ij} Y_j + \sum_h \overline{\tau_{MSCh}} p_i C_{hi} + \overline{\tau_{MSG_i}} p_i G_i + \overline{\tau_{MSX_i}} p_i X_i \right) \quad (51)$$

A.1.6. Government

Tax, social security contributions and fiscal policy

Tax and social security contributions form the larger share of government resources:

$$\forall X \in [CI, CF] \quad t_{TIPPX_i} = CPI \ t_{TIPPX_0}, \quad (52)$$

$$t_{AIP_i} = CPI \ t_{AIP_0}. \quad (53)$$

The various tax revenues are defined by applying these rates to their respective bases:

$$T_Y = \sum_{i=1}^n \overline{\tau_{Y_i}} p_{Y_i} Y_i, \quad (54)$$

$$T_{TIPP} = \sum_{i=1}^n \sum_{j=1}^n \overline{t_{TIPPCI_{ji}}} \alpha_{ji} Y_i + \sum_{i=1}^n \overline{t_{TIPPCF_i}} (C_i + G_i + I_i), \quad (55)$$

$$T_{AIP} = \sum_{i=1}^n \sum_{j=1}^n \overline{t_{AIP_j}} \alpha_{ji} Y_i + \sum_{i=1}^n \overline{t_{AIP_i}} (C_i + G_i + I_i), \quad (56)$$

$$T_{TVA} = \sum_{i=1}^n \frac{\overline{\tau_{TVA_i}}}{1 + \tau_{TVA_i}} (p_{C_i} C_i + p_{G_i} G_i + p_{I_i} I_i), \quad (57)$$

$$T_{IS} = \overline{\tau_{IS}} GOS_S, \quad (58)$$

$$T_{IRh} = \overline{\tau_{IRh}} GDI_{BTh}. \quad (59)$$

The rates τ_{IS} and τ_{IR} together serve as a variable to adjust government budget at -3% of GDP in the RP. They remain at RP levels in carbon tax scenarios except when targeted as recycling options.

Similar to excise taxes and for lack of more detail on its composition the sum of households' direct taxes other than the income tax T_{IR} is assumed to be constant in real terms:

$$T_h = CPI \ T_{h0}. \quad (60)$$

The sum of social contributions T_{CS} follows the same logic as other tax revenues again, and pension contributions T_{OCs} are calculated in a similar way, with their skill specific rates:

$$T_{CS} = \sum_{sk=1}^3 (\overline{\tau_{CS,sk}} \sum_{i=1}^n w_{sk,i} l_{sk,i} Y_i) . \quad (61)$$

$$T_{ACS} = \sum_{sk=1}^3 (\tau_{OCS,sk} \sum_{i=1}^n w_{sk,i} l_{sk,i} Y_i) . \quad (62)$$

So does the carbon tax on intermediate consumptions (t_{CI}) and on final consumptions (t_{CF})—which in fact is not differentiated in any of our scenarios. It is calculated over the emission intensity, γ , of the use of input i in sector j or respectively in final consumption by households:

$$T_{CARB} = \sum_{i=1}^n \sum_{j=1}^n \overline{t_{CI}} \gamma_{Cj} \alpha_{ji} Y_i + \sum_{i=1}^n \overline{t_{CF}} \gamma_{CFi} C_i . \quad (63)$$

Contrary to other dynamic IMACLIM-P frameworks, which apply budget neutrality in terms of constant D_G over GDP, IMACLIM-ZA applies a ‘constant budget position’ rule as a constraint on public deficit (AFC_G), enforced as a targeted ratio ($pct_deficit$) dependent on the reference setting, but in the present study maintained at -2% of GDP. The variables that adjust to meet this constraint are τ_{IS} and τ_{IR} , which are scaled up or down by a common factor. In the case of carbon tax revenue recycling scenarios these variables are fixed and other variables change to maintain budget deficit.

$$\frac{AFC_G}{GDP} = pct_deficit \quad (64)$$

Lastly, T is the sum of taxes and social contributions:

$$T = T_{CS} + T_Y + T_{TIPP} + T_{AIP} + T_{TVA} + T_{IS} + \sum_{h=1}^m T_{IRh} + \sum_{h=1}^m T_h + T_{CARB} \quad (65)$$

Gross disposable income, public spending, investment and transfers

Similar to households and firms, the gross disposable income of public administrations GDI_G is the sum of taxes and social contributions, of an endogenous share $\omega_{GOS,G}$ (responding to $\omega_{GOS,S}$) of GOS , and of an exogenous share ω_{ATG} of ‘other transfers’ A_T , from which are subtracted public expenditures $p_G G$, a set of social transfers R_U and R_A , and a debt service $i_G D_G$:

$$GDI_G = T + \omega_{GOS,G} GOS + \overline{\omega_{ATG}} A_T - \sum_{i=1}^n p_{Gi} G_i - R_U - R_A - i_G D_G \quad (66)$$

Public expenditures $p_G G$ are assumed to keep pace with national income and are therefore constrained as a constant share of GDP:

$$\frac{\sum_{i=1}^n p_{Gi} G_i}{GDP} = \frac{\sum_{i=1}^n p_{Gi0} G_{i0}}{GDP_0}, \quad (67)$$

Social transfers R_U and R_A are the sum across household classes of the transfers defined as components of their before-tax disposable income (Equation ...):

$$R_U = \sum_{h=1}^m \rho_{Uh} N_{Uh} \quad (68)$$

$$R_A = \sum_{h=1}^m \rho_{Ah} N_h, \quad (69)$$

Lastly, the interest rate i_G of public debt is fixed at Base Year rate as are i_H and i_S .

Public investment $GFCF_G$, the same as public expenditures $pG G$, is supposed to mobilise a constant share of GDP. Subtracting it from GDI_G produces AFC_G , which determines the variation of the public debt. For the calculation of the accumulation of debt we assume that gross auto-financing capacity $G AFC_G$, *i.e.* AFC_G net of interest payments, evolves linearly over time between our base year and our projection year, n years into the future ($n=30$):

$$\frac{GFCF_G}{GDP} = \frac{GFCF_{G0}}{GDP_0} \quad (70)$$

$$AFC_G = GDI_G - GFCF_G \quad (71)$$

$$D_G = (1 + \bar{t}_G)^n D_0 - \sum_{k=0}^{n-1} (1 + \bar{t}_G)^k G AFC_{G,0} - \sum_{k=0}^{n-1} (1 + \bar{t}_G)^k (n - 1) dG AFC_G + \sum_{k=0}^{n-1} k (1 + \bar{t}_G)^k dG AFC_G \quad (72)$$

Note that we assume debts to be held entirely in South African Rand. This is an approximation of the base year situation in which only 15% of total South African debts is financed by the Rest of the World, and the rest by household savings. The value of base year debt is then inflated by the consumer price index. For companies and households we apply a similar calculation of the accumulation of debt (or gross savings).

A.1.7. Rest of the World (ROW) and trade

Trade balance

Competition on international markets is settled through relative prices. The ratio of imports to domestic production on the one hand, and the ‘absolute’ exported quantities on the other hand, are elastic to the terms of trade, according to constant, product-specific elasticities:

$$\frac{M_i}{Y_i} = \frac{M_{i0}}{Y_{i0}} \left(\frac{P_{Mi0} P_{Yi}}{P_{Yi0} P_{Mi}} \right)^{\sigma_{Mpi}} \quad (73)$$

$$\frac{X_i}{X_{i0}} = \left(\frac{P_{Mi0} P_{Xi}}{P_{Xi0} P_{Mi}} \right)^{\sigma_{Xpi}} (1 + \delta_{Xi}) \quad (74)$$

The different treatment of imports and exports merely reflects the assumption that, notwithstanding the evolution of the terms of trade, import volumes rise in proportion to domestic economic activity (domestic production), while exports are impacted by global growth. The latter fact is captured by assuming an extra, exogenous δ_{Xi} increase of volumes exported. In total, as far as exports are concerned South Africa is depicted as supplying a terms-of-trade elastic share of a δ_{Xi} expanded export market.

Capital flows and self-financing capacity

Capital flows from and to the ‘Rest of the World’ (ROW) are not assigned a specific behaviour, but are simply determined as the balance of capital flows of the three national institutional sectors (households, firms, public administrations) to ensure the balance of trade accounting. This assumption determines the self-financing capacity of the ROW, which in turn determines the evolution of D_{ROW} , its net financial debt.

$$AFC_{ROW} = \sum_{i=1}^n P_{Mi} M_i - \sum_{i=1}^n P_{Xi} X_i + \sum_{K=H,S,G}^n i_K D_K - \sum_{K=H,S,G}^n A_{TK} \cdot \quad (75)$$

By construction the auto-financing capacities (AFC) of the 4 agents clear (sum to zero), and accordingly the net positions, which are systematically built on the AFCs, strictly compensate each other in the projected as in the present equilibrium. The hypothesis of a systematic ‘compensation’ by the ROW of the property incomes of national agents without any reference to its debt D_{ROW} may seem crude, but *in fine* only replicates the method of construction of the current and financial accounts. Indeed, in the 2005 calibration equilibrium the effective interest rate of the ROW (ratio of net debt to its property income), which ultimately results from a myriad of debit and credit positions and from the corresponding capital flows, is negative—unworkable for modelling purposes.

Finally, as previously mentioned other transfers A_T are defined as a fixed share of GDP:⁵

$$\frac{A_T}{GDP} = \frac{A_{T0}}{GDP_0} \quad (76)$$

⁵ The sum across agents of other transfers being nil by definition, A_T is in fact calibrated on the sum of the net transfers that are strictly positive. As a consequence the shares ω_{ATH} , ω_{ATS} , ω_{ATG} and ω_{ATROW} , summing to 0 by construction, are ratios properly speaking.

A.1.8. Debt accumulation

As in Schers et al. (2015), the calculation of accumulated net debt for all agents, $D_{ag=H,F,G}$, assumes that an agent's gross self-financing capacity $GSFC_{ag}$, i.e. SFC_{ag} net of interest payments, evolves linearly over time between BY (2005) and the projection year (2035), allowing to express the accumulation of net debt as follows (Eq.57 in this appendix, Eq.56 in the report, see below for its derivation):

$$D_{n,ag=H,F,G} = (1 + \langle \tau i_{ag} \rangle)^n \overline{D_{ag,0}} - \sum_{k=0}^{n-1} (1 + \langle \tau i_{ag} \rangle)^k \overline{GSFC_{ag,0}} - \sum_{k=0}^{n-1} (1 + \langle \tau i_{ag} \rangle)^k (n-1) dGSFC_{ag} + \sum_{k=0}^{n-1} k (1 + \langle \tau i_{ag} \rangle)^k dGSFC_{ag} \quad (77)$$

, with:

$\overline{D_{ag,0}}$ agent's BY calibration data net debt;

$\overline{GSFC_{ag,0}}$ and $GSFC_{ag,n}$ agent's Gross SFC, resp. from BY data, and in year n ;

n years projected into the future (in this thesis $n=30$);

$dGSFC_{ag} = \frac{(GSFC_{ag,n} - \overline{GSFC_{ag,0}})}{n}$, the average annual change in $GSFC_{ag}$;

$\langle \tau i_{ag} \rangle = \frac{(\overline{\tau i_{ag,0}} + \tau i_{ag,n})}{2}$, the approximated average projection period interest rate.

The summations $\sum_{k=0}^{n-1} (1 + \langle \tau i_{ag} \rangle)^k (n-1) dGSFC_{ag}$ and $\sum_{k=0}^{n-1} k (1 + \langle \tau i_{ag} \rangle)^k dGSFC_{ag}$ can be approximated by geometric series to ease model solving.

This formula for (non-linear) debt accumulation has been developed for IMACLIM-S style models by my PhD supervisor Frédéric Gherzi, as linear debt accumulation in early tests with IMACLIM-ZA led to enormous debts. The principle of the debt accumulation formula proposed here is that gross deficit or surplus, net of interest payments, develops linearly between BY and the projection (for 2035), while interest payments can develop more exponentially, allowing them to stay relatively low in early years, in comparison to an assumption of linear evolution of the net deficit, including interests assumptions.

The assumption is therefore that gross SFC (GSFC), meaning SFC but excluding interest payments, transitions linearly from its starting position $GSFC_0$ to its projected value $GSFC_n$. We can thus write for debt D_n at time step n , and for interest rate i (called $\langle \tau i_{ag} \rangle$ in formula 57 above):

$$D_n = D_{n-1} - SFC_{n-1} = D_{n-1} - GSFC_{n-1} + i D_{n-1} = (1 + i) D_{n-1} - GSFC_{n-1}$$

, which translates into:

$$D_n = (1 + i)^n D_0 - \sum_{k=0}^{n-1} (1 + i)^k GSFC_{n-1-k}$$

While the linear development of GSFC consists, for all of time t from $t = 0$ to $t = n$, of:

$$GSFC_t = GSFC_0 + t \left(\frac{GSFC_n - GSFC_0}{n} \right) = GSFC_0 + t dGSFC$$

In which $dGSFC$ is the incremental annual change of GSFC assuming that it changes linearly through time. Substituting D_n in the equation and rearranging this leads to:

$$D_n = (1+i)^n D_0 - \sum_{k=0}^{n-1} (1+i)^k GSFC_0 - \sum_{k=0}^{n-1} (1+i)^k (n-1) dGSFC + \sum_{k=0}^{n-1} k (1+i)^k dGSFC$$

As the sum of the terms $(1+i)^k$ and $k(1+i)^k$ are known, being geometric series, we can program the calculation of the accumulated debt, and use it as variable for model solution using a non-linear spreadsheet solver.

A.1.9. Market balances

Goods market

Goods market clearing is a simple accounting balance between resources (production and imports) and uses (intermediate consumption, households and public administrations' consumption, investment, exports). Thanks to the process of hybridization, this equation is written in MTOE for energy goods and consistent with the 2005 energy balance of the IEA at the base year (notwithstanding that the G and I of energy goods are nil by definition).

$$Y_i + M_i = \sum_{j=1}^n \alpha_{ij} Y_j + C_i + G_i + I_i + X_i \quad (78)$$

Of course the aggregate consumption of households C_i sums up the consumptions of all classes C_{ih} .

Investment & Capital flows

The demand of investment is constrained by the assumption that the ratio of each of its real components I_i to total fixed capital consumption (the sum of $k_i Y_i$) is constant. In other words, the capital immobilised in all productions is supposed homogeneous, and all its components vary as the total consumption of fixed capital.

$$\sum_{K=H,S,G} GFCF_K = \sum_{i=1}^n p_{fi} I_i \quad (79)$$

$$\frac{I_i}{\sum_{j=1}^n k_j Y_j} = \frac{I_{i0}}{\sum_{j=1}^n k_{j0} Y_{j0}} \quad (80)$$

The closure of the capital market operates through adjustment of interest rate of the 3 domestic agents a : firms ($a = S$), government ($a = G$) and households ($a = H$), $\tau_{S/G/H}$. The interest rate of ROW

results from calculating the rate of the negative of total net interest receipts by ROW (*minus* RK_{ROW}), over the total net debt position of ROW, D_{ROW} . Both are calculated as the counterpart to balance (and constrain) total domestic debt and interest payments:

$$\tau i_{S/G/H} = \bar{\tau} i_{S/G/H,0} VAR_{\tau i} \quad (81)$$

$$\tau i_{ROW} = -RK_{ROW}/D_{ROW} \quad (82)$$

$$RK_{ROW} = -\sum_{a=S,G,H} RK_a \quad (83)$$

$$D_{ROW} = -\sum_{a=S,G,H} D_a \quad (84)$$

Labour market

Labour endowment \bar{L} , proportional to total active population, is split in 3 skill levels \bar{L}_1 , \bar{L}_2 , \bar{L}_3 . For each skill sk the level of unemployment u_{sk} is endogenous, and linked to *real* sector-average wage w_{sk}/CPI by a wage curve – corrected for the share, ω_{LPsk} , of labour productivity gains, Φ_{sk} , accruing to workers (set at 100% in this PhD thesis) – and elastic to unemployment, with elasticity σ_{wu} :

$$(1 - u_{sk})\bar{L}_{sk} = \sum_{i=1}^n l_{sk,i} Y_i. \quad (85)$$

$$\frac{w_{sk}}{(1 - \omega_{LPsk})CPI + \omega_{LPsk}\phi_{sk}CPI} = w_{sk0} \left(\frac{u_{sk0}}{u_{sk}} \right)^{\sigma_{wu}} \quad (86)$$

B. Generation of the hybrid I-O table and other calibration data

Several steps needed to be taken to prepare the calibration of IMACLIM South Africa. This Appendix discusses these steps. First of all, it discusses assumptions in the adjustment of SAM data for the hybridisation procedure, which mainly consists of increasing detail on energy sectors and transport services (section B.1). Next, the calculation of the energy bills is explained (section B.2). The previous is used to arrive at the discussion of the hybridisation steps itself, and aggregation, resulting in the I-O table for the number of sectors in this thesis (section B.3). Next follow two appendices that discuss demography by household class and income distribution and transfers between economic agents (B.4 and B.4.1). Finally, an evaluation of the potential consequences for the results of this PhD thesis of uncertainty in the assumptions made in process of hybridisation are presented in section B.5. The evaluation is a detailed addition to the more discussion of the limitations to the modelling exercise of this thesis in Chapter 6.

B.1. I-O table data preparation

The IMACLIM framework is built around Input-Output (I-O) tables in which dual accounting of quantities and values of supply of and demand for energy are based on energy statistics and energy price data. Total values of elements of the I-O table, and values for non-energy sectors are based on data coming from the system of national accounts (SNA). In the case of the IMACLIM South Africa model (IMACLIM-ZA) this concerns South Africa's Social Accounting Matrix (SAM) of 2005 (StatsSA, 2010a). The South African SAM 2005 however presents separate accounts for use and supply of products, and sectors produce multiple products, meaning that they also produce products that are the core activity of other sectors next to their own core activity product. Data manipulation to generate a "one sector = one product" I-O table on the basis of the SAM is required for IMACLIM-ZA. First, however, an explanation follows on how for hybridisation required detail on energy sectors is added to the SAM, as the South African SAM does not cover energy sectors in great detail.

B.1.1. Adjustment of SAM data in preparation of hybridisation

For IMACLIM-ZA the following sectors needed to be added to the SAM in order to prepare it for hybridisation:

- a. Oil resources (extraction and trade) and Gas resources (extraction and trade) needed to be split out of the Other mining sector of the SAM 2005;
- b. Refineries needed to be split out from the Petro-chemical industry sector of the SAM 2005;
- c. Metals basic manufacturing needed to be split off from the Iron & Steel and the Non-ferrous metals sectors of the SAM 2005 to make a distinction between the production of the materials and manufacturing of metal objects, like it is the case in energy statistics;
- d. Officially gas distribution needed to be cut out of the electricity sector of the SAM 2005 so in

theory it could have been added to the Gas resources sector, but in view of a lack of information about the value of gas (industrial) distribution and considering its negligible size compared to that of power generation and electricity distribution, this split has not implemented;

- e. Education is considered a public service, while it is part of the Domestic and Other services sector in the SAM 2005 – Education has therefore been separated to become a sector of its own;
- f. Lastly, a transfer of value from the Communication to the Transport services sector has been performed as well, because postal services are considered as a transport services in energy statistics and should therefore be part of the Transport services sector.

Furthermore, some minor changes were made to rid SAM data of statistical errors and discrepancies, of CIF/FOB numbers, of supply of Rest of the World goods & services, and of purchases by foreign residents; The adjustments made for this reason, mainly to exports are negligible and will not be discussed here. The main steps and assumptions to perform the mentioned changes (a) to (f) on SAM data were the following:

Assumption 1: First of all, room is created for sectors that do not exist in the SAM in the goods & services and production accounts of the SAM 2005. On the resources side values of domestic output and imports are added on the basis of the Supply & Use tables (SU) of Statistics South Africa, which have more sectoral detail than the SAM (StatsSA, 2010b). The same has been done on the Uses side of the SAM, meaning for intermediate consumption, household and government final consumption, stock changes and gross fixed capital formation (investment), and finally exports. For Oil resources, Gas resources and Gas distribution the Supply & Use tables do not contain any information, and these added sectors are therefore left blank.

Assumption 2: The numbers for the sectors from which sectors have been split-off on the basis of Supply & Use tables causes the original sectors to have negative intermediary consumption of products of the original sector. These negative values have been replaced by zero values, and the original combined sector's total is maintained by reducing IC of the new sector: E.g. the first correction of this type has been made because consumption of petrochemical products by the education sector in SU data is bigger than the original consumption of petrochemical products by the Domestic & other services sector (from which education was split off) of SAM data when also reduced by the amount of Refinery products consumption of the Domestic & other services sector from SU data. As a result, the Domestic & other services sector has negative consumption of petrochemical products. To get rid of this anomaly, this negative amount is added to the consumption of Refinery products and the consumption of petrochemical products by the Domestic & other services sector is set to zero. The same type of correction has been made because of negative values appearing

for intermediate consumption of basic metals and non-ferrous metals products by the Domestic & other services sector after splitting of Education. This is corrected by reducing intermediate consumption of Iron & steel products by the Domestic & other services sector.

Assumption 3: To re-allocate postal services values of its supply and use as found in SU data have been shifted from the SAM's Communication sector to its Transport services sector.

Assumption 4: Imports of the Other mining sector are allocated completely to the Oil resources sector (prior to future adjustments from hybridisation with energy bills data: see below).

Assumption 5: Transport & commerce margins, and product taxes are re-allocated between sectors that have been split in the previous steps on the basis of the share in the new total value of products which these new sectors produce.

Furthermore, for distribution of labour and wages between Education, and Domestic & Other services (from which it has been separated), the assumption is made that Education consists for almost 75% of high skill labour, whereas Domestic & other services is assumed to consist by majority of low skill labour. Wages are assumed the same for both sectors for reason of simplicity;

Also, due to the use of the Use table to construct IC of products of transport and communication sectors by Education + Domestic & other services increases, to compensate, Domestic & other services sector's profit margins almost disappear. Due to Education's high salary payments resulting from the previous step, the sector obtains negative net operating surplus, while Domestic & other service retains profits equal to about 5% of the sectors total resources. To correct this difference, about three-quarter of IC by Education is transferred back to Domestic & other services, leaving Education with a smaller operating deficit and Domestic & other services with a close to zero operating surplus. With Domestic & Other services forming a big part of the Low Skill Sectors sector (LSS) the implication is that the integration of SU-table data in the SAM reduces the contribution of LSS to South Africa's Gross Operating Surplus. Under the fixed profit mark-up rates approach of IMACLIM-ZA this has the *theoretical* consequence that significant growth of the share of LSS in South African Value Added (VA) should lead to a reduction of the share of GOS in the economy, and therefore potentially to a reduction of rates of return to capital. In practise LSS does not grow much differently from the rest of the economy, and there is hardly any impact on macro-economic outcomes of IMACLIM-ZA from this assumption.

Finally, SU table data also have the Refineries sector's output consisting for almost one-quarter of its value of "Business Activities" products and for small amounts of other products. To prepare for hybridisation, with the goal of reducing differences between the SAM and SU-table data based I-O table, and the Energy bills, these non-refinery product outputs, plus equivalent transfers of the resources of the Refineries sector are shifted to the Business activities and the other corresponding sectors, with the exception of resource use for coal, gas and oil resource use by Refineries. Reversely,

Refineries output by the petro-chemical sector is transferred to the Refineries sector, including an equivalent part of the resources used in production.

B.1.2. Combination of supply and use tables into a (non-hybrid) I-O table

After the previous tailor-made adjustments which reduced the amount of output of non-energy products, a crude matrix multiplication is applied which moves resources, taxes and margins according to output share between sectors to arrive at an I-O table on the basis of the principle “one sector = one product”. The result is shown in Table B.1 and Table B.2.

Part 1 of the Input-Output (I-O) table that has been constructed on the basis of SAM and Supply & Use-table data from Statistics South Africa shows – in billions of Rands of 2005 (ZAR₂₀₀₅) – details for intermediate consumption, value added, imports and indirect tax revenue by sector.

Table B.1 Input-Output table for hybridisation - part 1 (in billions of ZAR₂₀₀₅)

	Agriculture	Coal	Gold	Other mining	Oil resources	Gas resources	Food	Textiles	Footwear	Refineries	Petro-chemical industry	Other non-metallic minerals	Basic iron & steel	Non-ferrous metals	Metals basic manufacturing	Electrical machinery	Radio	Transport equipment	Other manufacturing	Electricity	Gas distribution	Water	Construction	Trade	Hotels & restaurants	Transport services	Communications	Financial intermediation	Real estate	Business activities	General government	Health & social work	Education	Domestic & other services	Foreign Souvenirs sector	Total		
Agriculture	1.8	0.0	0.0	0.0	0.0	0.0	37.7	4.5	0.2	0.0	1.2	0.2	0.0	0.1	1.0	0.0	0.1	0.1	7.7	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.3	0.7	0.1	0.1	0.0	0.1	0.0	0.0	0.0	56	
Coal	0.0	0.0	0.0	1.3	0.0	0.4	0.6	0.3	0.0	3.9	0.4	0.6	1.3	0.1	0.2	0.0	0.0	0.0	1.1	8.7	0.0	0.7	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	0.3	0.0	0.0	0.1	0.0	0.0	0.1	20
Gold	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Other mining	0.8	0.1	0.1	0.2	0.0	0.0	0.9	0.5	0.0	6.8	0.5	6.3	17.1	7.7	3.7	1.6	0.6	2.7	4.0	0.0	0.0	0.0	3.0	0.1	0.0	0.7	0.5	0.0	0.3	1.3	0.7	0.5	0.0	0.5	0.0	0.0	61	
Oil resources	0.0	0.0	0.0	0.0	0.0	3.2	0.0	0.0	0.0	34.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	37	
Gas resources	0.0	0.0	0.0	0.1	0.0	0.3	0.1	0.0	0.0	3.1	2.5	0.4	0.8	0.1	0.4	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	8	
Food	9.3	0.1	0.1	0.1	0.0	38.6	0.2	0.0	0.0	2.2	0.0	0.0	0.3	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.1	5.9	4.8	1.2	1.3	0.1	0.6	0.8	1.1	0.4	0.0	0.4	0.0	0.4	0.0	69	
Textiles	1.8	0.1	0.2	0.4	0.0	0.0	0.5	10.9	1.3	0.0	1.4	0.1	0.0	0.0	0.6	0.1	0.1	4.4	2.1	0.0	0.0	0.0	1.4	0.5	0.1	0.8	0.8	0.0	0.1	1.5	0.7	0.6	0.0	0.6	0.0	31		
Footwear	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.1	0.0	0.1	2		
Refineries	4.1	0.4	0.2	2.2	0.0	0.0	0.1	0.0	0.0	0.2	2.0	0.1	3.9	0.8	0.3	0.5	0.1	0.7	0.1	0.8	0.0	0.1	3.3	5.1	0.1	25.6	4.8	1.0	3.2	4.2	2.4	0.6	0.0	2.3	0.0	69		
Petro-chemical industry	11.4	1.6	1.8	8.2	0.0	11.5	3.5	0.6	1.5	55.3	1.7	1.5	2.3	3.5	1.8	0.8	6.7	7.0	0.2	0.0	0.7	10.2	7.6	0.4	4.0	4.8	0.7	2.8	6.4	7.8	2.7	0.1	2.1	0.0	172			
Other-NMM products	0.3	0.1	0.4	0.3	0.0	0.0	1.9	0.1	0.0	0.0	1.1	5.8	0.2	0.1	0.4	0.1	0.1	2.0	0.5	0.1	0.0	1.1	24.9	0.6	0.1	1.0	1.0	0.1	0.9	0.8	1.2	0.3	0.0	0.3	0.0	44		
Basic iron/steel	0.1	0.0	0.1	0.4	0.0	0.0	0.1	0.5	0.0	1.0	1.0	0.3	7.3	1.6	18.5	2.7	1.1	10.6	0.5	0.3	0.0	4.2	0.0	0.0	0.5	0.5	0.0	0.3	4.5	0.1	0.0	1.0	0.0	1.0	0.0	56		
Non-ferrous metals	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.2	0.0	0.0	0.2	0.2	4.9	2.8	3.8	2.4	0.4	4.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.4	0.0	0.0	0.0	0.2	0.0	22		
Metals basic manufacturing	2.6	1.3	2.4	6.7	0.0	0.7	0.9	0.1	0.0	1.9	0.3	3.3	7.7	9.4	1.7	0.7	5.8	4.6	0.6	0.0	0.8	16.6	4.1	0.1	1.0	1.1	0.6	2.7	5.5	2.7	0.8	0.0	0.0	0.0	0.0	81		
Electrical machinery	0.1	0.4	0.3	1.0	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0	0.0	1.3	1.7	1.0	1.8	0.0	2.8	0.0	0.2	8.7	0.6	0.0	0.0	0.0	0.7	0.8	0.1	0.5	1.1	1.2	0.1	0.0	0.2	25		
Radio	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.1	0.0	0.0	3.5	2.6	3.3	4.3	0.2	0.0	0.0	0.0	0.0	0.5	0.0	0.4	0.4	0.3	0.6	2.5	5.6	2.2	0.1	1.8	0.0	1.8	0.0	29		
Transport equipment	1.1	0.5	0.1	2.1	0.0	0.0	0.5	1.5	0.0	0.6	0.2	0.3	0.0	2.7	0.8	0.3	34.7	0.2	0.1	0.0	0.0	6.0	0.0	0.4	4.5	0.3	0.7	8.5	8.3	3.5	0.1	3.5	0.0	88				
Other manufacturing	0.4	0.1	0.9	0.9	0.0	9.9	2.5	0.1	0.3	4.7	0.9	0.3	0.1	2.4	0.2	0.4	1.4	18.8	0.2	0.0	0.0	2.1	16.3	0.1	1.9	1.9	2.6	6.2	10.1	2.1	2.7	0.1	2.8	0.0	93			
Electricity	0.7	0.5	0.3	2.5	0.0	1.9	0.5	0.0	0.2	5.5	0.6	2.6	1.6	0.9	0.2	0.1	0.7	0.9	2.9	0.0	0.1	0.2	1.5	0.3	1.0	0.2	0.6	2.7	2.4	0.6	0.6	0.1	0.8	0.0	34			
Gas distribution	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0			
Water	0.2	0.1	0.1	0.7	0.0	0.0	0.7	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.8	0.0	0.7	0.0	0.1	0.0	0.1	0.3	0.3	0.1	0.1	0.1	0.0	0.1	0.0	11		
Construction	0.2	0.4	0.1	2.0	0.0	1.1	0.3	0.1	0.9	0.9	0.1	0.5	0.3	0.7	0.1	0.1	0.6	1.1	0.0	0.0	0.3	7.3	0.7	0.3	7.1	4.9	1.4	4.2	6.2	1.6	0.5	0.0	0.7	0.4	45			
Trade	0.2	0.0	0.0	0.1	0.0	0.0	1.1	0.3	0.0	0.9	0.1	0.4	0.1	0.5	0.1	0.1	0.8	0.6	0.1	0.0	0.0	0.2	2.5	0.2	5.1	3.8	1.7	8.4	7.2	0.6	0.0	0.4	0.0	0.4	36			
Hotels and restaurants	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	0.0	0.3	0.8	0.2	3.1	2.0	0.2	0.4	0.8	0.7	0.1	0.0	0.4	0.0	1.0	0.0	101		
Transport services	6.7	9.5	0.1	11.7	0.0	8.1	1.4	0.2	0.3	6.9	1.6	2.8	0.6	2.3	0.6	0.4	2.7	2.8	0.5	0.0	0.2	1.2	9.8	0.7	8.5	4.2	1.2	1.3	6.1	5.2	0.5	0.0	3.0	0.0	873			
Communications	0.1	0.1	0.0	0.6	0.0	2.1	0.8	0.1	0.0	1.8	0.2	0.3	0.1	1.6	0.3	0.3	0.8	1.1	0.2	0.0	2.2	2.5	12.3	1.3	5.0	2.2	6.6	3.8	9.9	18.9	3.9	0.2	6.6	0.0	173			
Financial intermediation	3.1	1.4	0.2	7.4	0.0	2.0	1.0	0.1	0.1	2.2	0.5	0.4	0.2	1.8	0.4	0.6	0.8	1.3	2.4	0.0	1.0	1.7	11.5	0.4	5.3	1.4	79.0	19.0	16.1	7.0	0.6	0.0	1.8	0.0	81			
Real estate	0.1	0.0	0.1	0.3	0.0	3.0	0.8	0.1	0.1	2.3	0.3	0.3	0.1	1.7	0.3	0.4	1.2	1.8	0.1	0.0	0.1	2.8	20.9	1.4	6.8	3.3	4.2	4.6	9.8	3.4	4.0	0.2	3.4	0.0	78			
Business activities	0.3	0.7	0.1	2.7	0.0	13.1	1.7	0.2	0.6	13.2	1.3	2.7	0.7	3.2	1.4	0.6	5.5	3.9	1.8	0.0	0.6	12.5	24.0	2.0	14.8	11.3	5.4	9.1	13.9	27.5	13.3	1.7	19.3	0.0	209			
General government	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.2	0.0	0.0	0.0	18.6	2.4	0.0	0.1	0.0	22			
Health and social work	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.4	1.8	4.0	3.3	5.6	0.2	0.2	2.1	0.0	20			
Education	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.4	0.1	0.1	0.0	0.0	0.0	0.2	0.0	1			
Domestic and other services	0.7	0.5	0.1	2.0	0.0	8.7	2.5	0.2	0.3	7.2	1.1	3.1	1.2	3.6	1.1	0.6	5.2	4.8	0.0	0.0	0.0	0.6	0.8	0.5	3.7	2.8	0.9	3.7	5.1	0.7	0.2	0.1	1.2	0.0	63			
Foreign Souvenirs sector	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0			
Total IC by sector of use (consuming)	48																																					

Part 2 of the Input-Output (I-O) table that has been constructed on the basis of SAM and Supply & Use-table data from Statistics South Africa shows – in billions of Rands of 2005 (ZAR₂₀₀₅) – details for final demand and investment, by product and by element of VA, as well as for imports and indirect taxes.

Table B.2 Input-Output table for hybridisation - part 2 (in billions of ZAR₂₀₀₅)

	Total	T:P1	T:P2	T:P3	T:P4	T:P5	T:P6	T:P7	T:P8	T:P9	T:P10	T:P11	T:P12	Total household & NPISH	Government	Stock changes	Gross Fixed Capital Formation	Exports	Total Uses
Agriculture	56	0.3	0.6	1.6	1.9	2.2	2.1	2.4	3.5	3.7	4.0	2.2	11.9	36	0.0	0.1	0.0	12.2	105
Coal	20	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0	0.0	0.3	0.0	19.2	40
Gold	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.1	0.0	27.9	28
Other mining	61	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0	0.0	1.7	0.0	70.2	133
Oil resources	37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	37
Gas resources	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	8
Food	69	1.2	2.5	6.4	8.5	10.0	10.5	12.4	17.4	18.3	22.8	15.4	71.9	197	0.0	0.6	0.0	23.8	290
Textiles	31	0.2	0.5	1.1	1.7	1.8	2.1	2.6	3.6	4.2	5.6	4.2	19.1	47	0.0	0.5	0.0	5.7	84
Footwear	2	0.1	0.1	0.3	0.4	0.5	0.6	0.7	0.9	1.1	1.3	0.9	4.3	11	0.0	0.0	0.0	0.6	14
Refineries	69	0.1	0.2	0.5	0.7	0.8	0.9	1.2	1.7	2.8	5.0	4.3	22.2	40	0.0	1.9	0.2	9.3	121
Petro-Chemical industry	172	0.1	0.3	0.6	0.8	1.0	1.0	1.4	2.0	3.3	5.9	5.1	26.4	48	0.0	1.5	0.0	29.0	250
Other NMM products	44	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.3	0.5	0.3	1.6	3	0.0	0.9	0.0	2.3	51
Basic iron/steel	56	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	1.0	0.0	34.6	92
Non-ferrous metals	22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.4	0.1	24.3	46
Metals basic manufacturing	81	0.0	0.0	0.1	0.3	0.4	0.6	0.8	1.0	1.3	1.7	1.6	8.9	17	0.0	1.1	66.6	29.0	194
Electrical machinery	25	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.8	2	0.0	0.5	15.5	2.9	45
Radio	29	0.0	0.1	0.2	0.4	0.6	0.6	0.9	1.2	1.4	1.8	1.2	5.4	14	0.0	0.1	15.6	5.0	63
Transport equipment	88	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	2.4	63.8	67	0.0	4.3	52.4	31.1	242
Other manufacturing	93	0.0	0.1	0.3	0.5	0.7	0.9	1.3	2.1	2.9	3.9	2.8	14.5	30	0.0	3.4	1.9	19.4	148
Electricity	34	0.1	0.1	0.4	0.5	0.6	0.7	0.8	1.2	1.4	2.1	1.4	6.1	15	0.0	0.0	0.0	0.8	50
Gas distribution	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0
Water	11	0.0	0.1	0.2	0.2	0.3	0.3	0.4	0.6	0.7	1.2	0.9	3.8	9	0.0	0.0	0.0	0.4	20
Construction	45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	1.2	1	0.0	0.0	99.0	0.3	146
Trade	36	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	2.0	38
Hotels and restaurants	10	0.1	0.1	0.3	0.4	0.4	0.6	0.7	1.1	1.5	2.8	1.8	14.5	24	0.0	0.0	0.0	20.1	55
Transport services	101	0.3	0.6	1.7	2.5	3.1	3.5	4.3	5.5	6.2	5.9	3.1	11.0	48	0.0	0.0	0.0	32.4	181
Communications	83	0.0	0.1	0.2	0.3	0.4	0.4	0.6	1.0	1.6	3.0	2.6	18.1	28	0.0	0.0	0.0	16.5	128
Financial intermediation	171	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.3	0.8	2.5	3.5	69.8	77	0.0	0.0	0.0	12.2	260
Real estate	78	0.1	0.3	0.7	0.9	1.1	1.3	1.7	3.1	5.2	10.7	9.3	66.8	101	0.0	0.0	9.4	8.6	197
Business activities	209	0.0	0.0	0.1	0.1	0.1	0.1	0.3	0.4	1.0	2.1	2.1	19.1	25	0.0	0.0	2.9	4.1	241
General government	22	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.3	0.5	1.0	0.8	4.3	8	305.7	0.0	0.0	0.4	335
Health and social work	20	0.0	0.1	0.2	0.3	0.3	0.3	0.6	1.0	2.1	6.5	6.9	34.4	53	0.0	0.0	0.0	3.0	75
Education	1	0.0	0.1	0.2	0.3	0.4	0.4	0.7	1.0	1.6	2.7	2.3	14.3	24	0.0	0.0	0.0	0.0	25
Domestic and other services	63	0.0	0.1	0.3	0.5	0.7	0.8	1.3	2.0	3.0	5.1	4.3	27.6	46	0.0	0.0	0.0	7.3	117
Foreign Souvenirs sector	0	0.5	0.3	0.4	0.4	0.4	0.5	0.7	0.9	1.2	2.2	2.1	9.0	19	0.0	0.0	0.0	0.0	19
Total IC by sector of use (consuming)	1 847	3	6	16	22	26	29	36	52	66	101	82	551	991	306	18	264	455	3 880
Net operating surplus and net mixed income	518																		
T: Legislators (4)	177																		
T: Professionals (4)	119																		
T: Technicians (3)	71																		
T: Clerks (2)	62																		
T: Service workers (2)	77																		
T: Skilled agricultural workers (2)	7																		
T: Craft workers (2)	58																		
T: Plant and machine operators (2)	37																		
T: Elementary occupations (1)	21																		
T: Domestic workers (1)	11																		
T: Occupation unspecified (1)	57																		
Total gross wages (skill level)	698																		
Total fixed capital formation	186																		
Total Gross Value Added	1 401																		
Total domestic production at producers' prices	3 248																		
Imports	462																		
Taxes & Subsidies products	170																		
Commerce & transport margins	0																		
Total Resources	3 880																		

B.2. Energy bills and their calculation

A number of assumptions were made to harmonize the different sources of energy data that together give a complete picture of South Africa's energy production and energy use. In this appendix I explain these assumptions. Two sets of assumptions will be discussed in the sub-sections of this appendix one by one and consist of assumptions:

- ... for the matrix of quantities of energy produced, traded and used;
- ... for the matrix of energy prices by user.

B.2.1. I-O matrix for energy quantities

Data issues in energy statistics required assumptions for the matrix of physical quantities of energy production, transformation and use. These issues were:

- Discrepancies in data on production and imports between two sources of energy balance data (IEA, 2012; DoE, 2009);
- Differences for some entries of both energy balances with ERC's estimations for calibration of the South Africa TIMES model (SATIM);
- Only 2006 data from ERC's SATIM for CTL, GTL and crude oil refining processes and electricity generation, which needed to be adjusted to IMACLIM-ZA's base year (2005);
- The inclusion of non-energy use of coal by the petrochemical industry in ERC's end use data, for which I correct as this inclusion will disturb the simulation of the impact of a carbon tax⁶;
- To allocate energy balance items (categories of use, transformation or production of energy) to the aggregate sectors and fuels of the hybridization matrix.

The following steps were taken to arrive at a complete and harmonized matrix for energy quantities for South Africa:

1. **Reducing the number of fuels** in the energy balances of DoE/RSA and IEA: in such a way that it matches the fuels from the SATIM model (which has less fuels);
2. **Choosing which energy balance to use for which fuel:** This, I do on the basis of comparing the energy balances, to each other and to end use data of SATIM;

⁶ Non-energy use of fossil fuels hardly causes CO₂ emissions. If this energy use would be included, it would make the average CO₂ emission factor of energy use by industry low and thus reduce the impact of a carbon tax on industry's energy use and costs of production. The few emissions that do originate from non-energy use of fossil fuels in industry, through process chemistry, are allowed to be neglected under the IPCC Tier 1 approach for estimating greenhouse gas emissions (IPCC, 2006).

3. **Adjusting production, trade and transformation of the new energy balance** to the end use demand from SATIM;
4. **Replacing CTL and GTL data by data from the ERC:** I use Coal-to-Liquids and Gas-to-Liquids data from SATIM, and adjust 2006 data received to 2005 quantities of energy use;
5. **Adjusting input and outputs for crude oil refining:** After this step the production of refinery products is in line with the end uses of these fuels;
6. **Adding SATIM data for power generation to the energy balance:** Now, all end use, and transformation of fuels is known;
7. **Adjusting imports, exports or production** (depending on the previous data we had from energy balance): This is done on a fuel-by-fuel basis;
8. Finally, we **aggregate the energy balance categories and fuels** into the sectors and fuels for IMACLIM-ZA, shown in Table B.3.

The result of the last step is shown in Table B.5 below. Below a detailed discussion of the assumptions made in steps 1 to 7 follows.

Table B.3 Allocation of categories and fuels from energy balances to sectors and fuels of the matrix of quantities of energy

Allocation of fuels from energy balance:		Primary energy	Electricity	Refinery products	Excluded
		Coal; Natural gas; Crude oil (petroleum)	Electricity	LPG; Gasoline; Kerosene; Diesel; Heavy Fuel Oil (HFO)	Other refinery products; Woody biomass; Other biomass; Nuclear and Renewables
Allocation of energy balance categories to IMACLIM-ZA-V0 sectors:					
IC	Composite sector	Blast furnaces; Gas works; Cokes ovens; Industry (SATIM); Agriculture (SATIM); Commerce (SATIM); and Transport (non-private, SATIM)			
	Primary energy	Coal mines			
	Electricity	Electricity plants; Autoproducer electricity plants; Pumped storage plants; Losses			
	Refinery products	Oil refineries; CTL; GTL; stock changes			
FC	Residential	Residential energy use (SATIM); Private transport (SATIM, being: person transport by SUV, car, and motor)			
	Government	Energy use is indirect, through public administration as a productive sector in the composite sector			
Investment		Assumed to have no consumption of energy, but only of composite goods			
Exports		Exports; plus International marine bunkers			
Production		Production; minus Feedstock use or Non-energy use			
Imports		Imports			

1. Reducing the number of fuels

In order to combine all these assumptions the following approach was used: First the number of fuels in the energy balances of DoE/RSA and IEA needed to be reduced, as the SATIM model has less detail on fuels than both the energy balances. Table B.4 below gives the fuels available in both energy balances and the categorization applied for harmonizing the data with ERC's SATIM end use data (it applies only to

fuels for which the energy balances contained data).

Table B.4 Assumed match of fuels in energy balances and in SATIM calibration data

Energy carrier in SATIM	Energy carrier in energy balances
Coal	Coking coal; Other bituminous coal;
Sub-category of coal: Other coal products (COO)	Coke oven cokes;
Gas	Natural gas;
Sub-category of gas: Other gas products (GAO)	Gas works gas; Coke oven gas, Blast furnace gas; Refinery gas;
Petroleum (Crude oil)	Crude oil (petroleum); Natural gas liquids; “other hydrocarbons”;
LPG	Liquified Petroleum Gas;
Gasoline	Motor gasoline; Aviation gasoline; Gasoline type jetfuel;
Kerosene	Kerosene type jet fuel; Other kerosene;
Gasoil/Diesel oil	Gasoil/Diesel oil;
Heavy fuel oil (HFO)	Fuel oil (IEA); Residual fuel (DoE/RSA)
Woody biomass	Primary solid biofuels (IEA); Charcoal (IEA);
Other biomass	Renewables & waste (DoE/RSA);
Electricity	Electricity.

Then there is a group of refinery products that is considered to be for non-energy use and is excluded from further analysis, but which does play a role in our assumptions on crude oil refining and in calculating the CO₂ emissions from refining processes. These are: white spirit, lubricants, bitumen, paraffin waxes, and non-specified oil products.

A last adjustment to the categorization of energy balances is that we, neither SATIM takes into account the production (or rather: harvesting) of energy resources from nuclear material⁷ and renewables with flow characteristics (sun, wind and hydro). Only the electricity produced from these sources is counted, but not the primary energy source. These energy resources in the energy balances are: nuclear, hydro, solar photovoltaic, solar thermal, and wind energy.

Also data for “other coal products” (COO) to “coal” and to add data for “other gas products” (GAO) to natural gas. Furthermore, case-by-case, additional assumptions have been made to deal with the energy balances categories “transfers”, “statistical differences” and “from other sources” (DoE/RSA).

2. Choosing which energy balance data to follow for which fuel

On the basis of the data from the detailed energy balances, and a comparison to energy end use data of the ERC, I choose which energy balance data to use for which fuel. Power generation is based on ERC, though adjusted from 2006 to 2005 proportional to the difference in GDP. For other fuels the following

⁷ Nuclear material could be considered as an energy carrier, and the energy content in relation to the nuclear decay process it undergoes in a nuclear reactor. We consider it as a non-energy product and thus as a product from the composite sector.

choices were made:

Coal production and use

As a starting point for the I-O tables for physical quantities of supply and use of energy IEA's energy balance for South Africa 2005 has been used (IEA, 2012). It has been compared to DOE's (DoE, 2009) and in case of too big statistical differences, either an adjustment of domestic production (extraction), imports, and transformation of energy (see details below) on the basis of DOE's energy balance has been made (in the case of domestic production and imports of natural gas), or on the basis of SATIM calibration data for 2005. For end use of energy ERC's estimates for SATIM have been used as well (ERC, 2013), for reason of its greater level of detail on transport and domestic energy use and industrial energy end use than IEA's and DOE's energy balances. To match supply and transformation data coming from IEA's energy balance with ERC's estimates for energy end use, the imports of energy and the inputs to CTL and GTL plants have been adjusted.

For thermal and coking coal estimates of the IEA have been used for reason of significant statistical differences in supply and use in DOE's energy balance. IEA finds a total supply for domestic end use of coal of about 15% lower than DoE. Compared to IEA's estimates of domestic production, imports, exports and transformation of coal, the domestic production is adjusted upwards, to match total domestic supply with final use of coal, for which IMACLIM-ZA uses ERC's estimates for SATIM. Coal supply to the domestic market is thereby increased again by 5% relative to IEA's energy balance data. Also, thermal coal and coking coal have been combined into one category – but this matches the level of aggregation present in ERC's estimates for energy end use for SATIM.

Gaseous fuels

For "other gaseous fuels" (coke ovens, blast furnaces and gas works gas out of transformation from coal) estimates of the IEA for their production have been used, whereas natural gas extraction and imports have been based on DOE's estimates – corrected for statistical differences, because IEA has no disaggregation of its products and estimates high conversion efficiency losses; The amount of gas used for liquifaction in a GTL plant has been reduced with almost 3% relative to DOE's estimate to keep a constant ratio over total end use of gaseous fuels; Imports of natural gas have been adjusted to make total supply (production + imports) match transformation and end use of gaseous fuels. The resulting numbers for gas and gaseous fuels mean that imports are estimated 20% lower than estimated by EIA and about 10% lower than DOE's estimate for natural gas "from other sources", domestic production is estimated equal to DOE's estimate when combined with the statistical differences they obtain for natural gas, or about 80% lower than IEA's estimate; DOE's estimate for the use of natural gas in GTL plants is almost half as low as IEA's estimate, but about 15% higher than ERC's estimate.

Oil and Refinery products

For fuels which are products of oil refineries, the part produced by CTL and GTL plants estimations has been based on SATIM's calibration data for 2006, adjusting the amount produced as a fixed ratio of fuels produced⁸ over the amount of coal or gas going into CTL and GTL plants (both estimated as the fixed ratio over end use of coal or gas found in IEA's energy balance).

Next, total input of crude oil to oil refineries for 2005 are assumed to equal the ratio of oil inputs over total refinery products in SATIM calibration data for refineries for 2006 – and multiplying this by the total amount of refinery products used as fuel which have to be produced by oil refineries. The latter is calculated by taking the total end use of refinery products for 2005 (from SATIM data) and reducing it with the total amount of refinery products produced by CTL and GTL. The amount of crude oil consumed in oil refineries, and therefore also the amount imported, is estimated about 15% lower than in DOE's energy balance.

Unfortunately, two errors have been made in data manipulation concerning oil imports and refinery output. These could not be corrected anymore at the stage of discovery, but their impact on results is estimated negligible (see Chapter 6):

- The first error is that exports have been based on ERC's data on refined products exports for 2006, and not on that for 2005, which is 62% lower than the export estimate for 2006. This mistake causes IMACLIM-ZA to underestimate BY exports of refined products (excluding non-energy use) by almost 50% (a correction of statistical differences makes that this number in the end is not as high as the initial underestimation of exports). And 15% of demand for crude oil (OIL) to produce the exported refined products (REF), is lacking;
- The second error is that in the calculation of the amount of crude oil needed to produce refined products not originating from CTL or GTL, the ratio has been calculated for oil to all refined products, including those for non-energy use, whereas when calculating the amount of oil used by oil refineries for IMACLIM-ZA's 2005 BY data the amount without non-energy products has been used. Due to this second mistake, oil use in refineries is reduced by about 10%. Combined with the first error this implies that crude oil use in refineries should have been 27% higher.

Surprisingly, these mistakes do not lead to a downward correction of oil import value or of export value compared to the values found in the SAM 2005. Instead, the oil import bill found (see below) matches that of the SAM 2005, whereas the export bill for refined fuels obtained with the quantities just described is

⁸ The total lists of products from refineries, CTL and GTL consists of: LPG, diesel, gasoline, heavy fuel oil, kerosene and other (non-energy) refinery products.

more than 60% higher than the bill obtained in the SAM 2005. It is however unknown whether there is an error in the estimation of crude oil prices for refineries.

Household energy demand

For household energy consumption, first SATIM's estimates of energy consumption for private transport need to be attributed to SATIM's three household classes, before they can be distributed together with residential energy use over IMACLIM-ZA's five household classes. The estimation of car fuel consumption for each of SATIM's three household income classes starts with the number of passenger kilometers for private transport obtained from SATIM's methodology note – all company or government car rental is attributed to the high income class. Next, assumptions about car fuel efficiency and car occupation are added to calculate the shares in vehicle kilometers and fuel consumption. For the high income class, assuming bigger cars, a fuel consumption per kilometer of 33% above median kilometer fuel consumption is assumed and an average occupation rate of 1.25 persons per car; For the middle income class median fuel efficiency is assumed and an occupation rate of 2.5 persons per car; For the lowest income class (assuming smaller cars) a fuel efficiency of 33% below median is assumed and an occupation rate of 4 persons per car on average. This estimation results in respective shares in private motorized vehicle fuel consumption of 10%, 17% and 72% for the low, middle and high income classes.

3. Adjusting production, trade and transformation of the new energy balance

The energy balances have different amounts of energy end use than SATIM, where 2005 data is adjusted to match the calibration of the model to its base year 2006. To correct the energy balances, I multiply all amounts of the new aggregated fuels by the ratio of total end use by fuel coming from the ERC over total end use from the energy balances (“total final consumption” in energy balance terminology). I do this fuel-by-fuel. In this way the total of production, trade and transformation gives the amount of end-use as given by SATIM data.

4. Replacing CTL and GTL data by data from the ERC

For Coal-to-Liquids (CTL) and Gas-to-Liquids (GTL) we have received detailed data on fuel use and output from the ERC as they have modeled it in SATIM. The received data was for their base year: 2006. To adjust it to 2005 numbers we use to the amounts of inputs of coal and gas (respectively) as taken from the energy balance. For CTL this meant that for each refinery product we multiplied the output per product from SATIM for 2006 with the ratio of coal input for CTL in the energy balance for 2005 over coal input for CTL according to SATIM for 2006; For GTL the same was done on the basis of the ratio of the input of gas from the energy balance 2005 over the input of gas according to SATIM for 2006. The same is done for electricity consumption by CTL plants.

5. Adjusting input and outputs for crude oil refining

I use crude oil (petroleum) refining as a first step in closing the energy balance for refinery products. To do this, I make the input of crude oil dependent on the output of other fuels:

- First I calculate the total of output of all refinery products together (in PJ) from SATIM for 2006;
- Then I calculate the total demand for all crude oil refinery products (in PJ) starting with the end use demand + exports and deducting the production coming from CTL and GTL;
- As a third step I multiply the input of oil from SATIM for 2006 by the ratio of this total remaining refinery products demand from the energy balance 2005 over the total of refinery products output from SATIM for 2005: This is the new crude oil input to oil refining;
- Finally, I take the new oil input to and calculate the outputs of refinery products – fuel-by-fuel – with the ratio of the new over the old (SATIM 2006) crude oil input: Now we have the new output of crude oil refining.
- These steps also apply to the electricity consumption in oil refineries.

6. Adding SATIM data for power generation to the energy balance

To match the consumption of fuels in the energy balance with model data from SATIM I take a few steps:

- I determine the total electricity generation that is needed, on the basis of end use demand for electricity plus exports from SATIM (including coal mines) and electricity demand from refineries as derived in steps 4 and 5. This is the demand without electricity lost for pumped storage (an electricity storage system) and Transmission & Distribution (T&D) losses;
- I calculate T&D losses on the basis of percentages of losses coming from SATIM, with Transmission losses applying to all end uses, but distribution losses only to residential, agricultural, commercial and light industrial demand (thus excluding heavy industry, mining, refineries, and exports) ;
- Then I calculate a new amount of electricity input to and output from pumped storage on the basis of the new total electricity demand (and neglecting line losses for this activity of electric power storage);
- I now calculate the amount of electricity generation needed, excluding pumped storage and take the ratio of this amount over the SATIM electricity output (excluding pumped storage) for 2006. All fuel inputs (mainly coal and a bit of nuclear, bagasse (own use only) and diesel) from SATIM for 2006 are multiplied by this factor to recalculate the fuel demand. The same is done for imports of electricity;

- We assume a certain split between public electricity plants and autoproducers in line with the split that was there in the energy balances and we replace the old power generation, losses, and imports data from the energy balance by the newly obtained numbers.

7. Adjusting imports, exports or production

Finally, after having replaced inputs and outputs, for refineries and electricity production (power generation) by values that fit the model data of SATIM, the energy balance needs to be re-balanced. For this I use either imports (for gas, oil, gasoline, kerosene, diesel), exports (other refinery products), or production (coal, biomass, nuclear & renewables). The only two exceptions to this rule are Heavy fuel oil, where the energy balances contain a category “international marine bunkers” – which should roughly be fuel oil tanked in South Africa by foreign ships. I simplify matters by assuming this to be exports and use the category to close the balance of supply and demand for heavy fuel oil. The other exception is LPG, where the assumptions on refining make us end up with a negative import. I solve this, without disturbing the trade balance for LPG, by assuming this to be LPG coming from stock changes.

The energy balance resulting from all previously described steps:

Table B.5 Energy balance for production, trade, transformation and end use of energy in 2005 for calibration of IMACLIM-ZA (in PJ)

Energy balance IMACLIM-ZA (PJ)	IC																	HHS - FC - residential			HHS - FC - transport			Production							Imports	Balance
	Other manufacturing (composite)	Mining (non-coal, gas)	Iron & Steel	Petro-chemical industry	Non-ferrous metals	Non-metallic minerals	Food, Beverage and Tobacco	Paper and Pulp industry	Commercial and Public services	Transport services	Commercial and Public services	Mining and Agriculture	Extraction of coal	Crude oil (imports)	Electricity (PG + T&D)	Refineries	Low	Middle	High	Gov	I	Exports	USES	Coal	Gas	Oil	Electricity	Refineries				
	COAL	163	56	133	-	1	57	34	69	-	81	1	-	-	267	2 541	769	15	13	1	-	-	-	1 906	6 107	6 046	-	-	-	-		
GAS	9	3	23	61	-	8	1	3	-	1	-	-	-	-	-	76	-	-	-	-	-	-	-	184	-	121	-	-	-	63	0E+00	
OIL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	651	-	-	-	-	-	-	-	-	-	-	-	-	-	651	0E+00	
ELECTRICITY	25	107	100	36	75	24	15	38	12	115	21	11	-	-	-	28	29	65	96	-	-	-	49	847	-	-	844	-	2	0E+00		
REFINERIES	8	29	4	-	-	-	-	-	-	448	23	49	-	-	-	1	-	15	9	1	280	-	-	141	1 008	-	-	943	65	0E+00		

The matrix of energy prices:

Table B.6 shows the matrix of energy prices, explained in section B.2.3.

Table B.6 Energy prices by user for exports, intermediate and end use, and imports of energy in 2005 for calibration of IMACLIM-ZA (in million Rand per PJ)

Energy prices (million Rand(2005) per PJ)	IC																	HHS - FC - residential			HHS - FC - transport			Imports						
	Other manufacturing (composite)	Mining (non-coal, gas)	Iron & Steel	Petro-chemical industry	Non-ferrous metals	Non-metallic minerals	Food, Beverage and Tobacco	Paper and Pulp industry	Commercial and Public services	Transport services	Commercial and Public services	Mining and Agriculture	Extraction of coal	Crude oil (imports)	Electricity (PG + T&D)	Refineries	Low	Middle	High	Gov	I	Exports								
	COAL	13.6	8.1	12.1	13.6	13.6	13.6	13.6	13.6	12.1	8.1	12.1	0.0	13.6	13.6	8.1	8.1	8.1	8.1	12.1	8.1	13.6	13.6		13.6	13.6	13.6	13.6	13.6	13.6
GAS	44	44	44	44	44	44	44	44	105	105	105	44	44	0.0	44	44	105	105	105	105	105	105	105	105	105	105	105	105	105	41
OIL	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57	57
ELECTRICITY	46	45	43	40	39	47	59	42	61	69	73	45	40	45	0.0	40	68	74	116	116	69	69	69	69	69	69	69	69	69	39
REFINERIES	141	142	287	-	-	-	-	-	144	124	141	142	144	144	142	0.0	124	129	181	163	124	124	118	118	118	118	118	118	142	142

B.2.2. I-O table for energy bills

Multiplying the matrices of energy prices and energy quantities, and allocating private transport energy use to the different household classes gives the Energy Bills that will be used to hybridise the I-O table based on the SAM 2005. The energy bills are shown in Table B.7.

Table B.7 Energy bills by user for exports, and intermediate and end use and imports of energy in 2005 for calibration of IMACLIM-ZA (in million Rand)

Energy prices (million Rand(2005) per PJ)	IC																	HHS - FC - res + transport			TOTAL USES	Imports			
	Other manufacturing (composite)	Mining (non-coal, gas)	Iron & Steel	Petro-chemical industry	Non-ferrous metals	Non-metallic minerals	Food, Beverage and Tobacco	Paper and Pulp industry	Commercial and Public services	Transport services	Commercial and Public services	Mining and Agriculture	Extraction of coal	Crude oil (imports)	Electricity (PG + T&D)	Refineries	Low	Middle	High	Gov			I	Exports	
	COAL	2 216	455	1 599	-	12	775	465	930	-	652	10	-	-	3 619	20 521	6 213	118	106	7			-	-	25 846
GAS	380	131	990	2 662	-	354	63	141	-	94	-	-	-	-	-	3 312	-	-	-	-	-	-	-	8 126	2 595
OIL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	37 168	-	-	-	-	-	-	-	37 168	37 168
ELECTRICITY	1 152	4 812	4 278	1 451	2 919	1 137	893	1 581	748	7 997	1 541	513	-	-	-	1 112	1 980	4 759	11 146	-	-	3 392	51 411	85	
REFINERIES	1 166	4 143	1 011	-	-	-	-	-	64 551	2 828	6 922	-	-	-	116	-	6 529	9 082	33 344	-	-	16 716	146 409	9 304	

B.2.3. Matrix for energy prices

Energy prices of a few sectors have been estimated on the basis of several assumptions, next for other sectors energy prices have been assumed similar to one of the original sectoral estimates. The most important assumptions are discussed here by fuel, one-by-one.

Coal sales price

For Coal (COA) use, different types of coal are used by different users. Therefore, for the calculation of the price per PJ, different heating values are used as well, next to different prices per tonne. For electricity production and refineries, low grade coal is assumed with a heating value of 21 MJ/kg, together with the local coal price for 2005 this results in a price of 8.1 mn R₀₅/PJ. For mining, households and public and commercial services the same quality of coal and price are assumed. For Iron&Steel the highest quality grade coal is assumed, with a heating value of 27 MJ/kg. The same price per tonne as the export price is assumed, leading to a price of 12.1 mn R₀₅/PJ. For exports, considering that it concerns thermal coal, and not coking coal, which is used in the Iron&Steel sector, a medium heating value of 24 MJ/kg is chosen. On the basis of numbers from the Chamber of Mines the export price per tonne should be estimated almost 4 times as high as the local price, but this would enormously inflate the energy bill for coal, meaning that it would double compared to the SAM. An average of the local and the export price of coal per tonne is therefore chosen, and this results in an export price of 13.6 mn R₀₅/PJ. The same price is assumed for all other industrial and manufacturing sectors, assuming that they prefer high quality grade coal over low grade coal, but that they do not need the high quality of coking coal that goes to the Iron & Steel sector.

Gas price

All mining, manufacturing and industrial activity is assumed to have the same gas price of 44 mn R₀₅/PJ. For commercial and public services a higher gas price of 105 mn R₀₅/PJ has been assumed. These prices have been based on differences in the regulated gas price with contract size (NERSA, 2009; and see Appendix B.1). For industry, mining and other manufacturing this is the average price – a price close to the lowest disclosed gas price of 41 mn R₀₅/PJ for the second-biggest contract size –, on the basis of the number of customers NERSA registered with contract size and NERSA's gas price with contract size. For commercial and public services, the assumption is that the gas price is that of the smallest contract size.

Crude oil import price

For crude oil, the average of Brent and Dubai crude oil prices has been taken. Furthermore, the lower heating value (LHV) has been used to calculate the price per MJ, together with specific densities for Brent and Dubai crude oil this allows to convert prices per barrel to prices per PJ. If the higher heating value (HHV) of crude oil had been used, then crude oil prices would have been a bit more than 6% lower. Had only the Dubai price been used as import price (for the LHV), then prices would have been 7% lower too (13% lower when combined with the HHV).

Prices of refined fuels

The assumption for REF prices is that there is no difference in fuel prices by user, but that the price for the aggregate good which REF represents differ due to different composition of fuel consumption by sector or user.⁹ For instance, Iron&Steel mainly consumes LPG, whereas other industrial sectors and agriculture mainly consume diesel oil, commercial and public services mainly heavy fuel oil (HFO), and households mainly kerosene for residential use and gasoline for transport. The assumption that everyone pays the same price for the same fuel is not very likely. First of all, households probably pay a number of taxes over their fuel consumption, such as the fuel levy, which are not likely. Furthermore, trade and transport margins which apply to small consumers are likely higher than those that apply to big companies, who probably are delivered bigger quantities at once. The used prices are likely average prices.

Electricity prices

For ELC prices detailed estimates by sector have been obtained from SATIM data (see previous footnote), which follow a logical pattern in the sense that they are lowest for large scale industries, closer to average for productive sectors with smaller energy consumption per enterprise and for low income households, and highest for high income households. There is therefore little reason to doubt these estimates or to obtain better estimates. It leads to a 10% lower estimate of electricity costs in total intermediate consumption (albeit differences per sector), despite the fact that own electricity generation has been integrated in electricity bills of sectors, rather than the costs of electricity generation (mainly fuel and capital costs). It also results in an about 20% higher electricity bill for households, and in total a 3% bigger electricity sector in BY calibration data.

B.3. Hybridisation details and Hybrid SAM

B.3.1. Characteristics of sectors SAM 2005

The data underlying the choice for the final sectoral aggregation of the IMACLIM-ZA model, as discussed in Chapter 3 of the thesis, is presented in Table B.8 below.

B.3.2. Hybrid 10x10 sector I-O table

The hybridisation procedure explained in section 3.1.2 of the main part of this thesis results in the hybrid I-O table for the year 2005 for calibration of IMACLIM-ZA presented in two parts (for production and imports) in Table B.9 and (for final demand and exports) Table B.10.

⁹ REF prices per fuel for 2005 are those available in calibration data of SATIM and were provided by Bruno Merven of the Energy Research Centre of the University of Cape Town.

Table B.8 Characteristics of sectors for criteria of sectoral disaggregation

SAM 2005 sector		Coal mining	Petro-leum	Gold mining	Other mining	Other non-metallic minerals	Basic iron/steel	Electrical machinery	Radio	Transport equipment	Textiles	Footwear	Wood, paper, pulp & products	Furniture, Jewelry, & Other	Food, Beverages & Tobacco
IMACLIM-SA sector after hybridisation		COA	OIL/REF /EIN	EIN	EIN	EIN	EIN/MAN	MAN	MAN	MAN	MAN	MAN	MAN	MAN	MAN
Value added	billion Rand	18	63	22	66	10	53	7	3	24	9	1.3	23	14	44
as % of total VA	-	1.3%	4.5%	1.5%	4.7%	0.7%	3.8%	0.5%	0.2%	1.7%	0.7%	0.1%	1.6%	1.0%	3.2%
Gross wages	billion Rand	8	24	15	19	3	26	4	2	14	6	1	14	5	19
as % of total wages	-	1.1%	3.5%	2.1%	2.7%	0.5%	3.8%	0.6%	0.3%	2.0%	0.9%	0.1%	2.1%	0.7%	2.7%
Number of employees	thousands	45	156	203	201	128	380	53	81	218	111	12	341		258
Jobs as % of total employment	-	0.4%	1.3%	1.6%	1.6%	1.0%	3.1%	0.4%	0.7%	1.8%	0.9%	0.1%	2.8%	0.0%	2.1%
Jobs over VA ratio	pct jobs / pct VA	0.3	0.3	1.1	0.3	1.5	0.8	0.9	2.7	1.0	1.4	1.0	1.0	0.0	0.7
Percentage high skill job types	-	20%	29%	14%	17%	19%	23%	32%	36%	26%	20%	15%	26%		18%
Percentage medium skill job type-	-	61%	49%	69%	65%	62%	57%	53%	44%	58%	57%	67%	55%		54%
Percentage low skill job types	-	19%	22%	17%	17%	19%	20%	14%	20%	15%	23%	18%	19%		29%
IC of energy as % of total IC	-	5%	33%	7%	11%	6%	9%	4%	1%	1%	2%	1%	4%	1%	2%
Imports / dom. output value	-	0.03	0.18	0.00	0.39	0.15	0.40	0.34	3.26	0.51	0.57	0.92	0.11		0.09
Exports / dom. output value	-	0.52	0.14	0.94	0.57	0.07	0.44	0.10	0.37	0.19	0.10	0.02	0.13		0.08
SAM 2005 sector		Elec-tricity	Agri-culture	Construc-tion	Trade	Hotels & Restau-rants	Other activities	Transport services	Communi-cation	Financial interme-diation	Real estate	Business services	Govern-ment + Health	Water	Total domestic production
IMACLIM-SA sector after hybridisation		ELC	LSS	LSS	LSS	LSS	LSS/HSS	TRA	TRA/HSS	HSS	HSS	HSS	HSS	HSS	
Value added	billion Rand	26	37	31	140	14	122	78	55	131	95	56	253	7	1 401
as % of total VA	-	1.9%	2.7%	2.2%	10.0%	1.0%	8.7%	5.6%	3.9%	9.3%	6.7%	4.0%	18.1%	0.5%	100%
Gross wages	billion Rand	10	12	16	82	6	49	34	15	66	6	39	202	2	699
as % of total wages	-	1.5%	1.7%	2.2%	11.7%	0.8%	7.1%	4.9%	2.1%	9.5%	0.8%	5.6%	28.9%	0.3%	100%
Number of employees	thousands	68	830	734	1 268	413	4 074	379	99	341	91	907	941	32	12 364
Jobs as % of total employment	-	0.5%	6.7%	5.9%	10.3%	3.3%	33.0%	3.1%	0.8%	2.8%	0.7%	7.3%	7.6%	0.3%	100%
Jobs over VA ratio	pct jobs / pct VA	0.3	2.5	2.7	1.0	3.3	3.8	0.6	0.2	0.3	0.1	1.8	0.4	0.5	1.0
Percentage high skill job types	-	29%	12%	18%	26%	22%	21%	25%	44%	55%	55%	33%	43%	34%	25%
Percentage medium skill job type-	-	57%	50%	61%	50%	49%	16%	61%	37%	35%	32%	51%	39%	48%	40%
Percentage low skill job types	-	14%	38%	21%	24%	30%	62%	14%	18%	9%	13%	16%	17%	18%	35%
IC of energy as % of total IC	-	57%	10%	4%	5%	3%	4%	17%	24%	0%	8%	8%	4%	8%	10%
Imports / dom. output value	-	0.00	0.07	0.00	0.00	0.15	0.05	0.21	0.04	0.02	0.01	0.06	0.00	0.00	0.14
Exports / dom. output value	-	0.00	0.12	0.00	0.01	0.22	0.04	0.09	0.06	0.04	0.00	0.02	0.00	0.00	0.12

Comments: 1. The pre-aggregation in which the table is presented is based on the maximum number of industries available from energy balances. The number of industries in the SATIM model is smaller, but these have been disaggregated with some additional assumptions. 2. Sources: Value Added (VA), Intermediate Consumption (IC) of energy products, and gross wages: Supply and Use tables 2005 (StatsSA, 2010b), and number of jobs, pct of jobs by job type, and import and export over domestic output value ratios: SAM 2005 (StatsSA, 2010a).

Table B.9 Hybrid Input-Output table 2005 for calibration of IMACLIM-ZA (millions of ZAR₂₀₀₅) – part 1

Hybrid I-O table IMACLIM-ZA (million ZAR'05)		Intermediary Consumption (IC)										Subtotals
		COA	OIL	GAS	REF	ELC	EN	MAN	LSS	HSS	TRA	
Inter- mediary Consump- tion (IC)	COA	-	-	3 619	6 213	20 521	2 840	3 610	58	604	-	37 464
	OIL	-	-	-	37 168	-	-	-	-	-	-	37 168
	GAS	-	-	-	3 312	-	4 137	449	158	70	-	8 126
	REF	-	-	-	-	116	5 154	401	8 571	1 944	64 551	80 738
	ELC	513	-	-	1 112	-	14 596	3 439	3 841	5 885	748	30 133
Consump- tion (IC)	EN	2 535	-	84	17 831	559	124 415	89 350	66 643	46 266	11 757	359 439
	MAN	3 407	-	83	830	2 804	30 051	126 607	86 450	85 484	23 968	359 685
	LSS	1 310	-	142	2 849	156	20 052	76 281	18 586	42 141	27 270	188 787
	HSS	2 976	-	99	1 685	3 558	34 999	39 951	108 352	225 340	63 509	480 469
	TRA	25 506	-	167	861	837	59 805	54 233	58 740	56 391	8 461	265 001
Subtotals		36 247	-	4 193	71 861	28 552	296 049	394 321	351 399	464 126	200 264	1 847 011
Value Added	High skill labour	3 005	-	135	2 709	4 095	24 773	34 159	56 474	205 685	36 243	367 277
	Medium skill labour	5 261	-	98	1 416	3 205	26 134	23 364	41 327	113 959	25 730	240 495
	Low skill labour	1 245	-	31	450	1 079	7 255	8 691	27 723	36 803	6 488	89 764
	Cons.of Fixed Capital (CFC)	2 125	-	152	1 805	11 560	16 461	16 712	21 095	95 842	20 041	185 793
	Net Operating Surplus (NOS)	10 943	-	923	1 943	923	73 036	53 925	117 334	175 290	55 163	489 481
	Production taxes/subsidies	373	-	-	-312	19	1 672	991	5 245	18 877	1 633	28 498
Domestic production total		59 199	-	5 531	79 872	49 432	445 380	532 163	620 597	1 110 583	345 561	3 248 318
Imports		823	37 168	2 595	9 304	85	58 569	251 522	43 452	21 721	36 627	461 865
Margins	Commercial margins	2 528	-	-	33 230	-	64 170	134 238	-234 167	-	-	-
	Transport margins	389	-	-	5 118	-	9 883	20 674	-	-	-36 064	-
Product Taxes	VAT	-	-	-	-	2 196	7 046	66 703	27 564	78 465	5 853	187 827
	Fuel levy IC	-	-	-	24 221	-	-	-	-	-	-	24 221
	Fuel levy FC	-	-	-	14 687	-	-	-	-	-	-	14 687
	Other ind. taxes/subs.	602	-	-	-20 022	-302	20 052	3 607	-3 203	-50 574	-6 879	-56 720
Total resources		63 541	37 168	8 126	146 409	51 411	605 101	1 008 907	454 243	1 160 195	345 098	3 880 199

Table B.10 Hybrid Input-Output table 2005 for calibration of IMACLIM-ZA (millions of ZAR₂₀₀₅) – part 2

Hybrid I-O table IMACLIM-ZA (million ZAR'05)		Subtotals	Final consumption (FC)					Investment	Exports, X	TOTAL USES	
			Hh1	Hh2	Hh3	Hh4	Hh5				Gov FC
Inter- mediary	COA	37 464	12	45	62	106	7	-	-	25 846	63 541
	OIL	37 168	-	-	-	-	-	-	-	-	37 168
	GAS	8 126	-	-	-	-	-	-	-	-	8 126
	REF	80 738	678	2 496	3 355	9 082	33 344	-	-	16 716	146 409
	ELC	30 133	164	727	1 089	4 759	11 146	-	-	3 392	51 411
Consump- tion (IC)	EIN	359 439	425	1 586	2 171	7 471	39 942	-	5 778	188 288	605 101
	MAN	359 685	4 581	19 659	28 305	71 738	253 905	-	164 962	106 072	1 008 907
	LSS	188 787	2 038	5 788	7 676	21 292	88 512	-	99 143	41 007	454 243
	HSS	480 469	773	3 492	5 688	24 280	286 719	305 732	12 246	40 796	1 160 195
	TRA	265 001	929	4 225	6 553	15 951	20 005	-	-	32 434	345 098
Subtotals		1 847 011	8 671	33 792	48 347	138 728	713 576	305 732	282 129	422 117	3 880 199
Value Added	High skill labour	367 277									
	Medium skill labour	240 495									
	Low skill labour	89 764									
	Cons.of Fixed Capital (CFC)	185 793									
	Net Operating Surplus (NOS)	489 481									
	Production taxes/subsidies	28 498									
Domestic production total		3 248 318									
Imports		461 865									
Margins	Commercial margins	-									
	Transport margins	-									
Product Taxes	VAT	187 827									
	Fuel levy IC	24 221									
	Fuel levy FC	14 687									
	Other ind. taxes/subs.	-56 720									
Total resources		3 880 199									

B.3.3. Evaluation of changes due to hybridisation

An evaluation of the impact of hybridisation shows that SAM-sectors that change most due to hybridisation (apart from energy sectors and transport services, and apart from the effect of aggregation of some sectors prior to hybridisation), are: Textiles & footwear; Machinery & electronic equipment; Financial intermediation; Trade & retail; and Business activities & communication.

These sector respectively see their total inputs and output value change by respectively +123%, -37%, -17%, -15%, and -14%, due to hybridisation. Other sectors see their inputs or output value change by less than 10% of its pre-hybridisation value. In all sectors except Trade & retail, more than three-quarter of the change in total inputs (resources) value comes from changes in intermediate consumption (IC), imports, trade & transport margins and product taxes – and in these categories the largest increase is due to expenditure on transport services. This is mirrored by a decrease in Trade & retails value added (VA), which changes its cost structure. The reason is that net operating surplus (NOS) and wages calculated have been transferred to the Transport services sector. Many sectors who see their consumption of Transport services increase, actually witness a small decrease in NOS and wages. A notable exception is the coal sector, whose VA increases together with the increase in its IC. The reason is that in hybridisation the assumption is that energy sectors maintain the ratio of VA over IC in their cost structure, if no other information about their cost structure has been used.

Translated to aggregated sectors of IMACLIM-ZA the changes due to hybridisation for non-energy and non-transport sectors are smaller: MAN sector's total value is defined about 7% lower; EIN's about 1% lower; that of LSS about 11% lower; and that of HSS about 10% lower. In terms of gross value added (excluding product taxes minus product subsidies) the changes are comparable: MAN's gross value added decreases 11%; EIN's gross value added decreases 9%; LSS gross value added decreases 8%; and HSS gross value added (VA) decreases 5% due to hybridisation. The biggest part of the decreases is due to adjustments to accommodate the increase of the size of the Transport services sector, which – due to externalisation of companies internal transport activities – almost doubles, both in VA terms and in total resources and output (uses) value. The coal mining sector sees its value increase due to hybridisation by a bit more than 50%, mainly due to growth of the value of intermediate consumption (IC) of transport services. The refineries sector sees its total resources and uses value grow by 21%, (also) mainly due to growth in the value of IC.

The isolation of transport activities from other parts of productive activities is considered a useful change, with the eye of possible future work, and in order to separately treat improvements in transport energy efficiency from those of industrial, manufacturing or buildings & appliances energy efficiency.

B.4. Demography and income distribution

B.4.1. Integrated Economic Accounts

To complete the integrated hybrid accounting of IMACLIM-SA, the building of a second macroeconomic table is needed: the current, financial and capital accounts (or integrated economic accounts (InEAc)) that describe the balance of sources and uses of income for each institutional agent (households, firms, government and rest-of-the-world). The final Integrated and Economic Accounts, that match with the hybrid I-O table of base year (2005) calibration data for IMACLIM-ZA is shown in Table B.12

The calibration of the distribution of primary and secondary income by economic agent also stems from multiple data sources. For instance, a breakdown of product taxes and subsidies by different types (fuel levy, VAT and other) was missing in the SAM and found in governmental financial statistics (StatsSA, 2012). Furthermore, the SAM 2005 only has one category of transfers between economic agents (accounts 4.4 and 5.5, table 2.1; StatsSA, 2010a). As a consequence, it is unclear what the size of transfers for social and pension contributions and benefits are, or how much income taxes are paid. The Quarterly Bulletin March 2007 and an “Integrated Economic Accounts” presentation of the South African Reserve Bank (SARB, 2007, 2012) were consulted to estimate these aspects of income transfers.

Also, multiple sources have been used to estimate net financial asset positions by economic agent (net debts and savings or other assets), including a SARB working paper reviewing balance sheets of assets and liabilities of households (Aron, Muellbauer, & Prinsloo, 2007). Partial information about financial assets and liabilities of companies is found in the SARB’s Annual Report 2012 (SARB, 2013a). The latter also serves to estimate South Africa’s net asset position relative to the rest of the world. Finally, I assume the Government account to balance other accounts of financial assets and liabilities, thus arriving at an estimate of net public debt of ZAR 678 billion for 2004.¹⁰

Due to the discussed lack of detail for what is required for IMACLIM in South Africa’s SAM 2005, we need to apply some assumptions to obtain the InEAc that is balanced with the I-O table.

Table B.11 below shows the items of the InEAc are required for IMACLIM in green, and whether it is available in the SAM or other documents. Items (in grey) are available from the SAM (either the SU tables or from the InEAc (StatsSA, 2010b, 2010a)) and can be used in calculating the desired numbers of the TEE. The last column shows the items where there is a link between the InEAc and the I-O for IMACLIM.

¹⁰ Unfortunately only after calibration had been completed a better estimate of public debt was found: R 500 billion in 2005 (SARB, 2013b).

Table B.11 Data need for current and financial accounts IMACLIM, availability SAM 2005, and match with I-O tables

Item no.	Item in Current and Financial Accounts	Source for data	Link to I-O for IMACLIM-SA
1	Gross wages	Available in SAM	-
2	Social (and pension) contributions paid/received	Estimated before on the basis of assumptions	Equals social contributions paid in VA
3	Net wages	Can be calculated by subtracting social contributions from gross wages	Equals total wages in VA
4	Net operating surplus		Equals net operating surplus in Value-Added
5	Consumption of fixed capital	Total for all sectors available in SAM	Part of Value-Added
6	Taxes (-subsidies) on production	Available from the SU tables	Part of VA
7	Gross Operating Surplus	Can be calculated by combining net operating surplus, CFF and taxes on production	(Indirectly through net operating surplus and CFF)
8	Total VA accruing to sectors	Equals net wages, plus social (and pension) contributions, plus gross operating surplus; and equals the value in the I-O	
9	Trade balance	Available in SAM from SU tables and current account of goods and services	Equals exports minus imports
10	Capital / property income	Available in SAM from primary income from property in current accounts	-
11	Taxes less subsidies on products	Available in SAM from SU tables and current account of goods and services	Equals total of product taxes
12	Fiscal revenue, besides ICRP	Can be calculated from total of social (and pension) contributions, taxes on production and taxes on products.	-
13	Social benefits	Hidden in "secondary distribution of income transfers" in current, financial and capital accounts	-
14	Taxes on income and property	Hidden in "secondary distribution of income transfers" in current, financial and capital accounts	-
15	Other transfers	Hidden in "secondary distribution of income transfers" in current, financial and capital accounts	-
16	Gross available income	= 3 + 7 + 9 + 10 + 12 + 13 + 14 + 15	-
17	Final Consumption	Available in SAM from SU tables and current account of goods and services	Equals consumption by House-holds and Government in I-O
18	Gross Fixed Capital Formation	Available by product but not by sector in SAM from SU tables and current account of goods and services	Equals Investment
19	Net surplus (+) or deficit (-)	= 16 - 17 - 18	-

Table B.12 Harmonised Base Year calibration data by agent for income distribution (top) and expenditures (bottom)

<u>Underlined means: part of primary distribution of income (part of VA)</u>	Firms	Government	Households	Total domestic	Rest of the World
<u>GOS and imputed rents</u>	<u>500 576</u>	<u>30 471</u>	<u>172 724</u>	<u>703 771</u>	
Returns on (financial) capital	-159 308	-46 498	177 097	-28 709	28 709
Social benefits and pensions	-50 620	-61 330	111 950	0	
<u>Gross salaries</u>			<u>697 536</u>	<u>697 536</u>	
Social and pension contributions	107 651	10 204	-117 855	0	
Income and property taxes	-98 779	223 292	-124 513	0	
<u>Other taxes (on production and products)</u>	<u>-28 498</u>	<u>198 513</u>		<u>170 015</u>	
Other transfers	16 195	-54 735	17 904	-20 635	20 635
Increase pension fund value HHS	-57 031	0	57 031	0	
Gross disposable income ($GDI_{S,G,H}$)	230 187	299 917	991 875	1 521 978	49 344
Final consumption	0	305 732	990 776	1 296 508	
Savings	0	0	1 099	1 099	
Gross Fixed Capital Formation	240 925	25 702	15 502	282 129	
<i>Trade balance</i>					7 314
Auto-financing capacity ($AFC_{S,G,H}$)	-10 738	-31 517	-14 403	-56 658	56 658
STOCK: Estimated net financial assets (negative means a debt)	-1 975 370	-938 238	2 483 608	-430 000	430 000

B.4.2. Demography by skill, employment status and household class

Table B.13 Estimated Distribution of 2005 working-age population (15 to 64 years old) by educational attainment and labour market status, thousand individuals

Educational attainment	Employed (A)	Unemployed (B)	Discouraged work-seekers (C)	"Broadly" unemployed (B + C)	Active (A + D = E)	Inactive (G – E)	Total (G)
None	699	153	276	429	1 128	825	1 953
Up to grade 3 / Std 1	440	112	144	257	697	432	1 129
Grade 4 / Std 2	303	111	102	213	516	306	822
Grade 5 / Std 3	366	133	125	259	625	376	1 001
Grade 6 / Std 4	505	213	193	406	911	578	1 489
Grade 7 / Std 5	786	299	300	599	1 386	899	2 284
Grade 8 / Std 6	942	366	385	751	1 694	1 152	2 846
Grade 9 / Std 7	769	433	423	855	1 624	1 264	2 888
Grade 10 / Std 8	1 078	515	427	942	2 020	1 281	3 301
Grade 11 / Std 9	977	633	365	998	1 975	1 097	3 072
Grade 12 / Std 10	3 311	1 302	466	1 768	5 079	1 430	6 509
NTC I to NTC II	123	31	16	47	171	50	221
Dipl/Cert with less than Gr12/Std10	166	26	8	34	200	26	226
Dipl/Cert with Gr12/Std10	1 094	127	52	180	1 274	167	1 441
Degree and higher	754	30	30	60	814	96	910
Total	12 315	4 486	3 312	7 798	20 113	9 978	30 091

Source: Authors' calculations and assumptions on the basis of SAM 2005 and QLFS 2005 data.

Table B.14 Demographic calibration data (for 2005) IMACLIM-ZA by skill (1=low, 2=med, 3=high) and household class

	Class 1	Class 2	Class 3	Class 4	Class 5	Total
Total population (thousands)	4 950	9 316	9 378	14 964	9 033	47 640
Pensionaries / 65+	123	463	634	738	125	2 084
Population of working age / 15-64	2 609	4 335	4 639	10 315	8 192	30 091
Number of children / <15	2 217	4 518	4 105	3 910	715	15 465
Employed	349	1 227	1 723	4 022	4 995	12 315
Unemployed	874	1 295	1 276	2 913	1 440	7 798
Active people at working age	1 223	2 522	2 999	6 935	6 435	20 113
Unemployment level by income class	71%	51%	43%	42%	22%	38.8%
Active people as percentage of working age	47%	58%	65%	67%	79%	67%
Inactive people at working age	1 386	1 814	1 640	3 381	1 758	9 978
Employed at skill level 3	-	-	100	900	2 701	3 701
Employed at skill level 2	50	100	774	2 722	2 194	5 840
Employed at skill level 1	299	1 127	849	400	100	2 775
Unemployed at skill level 3	-	-	75	550	709	1 334
Unemployed at skill level 2	120	242	1 116	2 333	726	4 537
Unemployed at skill level 1	754	1 053	85	30	5	1 927
Unemployment level at skill level 3	0%	0%	43%	38%	21%	26%
Unemployment level at skill level 2	71%	71%	59%	46%	25%	44%
Unemployment level at skill level 1	72%	48%	9%	7%	5%	41%
Actives at skill level 3	-	-	175	1 450	3 410	5 035
Actives at skill level 2	170	342	1 890	5 055	2 920	10 376
Actives at skill level 1	1 053	2 180	934	430	105	4 702
Inactives at skill level 3	-	-	40	330	776	1 146
Inactives at skill level 2	123	247	1 366	3 051	982	5 768
Inactives at skill level 1	1 264	1 566	234	-	-	3 064
Total population working age at skill 3	-	-	215	1 780	4 185	6 180
Total population working age at skill 2	293	589	3 256	8 105	3 902	16 144
Total population working age at skill 1	2 317	3 746	1 168	430	105	7 766
"broad" participation level at skill 3	0%	0%	81%	81%	81%	81%
"broad" participation level at skill 2	58%	58%	58%	62%	75%	64%
"broad" participation level at skill 1	45%	58%	80%	100%	100%	61%

B.5. Evaluation of assumptions for model calibration

Section 6.1.4 of the PhD theses discusses the limitations that assumptions and uncertainties in model calibration data – except for the electricity sector (ELC) – pose for the interpretation of modelling results. These limitations are the conclusion of an elaborate evaluation of the calibration data and the way it has been produced. As this evaluation is not intuitive, precisely because of the extensive nature of data manipulation procedures, this Appendix discusses the most important assumptions and their impacts one by one.

B.5.1. Construction of energy I-O tables in quantities

Appendix B.3 on the estimation of (I-O table) energy bills discussed several assumptions that were required to deal with a lack of detail in data sources or with discrepancies between different sources. Some assumptions on the other hand are meant to simplify matters and to aggregate data, for instance aggregating several types of coal into one average type of coal. These assumptions therefore contain uncertainty for model calibration, with in theory consequences for modelling results, especially for the sensitivity of energy production, transformation and use to a carbon tax. Here the most important assumptions are discussed one-by-one and evaluated in a deductive manner for their potential impact on results.

Technological coefficients for electricity production have been derived from SATIM. This being an essential part of IMACLIM-ZA's approach is the reason that the potential impacts on modelling

results of assumptions made for this part of IMACLIM-ZA are treated more into depth in the next subsection.

Coal production and use

For thermal and coking coal estimates of the IEA have been used for reason of significant statistical differences in supply and use in DOE's energy balance. IEA finds a total supply for domestic end use of coal of about 15% lower than DoE. Compared to IEA's estimates of domestic production, imports, exports and transformation of coal, the domestic production is adjusted upwards, to match total domestic supply with final use of coal, for which IMACLIM-ZA uses ERC's estimates for SATIM. Coal supply to the domestic market is thereby increased again by 5% relative to IEA's energy balance data. Also, thermal coal and coking coal and have been combined into one category – but this matches the level of aggregation present in ERC's estimates for energy end use for SATIM.

The consequence of these choices are that *if* DoE would have the correct estimate of South African coal consumption in 2005 (and ERC or IEA would be wrong), then this would mean that IMACLIM-ZA underestimates BY coal consumption and energy bills by about 10%, and CO₂ emissions from domestic non-energy sector coal would be 10% higher too – but considering that this only represents about 16% of CO₂ emissions from burning and transforming coal in BY data, and only 13% of total CO₂ emissions, the consequences of a 10% increase in non-energy sector coal emissions would translate in only a 1.3% increase in CO₂ emissions in BY calibration data. This therefore does not significantly increase the CO₂ tax sensitivity of the South African economy in IMACLIM-ZA.

Gaseous fuels

If the IEA would have the more accurate estimate and not DOE or ERC, this would mean that the efficiency of GTL is lower and about twice as much of imports of natural gas are required for the same output (fuels) of the refineries sector (REF) in IMACLIM-ZA, meaning its share as a fuel for REF would increase from about 5% to 9%, increasing its share in the total value of imports from about 0.5% to about 1%. To still respect the trade balance found in SAM data this would lead to a reduction of imports of EIN products (under unchanged hybridisation assumptions), which would be reduced by 4% compared to IMACLIM-ZA's BY data for this PhD thesis. For EIN this is a considerable amount, but considering that it only represents 0.5% of total import value and less than 0.5% of EIN's total resources, it can be considered to small to change macro-economic results.

Due to the aggregation of natural gas with gaseous fuels other than natural gas (from gas works, coke ovens and blast furnaces), an increase in demand for refined fuels, relative to an increase in energy demand by energy-intensive industries and other mining (EIN sector) in IMACLIM-ZA would only be translated to an increase in imports of about 1/3rd of the increase in demand for refined fuels. On the other hand, if demand for energy by EIN would increase, while demand for energy by REF would remain constant, also 1/3rd of this increase would be gas imports, whereas in BY data all industrial gas use comes from gaseous fuels other than natural gas. Ultimately, this will have negligible impact on

IMACLIM-ZA results, because REF and EIN energy demand will develop at similar pace (output of EIN increases faster (+114% in RP) than output of REF (+81% in RP), but after correction for energy efficiency gains (11% for EIN in RP, and 3% for REF), the difference in growth rates of energy use between the two sectors is between 5% and 10% only (depending on the scenario). The impact on the composition of inputs to the GAS sector is therefore considered to be negligible.

Refinery products

For fuels which are products of oil refineries, the part produced by CTL and GTL plants estimations has been based on SATIM's calibration data for 2006, adjusting the amount produced as a fixed ratio of fuels produced¹¹ over the amount of coal or gas going into CTL and GTL plants (both estimated as the fixed ratio over end use of coal or gas found in IEA's energy balance).

Next, total input of crude oil to oil refineries for 2005 are assumed to equal the ratio of oil inputs over total refinery products in SATIM calibration data for refineries for 2006 – and multiplying this by the total amount of refinery products used as fuel which have to be produced by oil refineries. The latter is calculated by taking the total end use of refinery products for 2005 (from SATIM data) and reducing it with the total amount of refinery products produced by CTL and GTL. The amount of crude oil consumed in oil refineries, and therefore also the amount imported, is estimated about 15% lower than in DOE's energy balance.

If one assumes that the prices used are right, and that only the quantities of oil imports and refining are too low, then this would mean that IMACLIM-ZA BY calibration data underestimates both the export value of refined products and of the value of imported crude oil. For CO₂ emissions the consequences would be small, because of the low CO₂ emission factor for oil refining, compared to production of fuels in CTL and GTL plants out of coal and natural gas, or compared to burning fuels.

An increase of OIL consumption by refineries would mean that total (resource) costs of the REF sector would be 6 to 7% in BY calibration data (OIL refining makes up 25% of the total REF sector's costs in BY data). The energy bill for REF products for other sectors and households would increase by about the same amounts.¹² For the projection in IMACLIM-ZA, taking into consideration that OIL and REF prices are assumed to increase substantially from 2005 to 2035, an increased use of OIL would cause the total (resource) costs of the REF sector to increase by about 8 to 9% in RP (where OIL makes up 34% of REF's costs). This would logically result in a slightly higher sensitivity of the South African economy to the carbon price. Parallely, the increase in costs per unit of REF between BY and 2035 would turn out to be about 2% higher in RP.

¹¹ The total lists of products from refineries, CTL and GTL consists of: LPG, diesel, gasoline, heavy fuel oil, kerosene and other (non-energy) refinery products.

¹² In hybridisation this would be compensated by a reduction in demand for products of other sectors, to respect the macro-economic totals of the SAM 2005.

An increase in the export volume and export value of REF products would make the South African economy projected in RP more energy-intensive. Currently, in hybridisation, all non-energy sector exports adjust to absorb differences with original SAM data value of exports. If REF exports would see an increase of 85% (the inverse of an underestimation of 45%) this would equal about 2 or 3% of South Africa's export value, and increase the share of REF in total export value in BY calibration data from 4% to 6-7%. Translated to RP, the share in export value of 6% of REF in the current results for RP in IMACLIM-ZA would increase to about 10%. A higher reference energy-intensity of the South African economy would translate into a slightly higher sensitivity to carbon pricing.

In reality, the consequences of a possible underestimation for the impacts of a carbon tax on the South African economy should be limited, because oil refining's relatively low CO₂ emission factor. But, in IMACLIM-ZA an increase in exports, and therefore production of the REF sector, would mean that higher exports would also cause higher coal and gas consumption by the REF sector, due to the Leontief structure for (lack of) trade-offs between energy products in the "Energy aggregate" in the production function. This would lead to higher CO₂ emissions for the REF sector, and consequentially, the impact of a carbon tax on the amount of exports would be stronger (though unjustifiedly).

Luckily, analysis in this PhD thesis also showed that the propagating effect of a reduction in exports is relatively small, due to the big role domestic demand pays in the South African economy. The impact which the mentioned two errors have on the estimation of the size of the economic impacts of a carbon can therefore still be considered very small.

Household energy demand

For household energy consumption, possibly, assumptions about differences in fuel efficiency and in car occupation rate are too high. Had fuel efficiency and car occupation rates been assumed equal for all household classes, then this would translate into a split of car fuel energy use of 35%; 25%; 40% over respectively IMACLIM-ZA's 50%, 30%, and 20% poorest to richest population by household expenditure quantile. Such a distribution seems to extreme either, considering the huge differences in per capita revenue and in car ownership. Still, it points as a potential overestimation of the share of the highest income classes in private vehicle fuel consumption, and therefore in consumption of REF, of up to 75%. In theory, this could translate (after including also residential REF consumption) into an underestimation of REF consumption by the middle income class (Hh4) of about 20%, and for the poorest three income classes (Hh1 to Hh3) of about 60%. This, in turn, could imply an underestimation of future demand for REF, and of future energy poverty in IMACLIM-ZA, considering the larger share of rigid REF consumption in the budget of the poorest 4 household classes (about 3%) than in that of the richest household class (only 2%) in IMACLIM-ZA's current BY calibration data. (Because total consumption budgets per household class of the SAM are retained, the differences are absorbed by consumption of EIN products, which would therefore turn out lower for the poorest 4 expenditure classes, and higher for the richest expenditure class.)

The amounts of private vehicle fuel consumption (REF) are added to the numbers for residential energy consumption by household income class. The distribution of estimates of household energy demand for SATIM's three *per capita* income classes over the five household classes of IMACLIM-ZA is based on SAM and SU-table expenditure shares for energy products (ELC, COA and REF) of comparable household class categories: The match in household classes is only approximate, with SATIM's low income household class representing 46% of population, whereas their energy consumption is attributed to the 50% lowest per household expenditure quantile of the SAM 2005. Their energy consumption is therefore underestimated by a few percentage points compared to energy consumption in SATIM's calibration data. SATIM's middle income class represents 34% of South Africa's population. Its residential energy consumption has also been distributed on the basis of SAM and SU-table expenditure shares for energy products to the *per capita* expenditure quantiles of the SAM representing the 51st to the 80th percentile of South Africa's population. Their per capita energy consumption is therefore slightly overestimated. For the richest 20% population quantiles between SATIM and IMACLIM-ZA correspond and there is no over- or underestimation in IMACLIM-ZA of *per capita* energy consumption relative to SATIM's calibration data. Overall, the expectation is that the differences are too small to have an impact on the results of IMACLIM-ZA. Moreover, they work in opposing directions concerning the rigidity of household energy use and therefore cancel each other out. Only the extent of energy poverty could be underestimated by a few percent due to these assumptions.

B.5.2. Limitations due to assumptions energy prices

Energy prices of a few sectors have been estimated on the basis of several assumptions, next for other sectors energy prices have been assumed similar to one of the original sectoral estimates. The most important assumptions are discussed here by fuel, one-by-one.

Coal prices

For Coal (COA) use, different types of coal are used by different users. ...

Criticism on these coal price assumptions is certainly possible. Some of them might have been made too quickly and could have deserved more research of underlying data. For instance, coal going to refineries is coal going to coke ovens, gas works and blast furnace. The part going to blast furnaces is actually an input to the Iron & Steel sector, and should not be the low grade thermal coal. Furthermore, one might wonder whether gas works and coke ovens might not use a higher quality grade coal than thermal power plants. This therefore leads to an underestimation of the costs of gas derived from coal, and therefore of the costs of the GAS sector. The GAS sector's weight in the South African economy, and gas usage's weight in total energy use, are luckily both relatively small and it can be expected to have negligible impacts on results. Ultimately, coke ovens and blast furnaces should have maybe been part of the Iron & steel sector, and not of the gaseous fuels sector (though gas works are probably at its place for the production of gas for other industries). The deviation of the

coal export price from price data on the export price from the available information, though leading to a result closer to SAM data, would require more research to evaluate whether it is not the SAM 2005 which underestimates the value of South Africa's coal exports. If this would be the case, a slight trade balance deficit of 0.5% of GDP would turn into a surplus of about 1%. Coal's specific margins would be estimated upward, and coal exports contribution would contribute more to South Africa's projected primary income. With the tested carbon tax only being levied on domestic burning of fossil fuels, this change should not affect the evaluation of carbon tax scenarios;

The next assumption which could be disputed is the assumption that non-Iron&steel industries (and manufacturing) sector's prices follow the average price between local and export prices, which is higher than their assumed higher grade quality would probably allow for. First of all, it is unknown which quality grade of coal is used by which industry, except for Iron & Steel. Secondly, domestic coal prices seem to be a lot lower than foreign coal prices. The consequence is that coal energy bills for especially EIN and MAN might be overestimated. For EIN this is possibly less of a concern, because the costs of COA only amount to 10% of its energy bills, or 1% of its intermediate consumption, or less than 0.5% of the total value of resources of the EIN sector in BY calibration data (it grows to 0.7% in RP). If the coal price would be (let's assume) about 1/3rd lower, this would mean that energy costs would for EIN would only be 3% lower. In the MAN sector, on the other hand, expenditure on COA, though only 0.4% of the total value of the sector's resources (both in BY calibration data and in RP), represents 46% of the sector's energy bill in current BY calibration data and 39% in RP. A reduction of the coal price by 1/3rd would reduce energy bills by 13 to 15%. Instead, consumption of EIN products would be a larger part of MAN's intermediate consumption. The relative impact of a carbon tax would thus be felt much stronger by MAN, and the price-elastic response would be stronger too – leading to stronger energy efficiency gains in Ctax scenarios. Still, energy efficiency gains obtained for MAN were already estimated to be too high (see section 5.5) – so despite that this assumption could increase future efficiency gains, and thus reduce the economic impacts of the same level of a carbon tax somewhat – it cannot be expected to be a more realistic result;

Gas price

The gas price for manufacturing sectors is possibly underestimated, whereas that of heavy industries is likely a bit overestimated – but with the negligible amounts of GAS consumption, the expectation is that this will not affect the outcomes of RP and Ctax scenarios.

Crude oil import price

Had only the Brent crude oil price been used, and not a mix of Brent and Dubai prices, then the average oil price would have been 7% higher. Another reason for which South African import prices could be underestimated is the exclusion of shipping costs. How much shipping costs would add to the crude oil import price is unknown. Considering the discussion above, about the likely underestimation of the amount of imported crude oil, it is possible that the crude oil price has been overestimated,

because it is unlikely that the SAM 2005 is mistaken about the value of an easily measurable flow as that of crude oil imports. The theoretical underestimation of OIL consumption in physical quantity and the theoretical overestimation of the crude oil import price would cancel each other and would thus not affect the Reference Projection very much. And like mentioned before, theoretically, it should have an almost negligible impact on CO₂ emissions of the REF sector, these potential estimation errors would therefore not change results of Ctax scenarios either.

Prices of refined fuels

Assumptions on refined fuel prices imply that heavy industry probably had lower energy bills for refinery products than used in IMACLIM-ZA, whereas services and households probably paid higher energy bills. Still, IMACLIM-ZA estimates households' energy bills for refinery products higher than can be found in SAM 2005 and SU-table data. No better information on user-specific prices has been sought, and it is therefore difficult to assess the size of uncertainty around energy bills for REF products. For REF as for other fuels, the fact that it only consists of a small part of total costs in production means that a small change in prices will probably only have a small impact on RP and Ctax scenarios.

Electricity prices

For ELC prices detailed estimates by sector have been obtained from SATIM data (see previous footnote), which follow a logical pattern in the sense that they are lowest for large scale industries, closer to average for productive sectors with smaller energy consumption per enterprise and for low income households, and highest for high income households. There is therefore little reason to doubt these estimates or to obtain better estimates.

Hybridisation can lead to a 10% lower estimate of electricity costs in total intermediate consumption (albeit differences per sector), despite the fact that own electricity generation in energy bills has been moved from sectors to the electricity sectors. It also results in an about 20% higher electricity bill for households, and in total a 3% bigger electricity sector in BY calibration data.

Electricity has a more important role in production costs and energy bills than coal for non-energy sectors, but if SAM estimates would have been used the production costs would likely not be much different. For households the difference between SAM data and energy bills data is important, but (see below) the assumption for 2035 is that electricity prices will increase due to a catch up after a period of underinvestment, present in 2005, for which capital amortisation costs are forced to increase, especially between 2005 and 2015. Compared to this exogenous electricity price increase in RP (it almost doubles) and Ctax scenarios, the difference between calibration year electricity bills and SAM estimates of household electricity expenditure turns out to be relatively small, even though non-negligible. Future evaluation of estimates of electricity bills by sector and household class is therefore recommended.

B.5.3. Additional assumptions for creation of the energy bills

Hybridisation of energy bills and SAM (and SU-table) data is performed on the basis of a 35x35 sector I-O matrix (see Appendix B.1). In SATIM's calibration data, there are less productive (or industrial) sectors available. Some amounts of productive (industrial) energy end use are therefore disaggregated. This is the case for "Other mining" (excluding coal mining) which is disaggregated into "Gold mining" and "Other mining" categories on the basis of shares in the value of (intermediate) energy consumption in the 35x35 SAM data I-O table. SATIM's "Other manufacturing" and "Paper & pulp" sectors' energy consumption is first added up and then disaggregated in the same manner as Other mining's (intermediate) energy consumption over 35x35 SAM sectors: Textiles, Footwear, Metals basic manufacturing, Electrical machinery, Radio equipment, Transport equipment, Construction and Other manufacturing. For SATIM's sector of "Commercial & public services" a similar disaggregation is applied, distributing its energy end use over SAM sectors: Water, Trade, Hotels & restaurants, Communication, Financial intermediation, Real estate, Business activities, General government, Health & social work, Education, and Domestic & other services. This assumption can be considered to be based on the best available information on sectoral energy use (that of SAM data). It is furthermore impossible to assess currently how more BU-based estimates for energy consumption by these sectors could change these numbers. The estimate for total energy use of aggregate sectors coming from SATIM is respected. And, finally, many sectors are re-aggregated, with in most cases the same sectors, to form aggregate sectors in IMACLIM (EIN, MAN, LSS or HSS). The assumed distribution is therefore considered acceptable, and any change which could be imagined in sectors energy use will have a negligible impact on results of IMACLIM-ZA due to re-aggregation of sectors.

B.5.4. Hybridisation and aggregation

The isolation of transport activities from other parts of productive activities is considered a useful change, with the eye of possible future work, and in order to separately treat improvements in transport energy efficiency from those of industrial, manufacturing or buildings & appliances energy efficiency. Whether Transport services VA should grow as much as the sector's IC of refinery products and other energy products is questionable though, because company-internal transport might not be other industries' most VA generating activity. Better data on the cost structure of Transport services should therefore be sought. For the coal and refineries sectors it has already been mentioned above that there is room for improvement of energy price data by user.

The conclusion is that hybridisation has been moderately successful by isolating energy activity, especially electricity production, refineries and transport services from the rest of the economy, while respecting aggregate macro-economic values as found in the SAM and without radically changing the economic structure of other sectors. The main criticism is that a similar result might have been obtained by simpler methods than the one described in Appendices B.1 to B.4.

C. Other calibration data and model parameterisation

C.1. Productivity gains by sector

Section 3.6 presented the assumption of a trend in average year-to-year productivity growth. To differentiate productivity growth between sectors around this trend three underlying assumptions were used: Firstly, manufacturing is a sector which is highly suitable for productivity increases; Secondly, services are assumed to have a low potential for productivity increases; Thirdly, all sectors stay within the same order of magnitude of productivity growth ($\pm 50\%$) of the assumed general trend. All other sectors' productivity gains were estimated by an ad hoc hypothesis about their place on the scale of potential productivity growth ranging between that of the services sectors and of manufacturing. This leads to the 2005-2035 productivity assumptions (prod increase) given in Table C.1 below, for capital (K), labour (L, all skill levels), and Materials & Services inputs (Mat&Serv). OIL is excluded from the table, because there is no domestic production assumed; ELC is excluded while the productivity or intensity in factors or inputs follows from a Bottom-Up model (section 3.1).

Table C.1 Assumed factor and input productivity growth by sector, 2005 to 2035

	COA	GAS	REF	EIN	MAN	LSS	HSS	TRA
K prod increase vs trend	100%	100%	100%	125%	150%	75%	50%	75%
Resulting K prod increase	+7.8%	+7.8%	+7.8%	+9.7%	+11.7%	+5.8%	+3.9%	+5.8%
L prod increase relative to trend (all skills)	100%	100%	100%	125%	150%	75%	50%	75%
Resulting L prod increase (total labour)	+34.8%	+34.8%	+34.8%	+43.5%	+52.2%	+26.1%	+17.4%	+26.1%
Mat&Serv prod vs trend	100%	100%	100%	100%	100%	100%	100%	100%
Resulting Mat&Serv prod increase	+8.4%	+8.4%	+8.4%	+8.4%	+8.4%	+8.4%	+8.4%	+8.4%

C.2. Armington elasticities for international trade

In IMACLIM-ZA foreign demand is modeled as a mirror image of demand for imports, with Armington style price elasticities to determine whether ROW will use South African, rather than international goods: Using the approach of Cabral and Manteu (2013) price elasticity of international demand are estimated by first calculating the shares of the main export destination-markets for South Africa's main export products, identified based on data by OEC (2017). Secondly, price elasticities for imports by type of goods and country or region were obtained (Zhang & Verikios, 2006). South African export price elasticities were estimated by weighing these import price elasticities by the share of South African export destinations, though limited to the most important products and region. Examples of these estimations of export price elasticities are given for some of the most important export products of South Africa in Table C.3 to Table C.10. On the basis of these relatively detailed estimates, approximate import price elasticities for IMACLIM-ZA sectors were chosen (Table C.2).

Table C.2 Reference projection and basic Ctax scenario Armington-style price elasticities of exports

	COA	OIL	GAS	REF	ELC	EIN	MAN	LSS	HSS	TRA
Assumed Armington elasticities exports	2.00	1.00	1.00	1.50	0.25	2.00	2.00	1.50	1.90	1.50

Table C.3 Estimation of export price elasticity of SA coal exports

Export destinations SA Coal (OEC, 2017)	Import price elasticities coal (Zhang and Verikios, 2006)	Approxim. average
India (33%)	India-c 4.0	3.03
Pakistan (7.8%)	Rest of SAs-c 3.6	
Turkey (4.2%)		
Malaysia (4%)	Malaysia-c 0.5	
China (3.9%)	China-c 8.5	
	(China-is 20)	
Other Asia & middle-east (9%)	MidEast-c 3.6	
Netherlands (8%)	EU-c 5.0	
Germany (4.1%)	EU-is 0.6	
Other Europe (mainly EU) (13%)		
Morocco (2.8%)	Africa-c 1.9	
Other Africa (6%)		
Brazil (1.5%)	LatA&C-c 6.3	
Other Lat (0.5%)		

Table C.4 Estimation of export price elasticity of SA ferroalloy metals

Export destinations SA ferroalloys (based on OEC, 2017)	Metal products import elasticities (Zhang & Verikios, 2006)	multiplied
China	27% china-ic	2.2 0.59
Japan	9.80% japan ic	5.6 0.55
South Korea	5.90% korea ic	1.9 0.11
Other Asia	5.40% restofSA ic	0.2 0.01
India	2.10% india ic	1.7 0.04
Other other asia	2% restofSA ic	0.2 0.00
Netherlands	5.70% EUN ic	5 0.29
Belgium-Lux	5.10% EUN ic	5 0.26
Germany	4.60% EUN ic	5 0.23
Italy	3.80% EUN ic	5 0.19
Spain	2.80% EUN ic	5 0.14
Rest of Eur	5.00% EUN ic	5 0.25
United States	16% USA ic	4.3 0.69
Rest of NA	2% Canada ic	4.5 0.09
Africa	1.60% Africa ic	1.9 0.03
Lat	1.30% LatAm&C ic	3.7 0.05
Austr Oceania	0.22% Austr NZ ic	4.7 0.01
	100.1%	Average elasticity 3.52

Table C.5 Estimation of export price elasticity of SA gold & other mining products

Export destinations SA Gold (OEC, 2017)	Import price elasticities other metals (Zhang and Verikios, 2006)	Approxim. average
Hong Kong (31%)	Hong Kong-c 6.3	1.42
India (15%)	India-c 2.9	
Thailand (4.7%)	RestofSA-c 0.8	
Other Asia & Mideast (3%)	Middle East 1.5	
United Kingdom (20%)	EU 2.1	
Switzerland (14%)		
Italy (8%)		
North Am. (3.8%)	US 6.1	
Export destinations SA platinum (OEC, 2017)	Import price elasticities other metals (Zhang and Verikios, 2006)	Approxim. average
Japan 28%	Japan-c 8.0	1.33
China 11%	China-c 6.3	
Hong Kong 9.7%		
South Korea 2.0%	Korea-c 4.7	
Rest of Asia 1.3%		
United Kingdom 13%		
Germany 8.5%		
Switzerland 4.7%		
Rest of Eur 2.8%		
United States 18%		
Export destinations SA diamonds (OEC, 2017)	Import price elasticities other minerals (Zhang and Verikios, 2006)	Approxim. average
China (14%)	China-c 3.2	1.18
India (12%)	India-c 1.8	
Israel (10%)	MidEast-c 4.3	
UAE (5.8%)		
Singapore (4.5%)	RestofSA-c 3.2	
Hong Kong (3.7%)	Hong Kong-c 2.0	
Rest of Asia (1%)		
Bel-LUX (32%)	EU 4.3	
Rest of Eur (2%)		
US (14%)	US 3.1	
Average export price elasticity Gold & Other mining products		3.93

Table C.6 Estimation of export price elasticity of SA metal products

Export destinations SA metals in general (based on OEC, 2017)		Metal products import elasticities (Zhang & Verikios, 2006)		multiplied
China				
	9.20%	china-ic	2.2	0.20
India	6.60%	india ic	1.7	0.11
Hong Kong	5.70%	hong kong	2.5	0.14
Japan	5.50%	japan ic	5.6	0.31
UAE	1.60%	mideast ic	1.3	0.02
Israel	1.30%	mideast ic	1.3	0.02
Rest of Asia and middle east	10.100%			0.00
RoSA	9.1%	RoSA ic	0.2	0.02
RoME	1.0%	mideast ic	1.3	0.01
				0.00
Europe	30%	EU ic	5	1.50
Africa	17%	Africa ic	1.9	0.32
North America	10%	USA ic	4.3	0.43
LatAm&C	1.30%	LatAm&C ic	3.7	0.05
Oceania	1.00%	Austr NZ ic	4.7	0.05
	99.300%	Average elasticity		3.20

Table C.7 Estimation of export price elasticity of SA cars

Export destinations SA cars (based on OEC, 2017)		Transp equipm. import elasticities (Zhang & Verikios, 2006)		multiplied
Germany	17%	EUN	6.2	1.05
Rest of Eur	20%	EUN	6.2	1.24
United states	27%	USA	6.7	1.81
Rest NA	2%	Canada	5.1	0.10
Japan	14%	Japan	6	0.84
Asia&MidEas	5%	RoSA	1.4	0.07
Austr&NZ	7.00%	Australia	2	0.14
Africa	6.90%	Africa	4.2	0.29
LatAm&Caribbean	1.10%	Lat	2	0.02
	100%	Average elasticity		5.57

Table C.8 Estimation of export price elasticity of SA centrifuges

Export destinations SA Centrifuges (based on OEC, 2017)		Import price elasticities other machinery (Zhang & Verikios, 2006)		multiplied
Eur	67%	EUN	4.8	3.22
Nam	15%	USA	4.6	0.69
Asia	11%	RoSA	0.3	0.03
Africa	5%	Africa	0.3	0.02
LatAm	1.10%	LatAm	3.1	0.03
	99%	Average elasticity		4.02

Table C.9 Estimation of export price elasticity of SA acrylic hydrocarbons

Export destinations Acyclic Hydrocarbons (based on OEC, 2017)		Import price elasticities of chemicals, rubbers and plastics (Zhang & Verikios, 2006)		multiplied
US	37%		4.5	1.67
CANADA	4.90%		4.5	0.22
THAILAND	20%		0.3	0.06
SINGAPORE	12%		0.3	0.04
REST OF ASIA	4%		0.3	0.01
EUR	16%		5.1	0.82
BRAZIL	5.40%		1.9	0.10
AFRICA	1%		1.6	0.02
	100%	Average elasticity		2.92

Table C.10 Estimation of export price elasticity of SA citrus fruits

Export destinations SA citrus fruits (based on OEC, 2017)		Import price elasticities Vegetables, fruits, & nuts	multiplied
Netherlands	16%	1.6	0.26
UK	9.90%	1.6	0.16
Eur	19.40%	1.6	0.31
Russia	8.70%	1.4	0.12
UAE	7.80%	0.6	0.05
Saudi	4.90%	0.6	0.03
Hong	6.40%	0.1	0.01
China	3.50%	3.5	0.12
MidEast	4%	0.6	0.02
Asia	10.40%	0.7	0.07
Canada	4.20%	3.2	0.13
USA	3.20%	1	0.03
Africa	1.70%	1.5	0.03
	100%	Average elasticity	1.34

C.3. KLEM production function elasticities of substitution

Table C.11 presents the elasticities of substitution for the different levels of the nested CES tree for production (of all sectors except ELC) used in IMACLIM-ZA in this thesis. The text below the table motivates the choice for these elasticities of substitution.

Table C.11 Nested-CES production function elasticities of IMACLIM-ZA sectors

Sector*	Elasticity of substitution with change in relative price, between ...				
	KLE & M	KL & E	KL23 & L1	KL3 & L2	K & L3
COA	0.1	0.25	4	1.5	0.1
GAS	0.1	0.25	4	1.5	0.1
REF	0.1	0.2	4	1.5	0.1
EIN	0.1	0.25	4	1.5	0.1
MAN	0.1	0.64	4	1.5	0.1
LSS	0.1	0.64	4	1.5	0.1
HSS	0.1	0.99	4	1.5	0.1
TRA	0.1	0.18	4	1.5	0.1

* No estimates for the OIL sector are given as its output is systematically projected to be nil in 2035.

Van der Werf (2008) and Okagawa and Ban (2008) provide recent international estimations of production function elasticities for KLEM-type nested-CES production functions (Table C.12). Because of differing sectoral disaggregation we can only use these estimates as guidance for our own assumptions. At the very least, the large set of sectoral values reported by both authors provides a range in which we may reasonably confidently place the values we pinpoint for each one of IMACLIM-ZA sectors. On this basis we decided to assume low KL/E elasticities (Table C.11) for heavy industries and energy intensive sectors.

Table C.12 Estimations of KLE elasticities of substitution by Van der Werf (2008) and Okagawa and Ban (2008)

Industry in literature		Basic metals	Non-metallic minerals	Food & Tobacco	Transport equip.	Paper industry	Textile industry	Construction
Corresponding IMACLIM-ZA sector		EIN/MAN	EIN	MAN	MAN	MAN	MAN	LSS
V. d. Werf	K/L elasticity	0.62	0.45	0.46	0.46	0.41	0.27	0.22
	KL/E elasticity	0.65	0.25	0.40	0.17	0.45	0.29	0.29
O. & B.	K/L elasticity	0.64	0.41	0.39	0.52	0.21	0.64	0.53
	KL/E elasticity	0.22	0.36	0.38	0.14	0.38	0.16	0.07

Also estimates of price elasticities were required for substitution between the different levels of K and L substitution. Based on US data for 1963 to 1992 Krusell *et al.* (2000) provide estimates of the substitutability of capital¹³ to skilled *vs.* unskilled labour. We estimate our KL elasticities on the basis of their insights. To understand the choice of elasticities we first compare their definition of labour. Krusell *et al.* define skilled labour as College completion or higher (16 years of schooling or more) and unskilled labour as below completed high school education. Their skilled labour category is thus slightly more selective than our skill 3 category, which for a large part consists of people with only high school degrees. Their unskilled labour covers the rest of the labour force. This means that their unskilled labour category partly consists of people with a higher degree than in our skill 2 and 1 categories at base year. Furthermore, in 1962 the US population with high school or higher education was about 50% of people over 25 years old,¹⁴ whereas in 2005 South Africa it was approximately 33% of the population of working age only. This means that the starting point of the analysis by Krusell *et al.* is an economy with already more skilled labour than 2005 South Africa, and therefore the potential substitutability of high-skilled labour to capital might be lower.

Ultimately, Krusell *et al.* (2000) find substitution elasticities of 0.67 between skilled labour and equipment capital, and of 1.67 between unskilled labour and equipment capital. As, to our knowledge,

¹³ They more precisely focus on equipment capital separated from infrastructure capital. For lack of more compatible estimates we ignore this refinement.

¹⁴ US Census, see: <http://www.census.gov/prod/2012pubs/p20-566.pdf> (accessed March 2015)

no such substitution estimates are available for South Africa, and as also Krusell *et al.* acknowledge that the skill premium in the US was not constant over time, we resort to reasonable estimates about the substitution between labour and capital:

In initial runs we applied their unskilled labour-equipment elasticity for our substitution function of low-skilled labour to capital & medium-to-high-skill labour aggregate, and their skilled labour-equipment elasticity to our high-skill to capital substitution elasticity. These runs showed low response of the production function to the availability of labour at different skill levels, and in regard of the *caveat* of the already large supply of high-skill labour in Krusell *et al.* (2000) we considered it necessary to introduce more flexibility in this part of our South African nested-CES production functions. Therefore we assumed a very low elasticity of 0.1 for high skill (L3) and capital (K) substitution, a high elasticity for our low-skill category (4) and an in-between value for the elasticity of substitution between the KL3 aggregate and medium skill labour (L2).

C.4. Assumptions for trade-offs in household final consumption

Lacking better information, trade-offs in household final consumption have been modelled through an *ad hoc* model with the objective to simulate *plausible* household consumption behaviour in the context of increasing oil and refinery product import prices and rising costs of power generation. The model therefore assumes a price-inelastic threshold for consumption of ELC, REF and TRA, and differences in price-elasticities between household classes. Table C.13 shows the assumed numbers: Floors of consumption are shares of BY calibration data per capita volumes of consumption, whose consumption is price-inelastic and therefore not part of the trade-offs in the nested CES structure for household consumption (see section 3.2.3). The motivations for these floors of consumption and for price-elasticities of substitution between the energy aggregate good (EAG) and the non-energy composite good (COMP), and for CES substitution between goods within these aggregates reflect the following considerations:

Floors of BY *per capita* volume of consumption of transport services (TRA, containing public and private passenger transport) increase from the poorest (Hh1) to the middle (Hh3) *per capita* expenditure-based household class: The idea is that the poorest households are so poor that their priority lies with buying food and paying their rent, that they will forego on using transport services, while somewhat richer households will depend more on transport, e.g. to travel to their jobs. For lower middle class households (Hh4) the assumption is that they have a higher share of leisure expenditure for transport, and that their floor of consumption of TRA is assumed to decrease. The richest household class is assumed to be too rich to give up on long-distance holiday travels, and e.g. using air plane travels, and therefore has a higher floor for TRA again;

The assumptions about floors of BY *per capita* volume of consumption of refinery products (REF) is that it shows a similar pattern as for TRA, except that the rich are assumed to have alternatives such as

buying more fuel efficient cars, or car pooling;

For floors of BY *per capita* volume of consumption for electricity (ELC) the assumption is that the poorest households spend a greater share of their electricity consumption on basic needs, while having less possibility to buy more energy efficient equipment.

The price elasticity between non-constrained consumption of EAG and COMP aggregates – which together make up the overall consumption aggregate (CONS) – have been chosen at a medium elasticity value of 0.5 (between Cobb-Douglas substitution and no substitution) lacking better information. The idea is that the floors of consumption sufficiently reflect rigidities in consumption;

Price-elasticity of substitution between unconstrained REF and ELC consumption is assumed highest for the poorest household class, and decreasing with increasing per capita expenditure by household class: The assumption is that the poor will be more prone to fuel switching, while the rich will consider energy an expense too negligible to change their behaviour, e.g. concerning the type of heating in their homes;

For substitution between non-energy goods within the COMP aggregate a relatively high price-elasticity of 1.5 is chosen under the assumption that people easily change preferences with changing prices.

Table C.13 Reference projection and Ctax scenarios assumptions about elasticity of Hh FC

	Hh1	Hh2	Hh3	Hh4	Hh5
Price-inelastic share of BY Hh FC of TRA	30%	40%	50%	40%	50%
Price-inelastic share of BY Hh FC of REF	30%	40%	50%	40%	30%
Price-inelastic share of BY Hh FC of ELC	80%	70%	60%	50%	40%
Elasticity of CES of CONS aggregate	0.5	0.5	0.5	0.5	0.5
Elasticity of CES of EAG aggregate	0.5	0.4	0.3	0.2	0.1
Elasticity of CES of COMP aggregate	1.5	1.5	1.5	1.5	1.5

C.5. Base Year consumption by product and household class

Table C.14 Calibration data (2005) budget shares for Hh FC by Hh class

	Class 1	Class 2	Class 3	Class 4	Class 5
REF	7%	7%	6%	6%	5%
ELC	2%	2%	2%	3%	2%
TRA	10%	11%	12%	10%	3%
EIN	4%	4%	4%	5%	5%
MAN	48%	52%	52%	46%	35%
LSS	21%	15%	14%	14%	12%
HSS	8%	9%	10%	16%	39%

C.6. Demography, education and skills

C.6.1. Constant Educational Skills with Low Educational Progress (CEA-LEP) demography

Table C.15 gives the evolution of educational enrolment in the Low Educational Progress scenario, which assumes constant enrolment numbers from 2010 onwards, in comparison to the “adjusted GET” scenario of De Franclieu (2015). This translates into the percentages of working age population by level of education attainment at the bottom of the table. These are combined with IMACLIM-ZA’s projection for South African demography (see section 3.6 of this thesis) to give the working aged by level of educational attainment shown in Table C.16. Assuming constant Base Year (2005) activity levels by level of educational attainment, the distribution of actives and inactives by level of skill is given in Table C.17.

Table C.15 Evolution of enrolment numbers and level of educational attainment of the working aged (15-64) for the Low Educational Progress scenario

Low progress scenario 2010 - 2035	2010	2015	2020	2025	2030	2035
No education	1552	1190	863	602	415	292
Incomplete primary	3576	3005	2398	1839	1362	1019
Primary	3780	3672	3466	3249	3023	2815
Lower secondary	12 942	13 948	14 947	15 648	16 212	16 648
Upper secondary	9 477	11 307	13 187	15 023	16 789	18 461
Post secondary	1 375	1 521	1 643	1 737	1 814	1 875
Corresponding enrollment numbers						
Adj. Primary	7 129	7 121	7 095	7 123	7 099	6 956
Adj. Secondary	4 688	4 688	4 688	4 688	4 688	4 688
Adj. Tertiary	570	570	570	570	570	570
"Natural" decrease no. c	-173	-196	-219	-248	-265	-281
Completed = gross adde	299	342	342	342	342	342
Added tertiary	126	146	122	94	77	61
degree with education times Second		0.39	0.40	0.39	0.38	0.36
Increase in upper secondary		1 830	1 880	1 836	1 766	1 672
<i>Degrees of working age population in percentages</i>						
Low progress scenario - SKILLS 2010 - 2035						
No education	4.7%	3.4%	2.4%	1.6%	1.0%	0.7%
Some primary	22.5%	19.3%	16.1%	13.4%	11.1%	9.3%
Lower secondary	39.6%	40.3%	40.9%	41.1%	40.9%	40.5%
Upper secondary	29.0%	32.6%	36.1%	39.4%	42.4%	44.9%
Post secondary	4.2%	4.4%	4.5%	4.6%	4.6%	4.6%

Table C.16 Population by age and working aged (15-64) by level of educational attainment for the CEA scenario

<i>Thousands of persons</i>	2005	2010	2015	2020	2025	2030	2035
Pop Child	15 465	15 287	15 679	15 705	15 167	14 739	14 407
Pop Working Age (WA)	30 091	33 477	34 751	35 916	37 485	38 903	40 356
PopWA non Educ.	1 953	1 591	1 194	849	592	408	287
PopWA primary	6 726	7 530	6 698	5 769	5 006	4 306	3 764
PopWA lower Sec.	12 106	13 248	13 991	14 706	15 396	15 921	16 343
PopWA upper Sec.	8 396	9 701	11 342	12 974	14 781	16 487	18 122
PopWA post sec.	910	1 407	1 526	1 617	1 709	1 781	1 841
Pop Elderly	2 084	2 689	3 061	3 510	4 013	4 454	4 765
TotPop	47 640	51 453	53 491	55 131	56 665	58 096	59 528

Table C.17 Active and inactive population of working age (15-64) for the CEA demography scenario

<i>Thousands of persons</i>	BY 2005	2010	2015	2020	2025	2030	2035
Actives low skill	4 702	4 920	4 249	3 556	3 002	2 524	2 165
Actives med skill	10 376	11 522	12 391	13 232	14 124	14 891	15 588
Actives high skill	5 035	6 136	7 066	7 968	8 959	9 881	10 756
Inactives low skill	3 064	3 180	2 735	2 280	1 917	1 606	1 374
Inactives med skill	5 768	6 359	6 731	7 087	7 454	7 752	8 012
Inactives high skill	1 146	1 361	1 579	1 792	2 028	2 249	2 460

C.6.2. Constant Shares of Labour Force (CSLF) demography

The same demography for education does not matter for the distribution of labour force over the three levels of skill in the positional demography model, because skills will be constant shares of the active population of working age. However to simulate this in IMACLIM-ZA the assumption is made that the shares of the level of educational attainment in the total population of working age remains constant too, and including the shares of inactives that are constant per level of education, this leads to the projection for actives and inactives by level of skill in the table below.

Table C.18 Active and inactive population of working age (15-64) for the CSLF demography scenario

<i>Thousands of persons</i>	BY 2005	2010	2015	2020	2025	2030	2035
Actives low skill	4 702	5 231	5 430	5 612	5 857	6 079	6 306
Actives med skill	10 376	11 544	11 984	12 385	12 926	13 415	13 916
Actives high skill	5 035	5 601	5 814	6 009	6 272	6 509	6 752
Inactives low skill	3 064	3 409	3 539	3 658	3 818	3 962	4 110
Inactives med skill	5 768	6 417	6 661	6 885	7 185	7 457	7 736
Inactives high skill	1 146	1 274	1 323	1 367	1 427	1 481	1 536

C.6.3. Estimating a reasonable size of an investment in skills

To estimate the size of a considerable investment in South Africa's education system to reduce education drop-outs and increase educational quality, the following comparison is made: One could imagine an overall investment in quality of education, at all levels – from kindergarten to vocational training – or, as the previous is hard to quantify in terms of investment, alternatively one could

imagine a specific investment creating more enrollment in certain types of education.

The latter is done to estimate the possible size and impact of an investment in skills. The assumption is that 200 000 additional places are created in good quality education high schools, which would translate to about 20% higher student numbers. Taking conventional drop-out numbers into account, as done in his methodology by De Franclieu (2015), this translates for any given moment in time into one million additional students enrolled in secondary education for the period 2020 until 2035 (Table C.19), relative to constant enrolment numbers of the demography scenario in Appendix C.6.1.

Table C.19 Educational attainment levels, and enrolment numbers investment in skills option, relative to LEP scenario

Additional investm in secondary education	2010	2015	2020	2025	2030	2035
No education	1 552	1 190	863	602	415	292
Complete primary	3 576	3 005	2 398	1 839	1 362	1 019
Primary	3 780	3 672	3 466	3 249	3 023	2 815
Lower secondary	12 942	13 948	14 546	14 855	15 043	15 122
Upper secondary	9 477	11 307	13 588	15 816	17 959	19 987
Post secondary	1 375	1 521	1 643	1 737	1 814	1 875
Corresponding enrollment numbers						
Adj. Primary	7 129	7 121	7 095	7 123	7 099	6 956
Adj. Secondary	4 688	5 688				
Adj. Tertiary	570	570	570	570	570	570
"Natural" decrease	-173	-196	-219	-248	-265	-281
Completed = gross	299	342	342	342	342	342
Added tertiary	126	146	122	94	77	61
with education times Secondary		0.39	0.40	0.39	0.38	0.36
Increase in upper secondary		1 830	2 281	2 228	2 143	2 028
<i>Degrees of working age population in percentages</i>						
Low progress w added secondary education - SKILLS 2010 - 2035						
No education	4.7%	3.4%	2.4%	1.6%	1.0%	0.7%
Some primary	22.5%	19.3%	16.1%	13.4%	11.1%	9.3%
Lower secondary	39.6%	40.3%	39.8%	39.0%	38.0%	36.8%
Upper secondary	29.0%	32.6%	37.2%	41.5%	45.3%	48.6%
Post secondary	4.2%	4.4%	4.5%	4.6%	4.6%	4.6%

An increase in educational spending might implicitly already be present in the Reference Projection (RP) and Ctax scenarios due to increasing *per capita* GDP and the assumption of an increase in governmental expenditure relative to GDP. To estimate additional investment to enroll an additional 1 million students per year, an expenditure of 7,500 ZAR₀₅ per student is assumed, based on average governmental spending on secondary education in 2010 of 2,000 \$(PPP) per student, estimated by De Franclieu (2015) on the basis of UNESCO (UNESCO, 2014) and CHET (CHET, 2014).¹⁵

¹⁵ A conversion rate of 3.48 ZAR₀₅/\$ (PPP) is used, in combination with data from the 2011 International Comparison Program (ICP) methodology, see World Bank data.

C.6.4. Estimating labour market impacts approach A

Appendix C.6.1 gives the demographic scenario (LEP) (also used by Schers *et al.* (2015)) compared to which the investment in skills scenario will have an educational impact. The assumption is that 200,000 additional places per school year are homogeneously distributed over all secondary schools, with 25% of these school's and students obtaining access to or qualifications for high skill jobs, independent of whether additional higher education is followed after the completion of secondary education.¹⁶ Starting 2015, and assuming 5% to still not complete high school, this gives 3.8 million additional persons of working age with completed secondary education by 2035. The average estimated (broad) activity rate of people with high school education for 2005 was estimated at 80%, assuming no change this leads to about 3 million additional active people with completed secondary education, out of which one quarter is assumed to have access to high skill jobs, thus creating 0.75 million more high skill workers in 2035 with a Constant Shares of Labour Force (CSLF) definition of skills (Table C.20).

Table C.20 Active and inactive population of working age (15-64) for CSLF demography with investment in skill scenario-approach A: additional high quality secondary education

<i>Thousands of persons</i>	2005	2010	2015	2020	2025	2030	2035
Actives low skill	4 702	5 231	5 430	5 612	5 857	6 079	6 306
Actives med skill	10 376	11 544	11 984	12 250	12 691	13 067	13 458
Actives high skill	5 035	5 601	5 814	6 231	6 658	7 082	7 506
Inactives low skill	3 064	3 409	3 539	3 658	3 818	3 962	4 110
Inactives med skill	5 768	6 417	6 661	6 743	6 938	7 090	7 253
Inactives high skill	1 146	1 274	1 323	1 422	1 523	1 624	1 724

C.6.5. Technical specifications for modelling approach B: productivity improvements

The assumed impact of an investment in skills of workers on output productivity is modelled as an increase in the rate of annual output productivity growth of a factor, or of annual input efficiency gains in the case of Mat inputs (materials & services products, or: non-energy products). Labour output productivity (the rate of Y over L) is used as leading in defining output productivity gains for capital and Mat. The assumption is made that for factor neutral or labour output productivity-equivalent productivity gains, the ratio of median cross-sectoral output productivity should improve equally over the 30-year period for both labour and capital. To simplify matters we ignore pre-existing inter-sectoral differences in parameterisation factor productivity growth rates and differences in factor endowment between sectors.

It will be illustrated by an example: In the case of a 7% acceleration of the annual factor-neutral

¹⁶ That there are several hundreds of thousands of potential pupils and students for each year of birth is shown by De Franclieu (2015) who for instance derives from data from the Global Educational Trend model by K.C. *et al.* (2013) that of people born between 2006 and 2010 almost 1.5 million out of 5 million people, by the age of 30-34 will not have completed secondary education, equalling on average 300,000 persons per year of birth.

productivity growth for *ex ante* median labour output productivity (from 1% per year to 1.07% per year), it will turn out to be 1.376 times that of 2005 in 2035, instead of 1.348 as in RP and the basic scenarios, meaning it will be 2.1% higher. For output over capital to increase 2.1% over the entire period too, the *ex ante* median capital output productivity in 2035 (relative to 2005) needs to be 1.10 instead of the 1.078 for RP and the basic scenarios. This means that it should grow by 0.32% per year instead of 0.25%: The annual growth *rate acceleration* for capital output productivity should therefore be 27.8%. In the case of material efficiency gains the story is quite similar, with the only difference that productivity improvements are defined inversely, as efficiency gains. The Reference and basic scenario 0.25% annual material efficiency gain therefore translates into a 7.80% total output productivity improvement, instead of a 7.78% as in the case of 0.25% productivity gains for capital output productivity. To obtain a 2.1% increase in output productivity, the annual efficiency gain needs to be 38.2% higher and become 0.35% per year instead of 0.25% per year. In most scenarios we only assume half of the productivity gain for Mat, in this example its annual growth rate would increase only by 19.1% to 0.30% per year.

C.7. Estimations of energy efficiency potentials Energy Efficiency scenario

To arrive at estimates for energy efficiency potentials on the basis of the analysis of mitigation options by sector in DEA (2014) the following steps were taken:

1. The non-fuel switch mitigation potential in megatonne (Mt) CO₂-eq (relative to DEA's WEM scenario) was determined on the basis of the MACC curves for all industries described in DEA (2014, Appendix D) for three different carbon prices – close to the carbon tax rates tested in the scenario analysis in IMACLIM-ZA when translated to Rand₂₀₁₀ (0 ZAR₁₀/tCO₂; 150 ZAR₁₀/tCO₂; and 450 ZAR₁₀/tCO₂);
2. These amounts were deducted from the trend in greenhouse gas emissions by sector in DEA's WEM scenario, to arrive at an index of greenhouse gas emissions for 2010 to 2050 (by sector);
3. Similarly, on the basis of sectoral output growth projections, assuming constant prices, an index was constructed for the volume of output;
4. For the DEA study's sectors that were assumed to be part of IMACLIM-ZA's EIN sector, and for the sub-sectors that made up DEA's Transport sector, total emissions and output were added up, weighed on the basis of 2010 shares in greenhouse gas emissions (CO₂-eq), to arrive at an aggregate sector index for greenhouse gas emissions and for output;
5. Calculating the index of emissions over the index of output gives the (proxy, or assumed) index for energy efficiency by sector.

C.8. Estimation of technological coefficients of ELC

C.8.1. Definition of scenarios in SATIM

The TIMES South Africa model (SATIM) is part of the TIMES/MARKAL family of energy system models (Loulou, Goldstein, Kanudia, Lettila, & Remme, 2016), which are partial equilibrium optimization models and which are an example of what can be called “Bottom-Up” models, due to their construction on the basis of engineering insights and technology assessment studies, as well as studies on behavioural choice for the use of technology. The term partial equilibrium refers to the lack of feedback on macro-economic development, with GDP growth, sectoral activity growth, and household revenue or consumption defined exogenously.

“Fundamentally, the modelling methodology of SATIM characterises the demand for energy by the energy services required by a sector. These services are supplied by technologies that require energy and the quantity of that energy supply will depend on the efficiency of the technology. The cost of supplying the service will depend on the cost of the energy carrier (fuels, electricity etc.) and the cost of the technology over time which together can be calculated as a levelised cost of supplying the service. The model will select technologies to minimise this cost subject to constraints.” (ERC, 2013)

Starting of from the same basic model, several versions of SATIM have been realized, such as a model focussing on the power sector and exogenous electricity demand (SATIM-E (ERC, 2015)), a model with all economic sectors (SATIM-F (Altieri et al., 2015; Burton et al., 2016)), and a version which has water use by the power sector added (SATIM-W (World Bank, 2017)). Furthermore, it is possible to run SATIM coupled to e-SAGE (Arndt, Davies, & Thurlow, 2011), which has recently been extended from a power sector-linked model to a full-sector linked model (Merven, Arndt, & Winkler, 2017). As Schers *et al.* (2015) this PhD thesis makes use of SATIM-F. A “run” of the model consists of a combination of different technology specific “scenarios” (ERC, 2013).

Selection of scenarios for SATIM runs for estimation of technological coefficients

For IMACLIM-ZA the version of SATIM-F (and its model files) of November 2014 was used, and this was run under the assumptions on investment costs and electricity demand of the updated IRP build plan (Merven, Moyo, Stone, Dane, & Winkler, 2014; RSA, 2013). Furthermore, the assumptions were made that there would be no gas imports from Northern Mozambique, neither Shale gas exploitation within the projection optimization period, which ran from 2006 to 2050, with results used until the projection year 2035. For the simulation of the impacts of taxation of fossil fuel-based CO₂ emissions (a carbon tax), to the scenarios containing the above assumptions scenarios with respectively a carbon tax of R₁₀ 100/tCO₂ and R₁₀ 300/tCO₂ were added. The carbon tax starts at a value of zero and linearly increases to its final value, which is achieved in 2020, after which it remains constant.

Assumptions in SATIM scenarios relevant for technological coefficients IMACLIM-ZA

SATIM scenarios include hypotheses about the capital costs of nuclear and renewables and their change over time due to technological learning. These capital cost assumptions are based on the underlying assumption that the (real) cost for materials and production of this capital remains constant over time. Furthermore, a constant discount rate (8%, as in the updated IRP build plan) is applied to estimate discounted energy costs for a technology and the net present value of investments, which feeds into the model's optimization decision-procedure for cost minimisation.

Real labour unit costs are also assumed to be constant, but implicitly total labour costs could change via changes in fixed and variable Operation & Maintenance (O&M) costs, but their break was not available. As such, the labour content of electricity production is not present in the consulted version of SATIM. Instead, they are estimated on the basis of O&M costs, which also include costs for materials & services used in production or maintenance of capital, and for existing power generation capacity they include the capital write-off costs of past investments (which lie before the model's projection period).

Aggregation of output of SATIM runs

The level of detail of energy products and technologies in SATIM is bigger than in IMACLIM-ZA. For instance, the consulted scenarios of SATIM contain 55 power generation technologies (for South Africa and (potential) origins of electricity imports). A large part of these 55 technologies use one of the 10 fossil or bio-energy based fuels for thermal power generation. The other technologies only have capital costs and O&M costs, which in the case of nuclear energy include fuel costs. Necessarily, outcomes of SATIM need to be aggregated to the lower level of detail of IMACLIM-ZA, starting with the 10 types of fuels for power generation: Table C.21 below lists the energy carriers available in SATIM, what they represent, and in which aggregate of IMACLIM-ZA they have been included.

Table C.21 Aggregation of SATIM fuels for translation to IMACLIM-ZA

IMACLIM energy product, or other	SATIM fuel names	Contains
COA	ETCLE*, ETCLD*	Low grade coal for power plants, and coal for discarded power plants
GAS	ETGAS*, ETGIC*	Local and imported gas for power plants, and imported LNG or gas extracted at sea
REF	ETODS*	Diesel for power plants
Excluded for IMACLIM-ZA	ETCRB*, ETGR*, ERBIO*, ERBIG*	Regional coal, and regional gas for imported electricity; Biomass, and landfillgas for domestic power generation
Excl in SATIM runs	ETGIH*	Indigenous shale gas for power generation

Some fuels for power generation have been excluded in the definition of technological coefficients for IMACLIM-ZA. ETCRB* and ETGR* have been excluded because they consist of respectively coal and gas inputs to foreign power generation, whereas the goal is to define the technological coefficients of domestic power generation. ERBIO* and ERBIG* are renewable biomass, which would form an

input to renewable electricity generation. They have been excluded for two reasons. Firstly, sectoral disaggregation in the current version of IMACLIM-ZA does not offer any possibility to include these fuels, while secondly they form only a marginally small input, even for the higher carbon tax scenario of maximally 8 PJ on a total of in-between 900 and 4000 PJ of inputs of fuels (depending on which year and what level of a carbon tax).¹⁷

Translating output of SATIM runs to IMACLIM-ZA

For power generation capital no aggregation by energy type is needed, because the current version of IMACLIM-ZA only has one (aggregate) technology for electricity (ELC) production. The use of exogenous technological coefficients is exactly meant to incorporate technological dynamics in what else is a “black box” of production technology of ELC in IMACLIM-ZA. Instead, the capital intensity, labour intensity and materials&services (Mat) intensity need to be estimated on the basis of aggregated outcomes of the SATIM runs.

Fuel intensities of electricity production follow from a division of total fuel consumed domestically (in PJ) by the total amount of electricity produced domestically (in PJ, minus the amount coming pumped storage). The resulting relative change in fuel intensity is read as an index for (future) fuel intensity of electricity production, and the BY value of fuel intensities for COA and REF are multiplied by this index, which is necessary due to small differences in BY calibration (see section C.8.2). Whereas for GAS the fuel intensity given by SATIM is copied directly due to lack of GAS consumption in electricity production in both IMACLIM-ZA and SATIM’s calibration year’s data.

To arrive at an estimate for aggregate capital intensity the following method was applied:

- To calculate the total amount of “volume units” on capital, the assumption was made that all investment consists of a homogenous capital good with a *constant price*. If capital unit costs for a certain technology decrease – for instance: costs per GW of installed capacity decrease due to technological learning – this implies that *less* of the homogenous capital good is required to generate the same amount of electricity;
- Annualized investment costs are used to estimate capital intensity (consumption of fixed capital) of power generation. They are annualized over the entire installation’s lifetime’s electricity production in two different ways, depending on whether it concerns power generation already existing in 2006 or power generation (to be) constructed from 2007 onwards:
 - For new capacity (>2006), the annualized investment costs as calculated by SATIM (with the COST_INV parameter) are used.

¹⁷ The fuel values in SATIM and in the hybrid I-O tables of IMACLIM-ZA should normally be based on Higher Heating Values of corresponding fuels.

- For existing capacity the annualized investment costs are hidden in the fixed O&M costs. The share of annualized investment costs in fixed O&M costs are estimated on the basis of a comparison between the fixed O&M costs per GW of existing capacity and similar new power generation technologies (installations) in 2007. The difference is assumed to be the annualized investment cost, and this share is applied to all years in the projection period.
- The total of annualized investment costs is divided by the total electricity production, which becomes the indicator for volume of physical capital intensity. Two remarks need to be made:
 - “Pumped storage”, a storage of power generation capacity in a hydro power reservoir to bridge power generation between low and peak hours of electricity consumption, is included in the calculation of capital costs, because it is needed to deal with intermittency, but excluded in calculating total electricity output, because it basically consists of “recycled” electricity;
 - Transmission capital costs have been excluded for reason of an initial focus on different power generation technologies, though retrospectively it might have been better to include them as part of the total power generation and electricity distribution system. Their exclusion causes a slight (<5%) overestimation of the *relative* growth in capital costs, due to transmission capital costs decreasing percentwise in total power generation capital costs in the consulted SATIM runs.
- This indicator for “volume” of capital intensity is considered to be an index for the future capital intensity of electricity production. This index is not applied one-on-one to the ELC sector’s Base Year (2005, BY) capital intensity, but an adjustment is made to the index derived from the SATIM runs. As mentioned in section 3.1, SATIM calculates total lifetime costs of the energy sector, whereas IMACLIM-ZA represents the price for different final users of electricity. In IMACLIM-ZA’s BY, 2005, only one year apart from SATIM’s calibration year, 2006, the average price of electricity was below the found costs of electricity. In IMACLIM-ZA this is assumed to be due to a too low capital cost. A comparison of the costs of electricity found in the calibration of IMACLIM-ZA, the consulted SATIM runs, and (unweighted) average electricity price of ESKOM shows these differences. When translating the difference to a lack of capital cost recovery, the conclusion is that IMACLIM-ZA’s BY data underestimates BY capital intensity strongly. Correspondingly it was decided to multiply the capital intensity found in SATIM with this factor from 2015 onward, and to assume that the capital cost recovery is linearly increased between 2005 and 2015 (for the sake of potential shorter model projection periods). This corresponds to the regulated electricity price increases (NERSA).

To arrive at an estimate for aggregate Materials&Services (Mat) intensity the following assumptions were and calculations were made:

- The share of labour in the total of labour and Mat costs in BY hybridised SAM data is assumed to represent the share of labour costs in fixed O&M costs. Furthermore, the labour inputs per PJ of electricity produced are interpreted as remaining constant under SATIM assumptions, although it could not be derived from SATIM's O&M cost data whether this would be a justified assumption.
- Labour inputs per PJ of electricity produced times constant labour costs give the evolution of total labour costs in total fixed O&M costs.
- The remainder of O&M costs is assumed to be Materials&Services costs. Assuming constant "Mat" costs per unit, this gives the evolution of material intensity in the projection period of the SATIM run.
- Like with capital intensity, this is then assumed to be an index for future "Mat" intensity of electricity production.

Due to the above assumptions, Mat intensity of electricity production roughly follows suit on capital intensity, which could reflect the increased need for maintenance and repair. Labour intensity in the mean time remains constant, although one could imagine installations such as renewable power generation to require at least as much labour per unit of capital as traditional coal-fired power plants. To allow labour intensity to increase with capital intensity too, the additional assumption is made that – compared to the just described assumptions for the interpretation of SATIM run output for IMACLIM-ZA – labour intensity increases between 2005 and 2035 for medium and high skill labour, whereas it will decrease for low skill labour, with respectively +37.5%, +25% and -37.5%. This distribution also copies the general hypothesis for this PhD that labour will continue to shift away from low-educated job types towards higher educated job types (see the discussion of labour market modelling in Chapter 3).

C.8.2. Results & Comparability

Outcomes: Technological coefficients for IMACLIM-ZA

The outcomes of above assumptions in terms of technological coefficients for IMACLIM-ZA in 2035 are summarised in Table C.22. It shows a clear increase in capital intensity with increasing carbon taxation, while intensity in coal use decreases strongly. Mat intensities increase as well, while labour intensities have not been differentiated by scenario, in view of the lack of further information. At constant BY 2005 prices the increase in intensities for capital, Mat and labour for the RP (without a Ctax) implies an increase of the production costs of electricity of 61%, while the share of capital write-offs increases from the 23% (a situation of underinvestment) to 50% and the share of expenses on coal

decreases from 41.5% to 22%. In case of R100 Ctax, at constant 2005 prices, the shares of capital and coal in total costs would become 55% and 16% respectively, while for a R300 Ctax these numbers would become 63% and 9%.

Table C.22 Technological coefficients or volume indexes for inputs and factors of ELC production in IMACLIM-ZA, BY and based on SATIM run output by Ctax scenario for 2035

IMACLIM-ZA technological coefficients ... based on SATIM scenario ...	kappa (CFC/Y)** index	COA/Y	REF/Y PJ/PJ ELC	GAS/Y***	Mat/Y index	high skill labour/Y	med. skill labour/Y	low skill labour/Y
						workers/PJ ELC		
2005 BY calibration*	1.00	3.01	0.003	0.0010	1.00	21	41	5
2035 upd. IRP w/o Ctax	3.47	2.55	0.003	0.0005	1.43	29	52	3
2035 upd. IRP + R100 Ctax	4.02	1.97	0.003	0.0005	1.77	29	52	3
2035 upd. IRP + R300 Ctax	5.02	1.18	0.004	0.0005	1.95	29	52	3

* By assumption intensities derived from SATIM's base year 2006 are equal to those of IMACLIM-ZA for 2005.

** Capital intensity is underestimated in IMACLIM's hybridisation, due to low capital write-offs in the hybrid I/O matrix for 2005, likely due to a period of underinvestment in new power generation and low capital write-offs costs due to an old electricity stock. The 2005 index value is 3 times lower than in SATIM for this reason. By 2015, after electricity price increases, this is corrected.

Capital intensity taken from SATIM is average write-offs per year, and is defined to be equal to volume index-units of capital (CFC/Y); a volume-index-unit of capital from SATIM is assumed to have a constant price, with capital costs per GW capacity reflecting the capital intensity of a technology (the discount rate is constant in the SATIM runs).

*** The base year for GAS/Y intensity is 2010, when the first gas-fired power generation appears in SATIM runs. No gas-fired power generation is assumed for 2005.

More on technological coefficient plus table

Comparison of trajectories (discussed in Chapter 6) also shows big differences for relative change of capital intensity between BY and the projection in 2035 (Table C.8.3), but this is only virtual, because of a difference in calibration between the two models. For the intensity in inputs of materials & services, and for labour intensity of electricity production a different assumption was made in IMACLIM-ZA, compared to SATIM, that these intensities increase in time with the share of renewables in electricity production.

Table C.23 Comparison of variables and parameters related to electricity production in SATIM runs and IMACLIM-ZA

Model & Scenario Base Year (BY) or 2035 with or w/o Ctax	Unit	SATIM runs Upd.IRP-2010 (2035)				IMACLIM-ZA for RVAT (2035)			
		BY 2006	No Ctax	R100 Ctax	R300 Ctax	BY 2005	No Ctax	R100 Ctax	R300 Ctax
Physical intensities per PJ ELC									
CO ₂	Mt CO ₂ /PJ	0.28	0.24	0.18	0.11	0.28	0.24	0.19	0.11
Coal	PJ COA/PJ	2.95	2.45	1.90	1.13	3.01	2.55	1.97	1.18
Capital (index)	Index	1.00	1.16	1.34	1.67	1.00	3.47	4.02	5.02
<i>Capital intensity vs Reference Projection</i>			1.00	1.16	1.45	1.00	1.16	1.45	
O&M (index)	Index	1.00	1.07	1.12	1.11				
Materials & Services (assumed)	Index					1.00	1.43	1.77	1.95
Labour (assumed, unweighted avg)	Index					1.00	1.25	1.25	1.25

Comparability of SATIM runs and IMACLIM scenarios

An elaborate overview of similarities and differences between the inputs and output of SATIM runs with the change in parameters and variables of corresponding IMACLIM-ZA scenarios has already been given in section 6.1. Some differences require further explanation, these are:

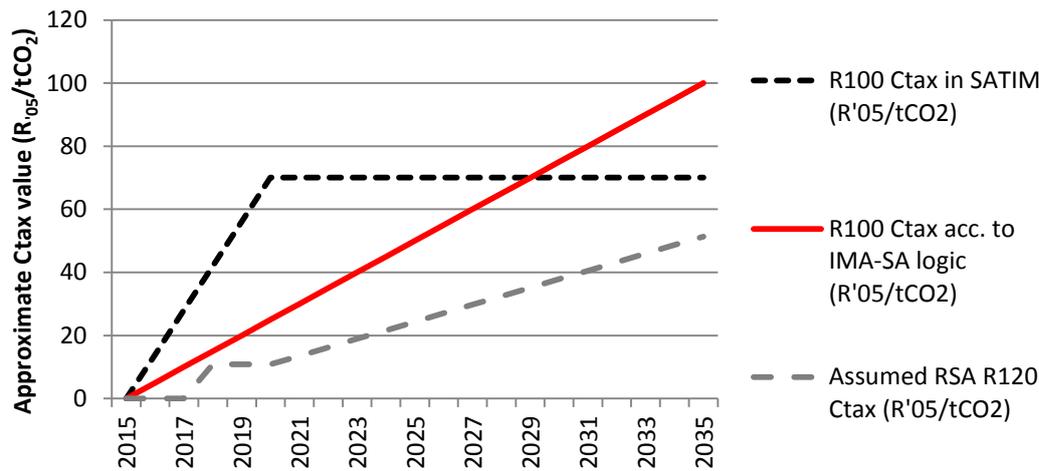
Difference in value of carbon tax, and its timing: The value of the carbon tax differs between the SATIM runs and IMACLIM-ZA, because 100 R₁₀/tCO₂ equals 69 R₀₅/tCO₂ and 300 R₁₀/tCO₂ equals 207 R₀₅/tCO₂. The value of the carbon tax is therefore 31% higher in IMACLIM-ZA's Ctax scenarios of this PhD, than in the corresponding SATIM runs. Likely, at a higher carbon tax it would be more beneficial to further decarbonise the electricity sector, and projections with intertemporal optimisation show that it would be economically cheaper for South Africa to decarbonise the electricity sector rather than most other sectors (Burton et al., 2016). However, in line with the approach behind IMACLIM-ZA – which assumes economic behaviour based on limited foresight, and with the use of CES structures implying gradual price changes – the Ctax would be implemented more gradually than in SATIM, and the lack of foresight in economic (investment) decision making would result in slower responses to the Ctax, both in power generation infrastructure, as in investments relevant for energy efficiency and therefore electricity demand. The consequence is that a higher Ctax would be needed to achieve the same technological change as in the intertemporal optimisation runs of SATIM. For this reason, the Ctax rate has not been corrected for the deflation in the SA Rand between 2005 and 2010.

A comparison between SATIM's Ctax rate trajectory, and IMACLIM-ZA's assumed Ctax trajectory is shown in Figure C.1. For reason of comparison, also author's own interpretation of the South African National Treasury's Carbon Tax proposal (National Treasury, 2015; RSA, 2015) has been added to show how this proposal relates to the modeled scenarios.¹⁸ Clearly, a R₁₈ 120/tCO₂ Ctax which starts in 2018, with sectoral exemptions between 65% and 95%, translates into a much lower Ctax rate than the low rate as modelled in the consulted SATIM runs and IMACLIM-ZA scenarios.

Differences in electricity demand: For completeness this section recalls that in report section 6.1 it was shown that SATIM scenarios foresee higher domestic production and higher imports of electricity than the IMACLIM runs. The cause for the first mainly lies in higher GDP growth in the Updated IRP outlook than modelled in the IMACLIM-ZA RP and Ctax scenarios. Another likely reason are differences in projected efficiency of industrial energy demand. The cause for lower imports, as discussed in report section 6.1, in IMACLIM-ZA mainly lies in differences in calibration and in differences in modelling. The consequences in terms of the technological coefficient for coal inputs to electricity production is discussed in the next sub-section.

¹⁸ The assumption behind this interpretation is that the Ctax rate remains constant with GDP deflation at 120 R₁₈ /tCO₂, while the exemptions, assumed to be 80% on average in 2018, are slowly reduced with 5 pct. points per year from 2021 onwards.

Figure C.1 Comparison of (assumed) Ctax rates between 2015 and 2035 in constant R₀₅/tCO₂



Difference in resulting average electricity production cost: Similarly, report section 6.1 presented future electricity prices for all scenario in IMACLIM-ZA to be higher than in SATIM. The main reason are differences in the cost development of coal and labour, with the former resulting from a higher carbon tax rate in IMACLIM-ZA in SA Rand of 2005 and the latter resulting from decreasing unemployment and therefore higher real wage demands in IMACLIM-ZA against an assumption of constant labour (unit) costs in SATIM.

C.8.3. Share of coal-based power generation with future electricity demand

Due to the previously described difference between corresponding SATIM runs and IMACLIM-ZA scenarios regarding demand for electricity, and acknowledging the fact that the updated IRP build plan (RSA, 2013) still foresees near future installation of coal power plants, it might not be so sure that under lower electricity demand growth, there will be as much additions of renewable energy and nuclear energy as in the consulted SATIM scenarios.¹⁹ This annex therefore analyses the potential ranges for the intensity of coal use of South Africa’s electricity production, being a very important factor for South Africa’s future CO₂ emissions. The parallel discussion regarding the capital intensity of electricity production is left aside, as it can be expected to roughly show the inverse development of that of uncertainty in coal intensity of electricity production.

To estimate uncertainty margins around the coal intensity of power generation with lower electricity demand, as in the IMACLIM-ZA scenario’s, the following approaches were used:

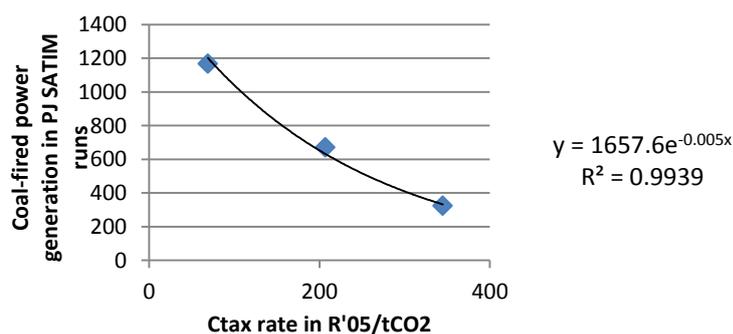
- To estimate the maximum share of coal-fired electricity production in IMACLIM-ZA the amount of coal-based electricity production from the to the Ctax rate corresponding SATIM

¹⁹ This discussion does not take into account whether the scenarios ran in SATIM are still the most relevant for the debate about South Africa’s energy future. For example, cost estimates for nuclear energy require revision since 2014 (ERC, 2015).

runs was calculated as a share of the electricity production foreseen in IMACLIM-ZA scenarios with the RVAT revenue recycling mechanism (in case of a Ctax);

- In the opposite case, calculating the minimum share of coal-based power generation in electricity production for IMACLIM-ZA (RVAT scenarios, when implementing a Ctax) the basic assumption is that the pricing mechanism of the carbon tax is all-defining for the electricity mix, and that the installed capacity of power plants plays a negligible role (except for maximum output). To calculate the impact of the carbon price mechanism the Ctax rates in the consulted SATIM runs were translated to Rand of 2005 values, after which a trend estimation was made of the amount of coal-based electricity production on the basis of 3 SATIM runs (with a Ctax rate of 100, 300 and 500 R₁₀/tCO₂, equivalent to respectively 69, 207 and 345 R₀₅/tCO₂)²⁰ (Figure C.2). On the basis of the trendline estimate of these outcomes, the output of coal-based electricity generation was calculated for Ctax rates of 100 and 300 R₀₅/tCO₂ and divided by the amount of electricity produced in the corresponding IMACLIM-ZA scenarios;

Figure C.2 Estimation of coal-fired electricity production with Ctax rate in R'05 on the basis of SATIM runs



- For RP the minimum estimate for the share of coal-fired power generation is calculated differently, and based on the assumption that all non-coal fired power generation in the updated IRP is based on committed build of renewable and other non-coal-based power generation capacity, with the former having guaranteed sales of its production in 2035 in one way or another (either through guaranteed sales, or through subsidies or proper feed-in tariffs). The coal-based amount of electricity production is then calculated as the total amount of electricity production in RP of IMACLIM-ZA minus the non-coal based amount of electricity production in the SATIM run without a carbon tax. This, again, is then divided by the total amount of electricity production in the corresponding IMACLIM-ZA scenario (RP) to obtain the minimum estimate for coal's share in 2035 electricity production.

²⁰ For the purpose of this estimate an additional run with SATIM and a higher Ctax rate was performed. The run was not considered relevant for IMACLIM-ZA, because scenario analysis (see Chapter 4) showed that a Ctax of 300 R₀₅/tCO₂ already proved to have serious economic impacts without different assumptions about technological change or economic policies.

The outcome of this procedure (Table C.24) notably shows that for a 100 R₀₅/tCO₂ Ctax rate the estimated coal-based power generation is about one fifth higher than coal's share in electricity production which has been used in SATIM (82% vs 67%). This means that if South Africa sticks to the updated IRP for investment in power generation, while lower GDP growth than foreseen in the Updated IRP continues, or if future electricity demand will be lower for another reason, the share of coal in power generation will be much higher than foreseen. But, this analysis does not reflect uncertainty behind this uncertainty, and for instance Merven et al. (2014) show that in SATIM-E a “tipping point” in decarbonisation of electricity production seems to exist between a Ctax of 10 and 20 USD₁₀/tCO₂, which would be equivalent to about 73 to 146 R₁₀/tCO₂, and 50.5 to 101 R₀₅/tCO₂. In other words: The curve in Figure C.2 should be more like an *S-curve*, and the tipping point might have been passed for a 100 R₀₅/tCO₂ Ctax, and it might well be that the lower share of coal-based power generation would be realised despite the lower output of electricity generation. This uncertainty is hard to quantify though. For a 300 R₀₅/tCO₂ Ctax rate the carbon price mechanism can be expected to push out coal-fired power generation from the electricity mix as in the SATIM run with higher electricity production.

Table C.24 Minimum and maximum estimates for share of coal-based power generation for IMACLIM-ZA on the basis of SATIM runs

BY or 2035 scenario	BY	RP (no Ctax)	R100 Ctax	R300 Ctax
Share of coal-based electricity production in SATIM runs, used to set technological coefficient*	97%	88%	67%	40%
Max. estimate of share of coal-based ELC for IMACLIM-ZA	-	100%	95%	66%
Min. estimate of share of coal-based ELC for IMACLIM-ZA	-	85%	82%	36%

* The share of coal-based electricity production, or rather its index, is not the same as the technological coefficient of coal inputs to ELC production: Due to increasing energy efficiency the index of coal-fired power generation's share in electricity production does not decrease as much as the technological coefficient for coal inputs.

Despite the mentioned uncertainty behind the uncertainty, the conclusion of the above described approach is that for a R100 Ctax the share of coal in production of electricity in IMACLIM-ZA is likely underestimated, and might be one fifth higher than used in model runs. As a consequence, the cost of coal use for electricity production should increase by about 20% as well, and as coal makes up about 35% of the average cost of electricity production it might cause the electricity price to go up by 7%, if one ignores the possible decrease in capital costs under this more coal-dependent projection. If, on the contrary, one assumes that under lower future electricity demand investment in renewables or nuclear power generation will also be lower than the increase in electricity price might not be as high. In contrast, the CO₂ intensity of the South African economy will be higher, with coal use for power generation in the Ct100 RVAT scenario already being 43% of total South African CO₂ emissions, a one fifth or higher increase in coal use could translate into CO₂ emissions of 9% higher or more

(assuming the price of electricity does not notably change).

As a reminder it is mentioned that for a R300 Ctax there is not the same uncertainty around the coal intensity of electricity production, , because the above mentioned “tipping point” has been passed, and a SATIM run with a Ctax of 500 R₁₀/tCO₂ (345 R₀₅/tCO₂) showed that a CO₂ price is capable of rendering underutilised the same amount of coal-based power generation as available in the SATIM run with a Ctax of 300 R₁₀/tCO₂.

D. Additional detail on scenario results

D.1. Additional detail on Reference Projection outcomes

D.1.1. Detailed composition of income and expenditure by household class for RP

Table D.1 Average per capita revenue, expenditure, investment and net savings per household class in RP

Household class RP avg. per capita income or expenditure	Hh 1		Hh 2		Hh 3		Hh 4		Hh 5		Average	
	R'05 per capita	change vs BY	R'05 per capita	change vs BY	R'05 per capita	change vs BY	R'05 per capita	change vs BY	R'05 per capita	change vs BY	R'05 per capita	change vs BY
High skill net wage	0	id.	0	id.	333	+115%	3 752	+107%	62 364	+86%	14 590	+110%
Medium skill net wage	98	+118%	151	+108%	2 059	+98%	8 090	+91%	27 710	+72%	8 935	+94%
Low skill net wage	377	+109%	1 465	+99%	1 532	+90%	926	+83%	1 184	+65%	1 146	+86%
GOS: mixed inc, imputed rents	111	+78%	395	+69%	976	+65%	3 204	+64%	22 929	+53%	6 192	+71%
Property income	0	-101%	48	+14%	103	+20%	590	+96%	20 618	+9%	4 623	+24%
Soc. security Pension inc. Oth transfers	2 081	+34%	4 140	+47%	5 188	+76%	4 356	+133%	6 232	+39%	4 668	+71%
Before Tax GDI	2 667	+45%	6 200	+59%	10 191	+81%	20 918	+96%	141 038	+59%	40 154	+81%
Minus: Revenue and property tax	28	+76%	96	+94%	223	+121%	2 198	+139%	23 459	+94%	5 778	+121%
Gross Disposable Income (GDI)	2 638	+44%	6 104	+59%	9 968	+81%	18 719	+92%	117 578	+53%	34 376	+75%
Minus: Consumption	2 572	+33%	5 920	+45%	9 669	+65%	17 877	+73%	111 112	+37%	32 628	+57%
Gross savings	66	+533%	183	+2 188%	299	+8 099%	842	+5 255%	6 467	+8 206%	1 748	+7 477%
Minus: Gross Fixed Capital Formation	41	+35%	95	+49%	156	+70%	292	+81%	1 838	+45%	537	+65%
Net savings (self-financing capacity)	25	-225%	88	-257%	143	-263%	550	-477%	4 629	-488%	1 211	-500%

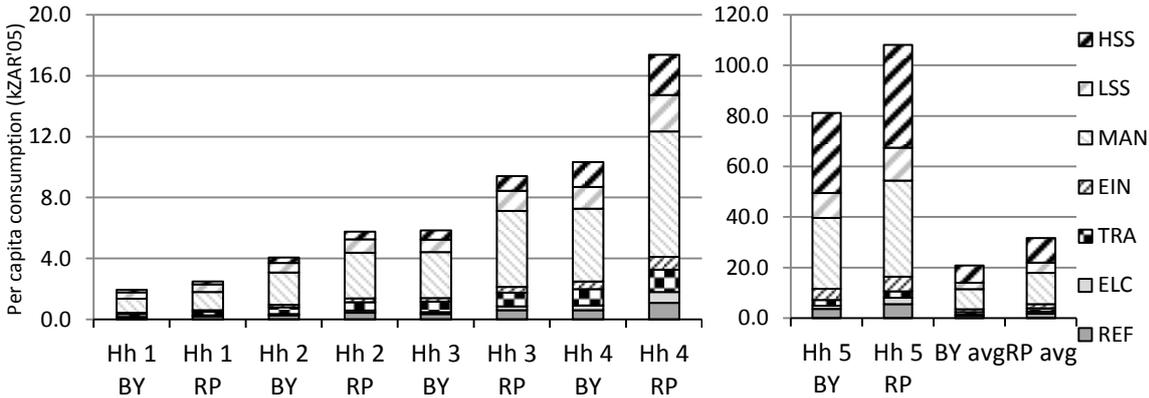
D.1.2. Household consumption's contribution to structural change

Section 4.1 reported how increases in consumption budgets in RP translated into higher spending per product. A small correction is needed to adjust these consumption budgets to the Consumer Price Index (CPI): the real (GDP PI deflated) *per capita* consumption budget of households increased with 57% on average. Taking into account the real CPI (GDP PI deflated) of 102.8% this implies an increase of the volume of consumption of 53% (Table D.2).

There are not much eye-catching differences between the different household classes and between BY and RP in terms of budget shares per item, but still the electricity bill increases strongly for all household classes (Figure D.1: compare for instance Hh4 BY and RP). More remarkably is that behind these budget shares completely different changes in relative prices are hidden. Taking into account the developments in prices, it turns out that the per capita volumes consumed grow at different rates.

When comparing their evolution with the change in per capita Hh consumption budget: If there were no change in relative prices, then all consumption above the assumed price inelastic (minimum) consumption thresholds would increase at the same rate. But, relative prices change: They decrease for MAN and EIN, whereas they increase for HSS and energy products. As a consequence, the volume consumed increases faster for MAN and EIN, though the part of budget spend on them does not change relative to that of other goods.

Figure D.1 Per capita consumption budgets by Hh class, BY & RP (in kZAR₀₅)*



* Comment: Because these figures deal with household consumption, budgets have been deflated using the CPI and not the GDP PI.

The impact of income distribution thus turns out to favour the consumption of HSS goods, which is relatively more preferred by Hh 3 to Hh 5, though on average MAN stays the preferred good whose consumption increases (Table D.2). Still, the impact of income distribution should not be exaggerated, because consumption differences between household classes are only a few percentage points, and at an absolute level Hh 5's consumption makes up 76% of total consumption and therefore dominates overall consumption.

Table D.2 Preference in volume consumed per capita relative to average growth in consumption budget, by Hh class

Household class	All	Hh1	Hh2	Hh3	Hh4	Hh5	
RP vs BY change in per capita cons. budget*	+53%	+29%	+41%	+61%	+68%	+33%	
RP vs BY change in real consumer prices (pCC)	Volume per cap.	Relative change in preference for volume consumed (relative to all Hh's average)					
ELC	+43%	+20%	+5.6%	+1.8%	-5.1%	-5.5%	+1.7%
REF	+93%	+15%	+1.4%	-4.2%	-8.7%	-8.4%	+2.7%
EIN	-2%	+54%	-1.9%	-0.8%	+1.2%	+0.4%	+0.0%
MAN	-8%	+70%	-2.4%	-1.2%	+0.7%	-0.1%	-0.4%
LSS	-5%	+61%	-2.0%	-0.8%	+1.1%	+0.3%	-0.1%
HSS	+3%	+42%	-1.2%	-0.0%	+1.9%	+1.1%	+0.7%
TRA	-3%	+35%	+5.5%	+0.8%	-6.4%	-3.6%	+0.2%

* Comment: Budgets are CPI deflated, and for the comparison BY consumption of COA has been left out of consideration

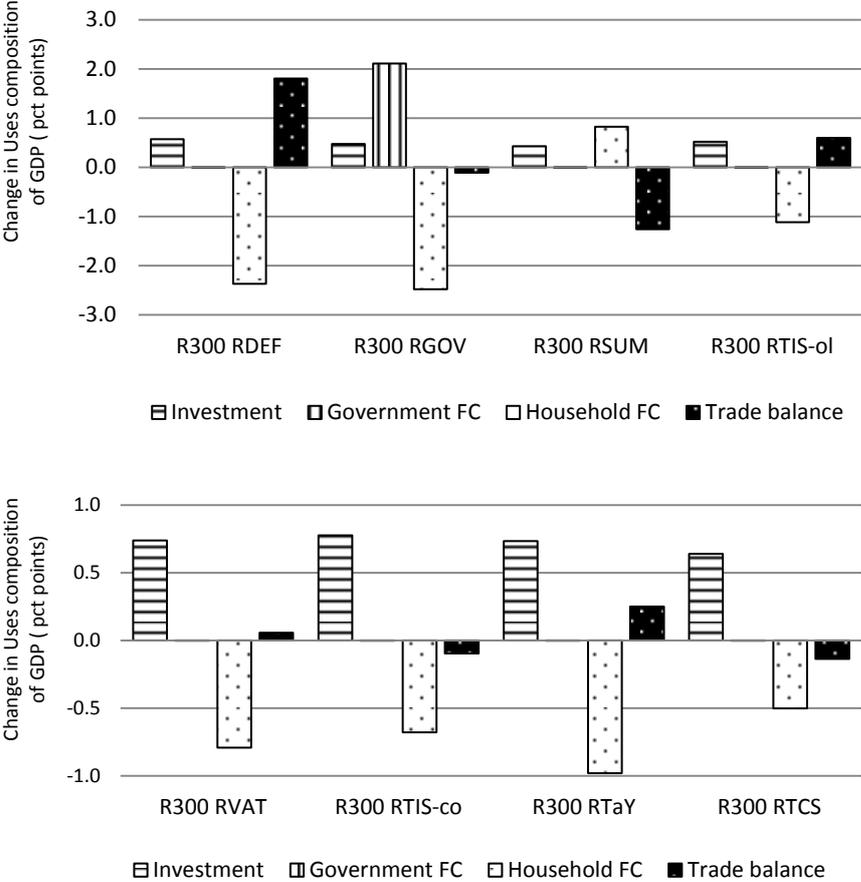
A last remark is that these results are not only a consequence of changes in relative consumer prices, but also of the consumption functions differentiated by household class (see section 3.7). In this sense,

electricity consumption is for the majority fixed to BY values for Hh 1 to Hh 3, whereas consumption of REF and TRA is fixed most strongly for Hh 3 and Hh 5. This might prevent ELC consumption to decrease in face of increasing prices, but it also has the opposite consequence, namely that it does not increase much with increasing consumption budgets. In this way, the finding that Hh 1 and 2 have an above average preference to increase spending on ELC and TRA, is likely an artifact of the model.

D.2. Additional detail Ctax scenarios

D.2.1. Changes in the uses composition of GDP growth in basic Ctax scenarios

Figure D.2 Changes in Uses composition of GDP, selected scenarios relative to RP



D.2.2. Results for very strong productivity growth in skill investment variant B

Table D.3 Results for additional variants of productivity impacts of skills investment variant B, for Ct100 RVAT

Variant	Assumptions (increase of product. growth rate vs RP + resulting 2035 productivity multipliers: BY=1.00)			Assumptions (increase of product. growth rate vs RP + resulting 2035 productivity multipliers: BY=1.00)				
	Change in L prod. growth rate and final LP	Change in K prod. growth rate and final KP	Change in Mat prod growth rate and final prod	GDP	Unempl. (pct pt)	CO ₂ em.	GDP CO ₂ intensity	Class 5/ Class 1 income
Strong Labour augmenting	+15.0% 1.409	id. 1.078	id. 1.078	-0.5%	+3.1pt	-0.63%	-0.12%	-0.03%
Very Strong Labour augmenting	+25.0% 1.452	id. 1.078	id. 1.078	-0.6%	+4.9pt	-0.75%	-0.11%	+0.09%
Strong Capital augm. (eq. to +10% L augm.)	id. 1.348	+36.1% 1.107	id. 1.078	+0.05%	+0.2pt	-0.09%	-0.14%	+0.30%

D.2.3. Additional outcomes energy efficiency scenario

Figures F.1 and F.2 give real cost decreases for setting the producer's price of RTCS scenarios for a R100 and a R300 Ctax when an AEEI is applied, compared to the same scenarios without the assumption of an AEEI to correct future energy efficiency outcomes (the basic Ctax scenarios).

Figure D.3 Real cost decreases for producer's price by component, Ct100 RTCS with AEEI vs w/o AEEI

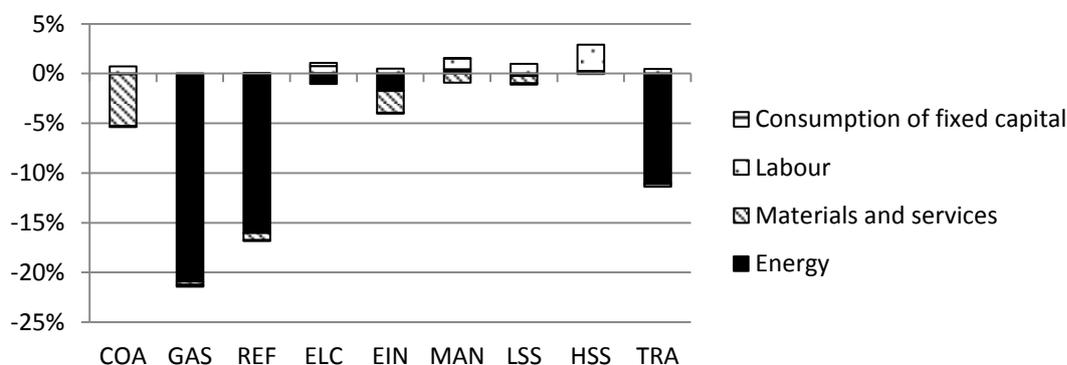
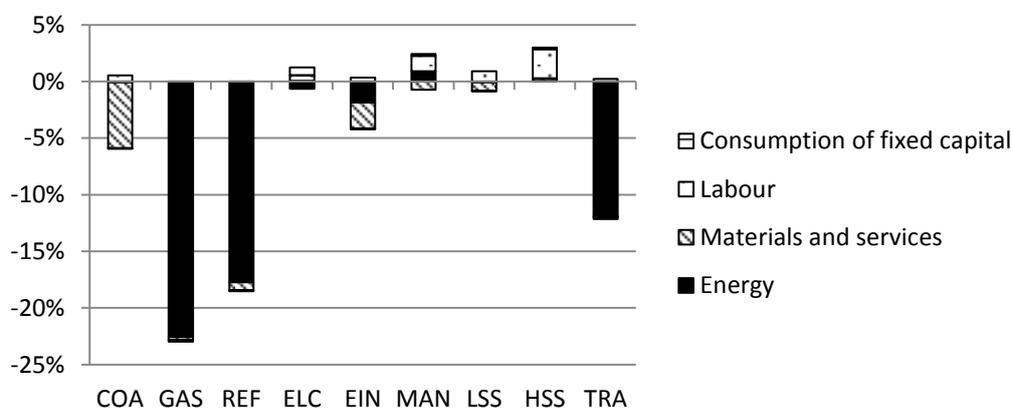


Figure D.4 Real cost decreases for producer's price by component, Ct300 RTCS with AEEI vs w/o AEEI



E. Additional explanations to theory and discussion

E.1. A neoclassical description of a transition from a non-renewable resources to a renewable resources based sustainable economy

Many neoclassical models analysing the question of the double dividend (see section 2.1.4) are static models, in which the difference between clean and polluting capital is only implicitly present in the price-elastic response of resource use under environmental taxation. However, the change over time between the two types of capital is relevant too in a transition. This is discussed, using a conceptual neoclassical model, by Smulders *et al.* (2014). They discuss a model for a transition from a polluting, resources-depleting or “brown” economy, to a renewable resources-based “green” economy could look like.²¹ Their model is a simple neoclassical model in which production (output) Y depends on man-made capital K , resource extraction R , and services from nature (environmental quality) N (Eq.1). Labour is assumed constant and left out of consideration in their model.

$$Y = F(K, R, N) \quad (1)$$

Smulders *et al.* define change of the capital stock as the output not consumed and not used for resource extraction at cost μR , minus depreciation of capital δK , at depreciation rate δ (Eq.2). Change in environmental quality in their model depends on natural regeneration, defined as a function E of stock N , minus resource extraction R (Eq.3):

$$\dot{K} = F(K, R, N) - C - \mu R - \delta K \quad (2)$$

$$\dot{N} = E(N) - R \quad (3)$$

No formal link between N and R is established, but one could imagine that R is positively related to N and at some point ceases to exist if too little N is left. Also, if the model would resemble typical resource extraction cost curves μR should initially be high, decrease and then increase again once the easily winable reserves of a resource start to get depleted.

On the basis of this model, Smulders *et al.* reason that an economy which is strongly based on renewable resources (N) is capable of producing more growth by increasing man-made capital K (one of the inputs to production of output Y), on the condition: $R \leq E(N)$. But, what interests us is the transition from a non-renewable resource (R) based economy to such a renewable resource (N) based economy. Would an economy heavily depend on non-renewable resource extraction R and have R exceed $E(N)$ for a long time, then an increase in man-made capital K could in theory compensate for the unavoidable reduction in resource extraction R due to deterioration (depletion) of nature N . But, in this case, returns to investment are likely going to fall, because continually more investment in K will

²¹ With its enormous dependence on coal as an energy source, and with a large role for coal and mineral resources in South Africa’s exports and above global average per capita CO₂ emissions, South Africa probably mostly resembles the Brown economy case, and should in theory count with a strong or long transition period with, following the model discussed by Smulders *et al.*, below average GDP growth.

be needed to replace a reduction of R while not increasing Y .²² But, not intervening will see Y in the long run suffer from overexploitation of nature and decrease due to a lack of available R .

Shifting away from an R -dependent to an N -dependent economy also creates a short-term reduction in growth, because R has to be reduced and K has to be replaced by N -utilising technology, probably initially without new K being more productive per unit of K (otherwise this new K should have been able to produce Y in a cheaper way, in which case neoclassical economics assumes that it would have existed already). In some specific sectoral cases, e.g. certain fishing industries, there might not even be an alternative technology (and K), available and reducing R and consumption C is the only option to restore a maximum, long-run sustainable output Y .

In Smulders *et al.*'s (2014) discussion, the trade-off between investment and consumption is important in the sense that they foresee that savings (to provide investment) need to be higher during the transition phase to replace brown (R -using) capital by green (N -using) capital, while maintaining the same rate of GDP growth as in a "non-transition" future. By definition household's temporal material welfare decreases during this transition period. Nevertheless, clearly this transition is better made sooner than later, when due to environmental stress and scarce resources the generation of new "green" capital with old "brown" technology will have become expensive. The situation that Smulders *et al.* describe should therefore be considered a motivation to use environmental taxation to improve intertemporal welfare, in case of myopic behaviour by economic agents. Environmental taxation discourages pollution and generates revenue to pay for additional new and "clean" capital, while the generation of new capital is still cheap, assuming that the tax itself will not make the production of new capital too expensive.

Of course, Smulders *et al.*'s treatment is only theoretical and ignores the role of labour. It serves as an illustration to get a feeling of intertemporal dynamics in a neoclassical model with non-renewable and renewable resources. The model they present does not deal with the dynamics of technological change, though they do suggest papers that deal with that question. The unknown nature of technological change during such an "ecological" transition is important for future growth, and Smulders *et al.* therefore also insist that policies to enhance R&D and positive knowledge spillovers from R&D need to be put in place and further researched, to improve future GDP growth. It should also be clear, if one pulls this reasoning a bit further, that the technological change, GDP growth and the likely productivity and household welfare losses that Smulders *et al.* expect for an ecological transition cannot be modelled by assuming that historical growth in TFP continues and a production function which does not take into account resource use.

²² "In this case" here implicitly assumes that there will not be a sudden technological revolution that enhances output over resource use.

E.2. Example of a shock in factor prices in a non-neoclassical equilibrium

This Appendix is an illustration for the mechanisms explained in section 2.1.4 of the main text of this thesis. Its purpose is to show that a multisectoral model that does not make use of the neoclassical production function can still perfectly simulate impacts on GDP and/or welfare of changes in factor pricing relative to factor productivity. Specifically, this concerns that there are no perfect factor markets in which prices reflect positive but diminishing marginal productivity, and neither having the assumption of intertemporal welfare and profit maximisation. To this end this Appendix presents a numerical illustration which is simple and at the same time insightful in how factor pricing affects output and GDP in a non-neoclassical macro-economic model with differentiation in product preferences.

For this example I present an imaginary, closed (island) economy with 3 sectors: “Bread”, “Eggs” and “Coconuts”. Three families of for example five persons, called households (Hh) 1 to 3, have each specialised in running one of these sectors. These households provide their labour 5 days a week, and own and maintain other inputs like grain fields, a mill, an oven, chicken, or coconut trees. For simplicity I assume that the only factor of production is labour, and that all income consists of wage.

Now let’s assume that at a certain point in time, this economy has reached maximal output capacity. To get a feeling for this economy, I first present a situation in which output was divided perfectly equal between all 3 households. This situation is represented for one week in Table E.1. Consumption preferences (the consumption basket of goods) of all households are assumed to be the same. At completely equal distribution it consists of 10 breads, 50 eggs and 20 coconuts, valued €60 each here. I define household welfare as consumption above a minimum need, which I assume to be bread; More precisely: as the total quantity of eggs and coconuts combined.

Table E.1 Production and consumption for one week in an imaginary closed 3-sector (island) economy: Original situation

Sector	Bread / Hh1	Eggs / Hh2	Coconuts / Hh3	Total economy
Output volume (Y)	30	150	60	100 (index)
Price	€ 2.-	€ 0.40	€ 1.-	€ 1.80 (PI = 1.0)
Output value (VA)	€ 60	€ 60	€ 60	€ 180
Person-days worked	25	25	25	75
Daily (& real) wage *	€ 2.40 (€ 2.40);	€ 2.40 (€ 2.40);	€ 2.40 (€ 2.40);	€ 2.40 (€ 2.40)
% total weekly output	1.33%	1.33%	1.33%	1.33%
Final consumption by household : Volumes (and values)				
Bread (value)	10 (€ 20)	10 (€ 20)	10 (€ 20)	30 (€ 60)
Eggs (value)	50 (€ 20)	50 (€ 20)	50 (€ 20)	150 (€ 60)
Coconuts (value)	20 (€ 20)	20 (€ 20)	20 (€ 20)	60 (€ 60)
Welfare ** (pp-day)	70 (2.80)	70 (2.80)	70 (2.80)	210 (2.80)

* The wage rate is a person-day wage, divided by Fisherian GDP price index (PI) gives real wage. It is also expressed as percentage of national weekly output; ** Household welfare is defined as consumption beyond minimum needs and equals the quantity of eggs and coconuts. In between brackets “pp-day” gives welfare per person-day worked.

Now, let’s assume that at some point in time – for whatever reason, maybe a conflict between Hh1 and

Hh2 on the one side and Hh3 on the other – Hh1 (Bread) and Hh2 (Eggs) step away from the previously presented rigid equal income distribution rule, and try to increase their welfare while lacking changes in productivity. I assume a simplistic exogenous change in the prices of Bread and Eggs, which each increase nominally by 25%.

The rigid and equal composition of consumption of the original situation in Table E.1 is replaced by a situation in which each household is still allowed to fulfil its minimum need for consuming bread, and equal to the amount originally consumed (bread consumption is therefore completely inelastic to price or income). I furthermore assume that Eggs are the most desired product, while Coconuts are only a nice addition to the menu, of less importance than bread and eggs.²³ I assume that Hh1 and Hh2 have agreed to maximise their egg consumption but that each still consumes equally much. This is represented by the unknown equilibrium of Table E.2: The question is how the Household 3 and Coconuts production will respond.

Table E.2 Assumed changes in the imaginary island economy: A nominal price increase of Bread and Eggs

Sector	Bread / Hh1	Eggs / Hh2	Coconuts / Hh3	Total economy
Output volume (Y)	30	150	??	??
Price	€ 2.50	€ 0.50	€ ??	€ ?? (PI = ??)
Output value (VA)	€ 75	€ 75	€ ??	€ 150 + ??
Person-days worked	25	25	??	??
Daily (& real) wage	€ 3.-	€ 3.-	€ ??	?? (real = ??)
Final consumption by household : Volumes (and values)				
Bread (value)	10 (€ 25)	10 (€ 25)	10 (€ 25)	30 (€ 75)
Eggs (value)	X (€ ??)	X (€ ??)	150 – 2X (€ ??)	150 (€ 75)
Coconuts (value)	?? (€ ??)	?? (€ ??)	?? (€ ??)	?? (€ ??)
Welfare*	<i>Maximised</i>	<i>Maximised</i>	??	??

* Household welfare is defined as consumption beyond minimum needs, and equals the quantity of eggs and coconuts.

A few options for the response of the Coconuts sector can be imagined: First of all, the Coconut sector could completely accept the conditions imposed by Bread and Eggs, keeping its production at full output capacity, and accepting to consume whatever proportion of Eggs is left. However, such a response by Hh3 might not be very representative for normal economic behaviour –i.e., that people would provide the same output against less remuneration. I therefore add the assumption that what counts for the provision of labour by a household, and thus for output, is the volume of eggs consumed by a household: In other words, output is proportional to the amount of Eggs consumed.²⁴ However, I

²³ Eggs can be considered to have the highest (and positive) *upward* income elasticity, compared to the original situation, and coconuts the highest (and positive) *downward* income elasticity.

²⁴ Lacking sufficient real income, household members might be less motivated to work. E.g., a part of the family goes on strike out of protest to the price increases of Eggs and Bread, or they are too malnourished or unmotivated to be productive at all. Another interpretation of this assumption is that final consumption of Eggs in the example resembles the role of fuels in intermediate consumption in real world economies.

had assumed that the economy is at maximal output, and that output (of Bread and Eggs) cannot increase beyond the original output level presented in Table E.1.

The new consumption preferences of Hh2 and Hh3 leave Hh3 with less Eggs to consume (in exchange for their output of Coconuts). As assumed, the reduction of the amount of eggs consumed by Hh3 will lead to a proportional reduction in output by the Coconut sector. Were there no change in the nominal wage rate of Hh3 (and therefore in the nominal price of coconuts, which remains at €1.-) then the new consumption preferences of Hh2 and Hh3 would lead to a disequilibrium: E.g. suppose Hh1 and Hh2 consume 60 eggs each (valued nominally at €30). In that case Hh1 and Hh2 would have more budget to spend on Coconuts (€75 (revenue) - €25 (bread) - €30 (eggs) = €20; or 20 coconuts) than there would be coconuts available (only 60% of original output or 36 coconuts, valued €36). If Hh1 and Hh2 would then decide to increase their consumption of Eggs even further, output of Coconuts would fall even further, etcetera. This would thus lead to a vicious cycle that eventually would lead to the disappearance of the Coconut sector and Hh3. This would be a socially unacceptable outcome, and therefore a model solution to be avoided. I therefore consider two alternative responses:

1. The Coconut sector adjusts its wage rate and thus the price of coconuts in such a way that it's welfare is maximal. For this purpose, I model consumption behaviour for households 1 and 2 regarding the choice between Eggs and Coconuts as a welfare maximisation problem. Note that this is not 100% a welfare maximisation problem: I stick to the assumption that both these two households consume the same amount of Eggs, and that their nominal wage rates and prices have been defined exogenously, as described before.

This problem can be solved with a simple spreadsheet solver: In discrete steps I test different wage rates for Hh3 to approximate an equilibrium solution with maximal welfare for Hh3. This solution is presented in Table E.3: The price of coconuts is found to be €1.1 nominally (€0.91 when divided by the GDP Price Index, PI), which means that Hh1 and Hh2 consume 59.75 eggs, and 18.3 coconuts. Hh1 and Hh2 welfare increases from 70 originally with rigid equal consumption to 78 now. Hh3's welfare reduces from 70 to 30.5;

2. Now let's assume that the response by the Coconut sector is to increase its wage rate, and thus its price, similar to the other two sectors. In other words, there is one average wage for the entire economy. Hh1 and Hh2 still maximise welfare and change their consumption of Eggs and Coconuts as specified. Solving the model with a rigid real wage leads to a higher price of Coconuts compared to the situation with flexible Hh3 wages presented in Table E.4: Hh1 and Hh2 now consume more Eggs and less Coconuts. In the new distribution Hh3 is left with only 25 eggs to consume, 50% less than in the original situation (see Table E.5), and Coconut output is 50% lower too: at only 30, entirely sold to Hh1 and Hh2 (see Table E.4). Welfare of Hh1 and Hh2 is only slightly lower compared to the situation with flexible wages in the Coconut sector, while welfare of Hh3 is significantly lower (25 versus 30.5 in Table E.4).

Table E.3 The imaginary island economy with maximised welfare for Hh1 and 2 and flexible wage in Coconuts sector

Sector	Bread / Hh1	Eggs / Hh2	Coconuts / Hh3	Total economy
Output volume (Y)	30	150	36.6	87.7
Price	€ 2.50	€ 0.50	€ 1.1	€ 2.17 (PI = 1.21)
Output value (VA)	€ 75	€ 75	€ 40.3	€ 190.3
Person-days worked	25	25	15.3	65.4
Daily (& real) wage;	€ 3.- (€ 2.48);	€ 3.- (€ 2.48);	€ 2.64 (€ 2.19);	€ 2.92 (€ 2.41);
% total weekly output	1.57%	1.57%	1.39%	1.53%
Final consumption by households : Volumes (and values)				
Bread (value)	10 (€ 25)	10 (€ 25)	10 (€ 25)	30 (€ 75)
Eggs (value)	59.75 (€ 29.9)	59.75 (€ 29.9)	30.5 (€ 15.2)	150 (€ 75)
Coconuts (value)	18.3 (€ 20.1)	18.3 (€ 20.1)	0 (€ 0)	36.6 (€ 40.3)
Welfare (pp-day)	78 (3.12)	78 (3.12)	30.5 (1.99)	186.5 (2.85)

Table E.4 The imaginary island economy with maximised welfare for Hh1 and Hh2 for the case of rigid real wages

Sector	Bread / Hh1	Eggs / Hh2	Coconuts / Hh3	Total economy
Output volume (Y)	30	150	30	83.3
Price	€ 2.50	€ 0.50	€ 1.25	€ 2.25 (PI = 1.25)
Output value (VA)	€ 75	€ 75	€ 37.5	€ 187.5
Person-days worked	25	25	12.5	62.5
Daily (& real) wage;	€ 3.- (€ 2.40);	€ 3.- (€ 2.40);	€ 3.- (€ 2.40);	€ 3.- (€ 2.40);
% total weekly output	1.60%	1.60%	1.60%	1.60%
Final consumption by households :				
Bread (value)	10 (€ 25)	10 (€ 25)	10 (€ 25)	30 (€ 75)
Eggs (value)	62.5 (€ 31.25)	62.5 (€ 31.25)	25 (€ 12.5)	150 (€ 75)
Coconuts (value)	15 (€ 18.75)	15 (€ 18.75)	0 (€ 0)	30 (€ 37.5)
Welfare (pp-day)	77.5 (3.10)	77.5 (3.10)	25 (2.00)	180 (2.88)

Actually, in the second situation (Table E.4) real prices and wages did not change compare to the original situation of Table E.1. The situation in Table E.4 therefore only shows what happens when the constraints on consumption of Hh1 and Hh2 are released, even if there would not have been exogenous nominal price changes. Note however that the changes in consumer preferences cause daily wages to correspond to a higher proportion of weekly output in Table E.4 compared to Table E.1, even if they are constant in real terms. Also compared to the situation with flexible, Hh3 welfare maximising Coconut sector-wages in Table E.3, the rigid real wage-case leads to a higher wage in terms of weekly output (1.60% in Table E.3 vs 1.53% before). The difference in terms of daily real wage, as measured through the GDP PI, is however small (€2.40 vs €2.41). The difference is that in the case with rigid wages, a sector which produces little output value requests high pay in terms of output value, whereas as soon as it releases this demand, output becomes cheaper, and the purchasing power of average wage increases. This does not lead to more welfare per day worked for Hh3 (in both situations 2.0), but it does increase demand for Coconuts and thus total welfare for Hh3.

The point to be made with the example here is that a multisectoral model is capable of reproducing impacts on GDP from exogenous shocks and cost increases (here through changes in consumption preferences, and by the introduction of wage rigidity) without the assumptions of perfect factor markets and profit maximisation in a closed economy on the simple basis of having an economic equilibrium model with multiple sectors and heterogenous consumer preferences.²⁵

E.3. Intermediate inputs and GDP growth in IMACLIM-ZA: an illustration

One aspect which is logic from an engineering perspective on productivity growth is increasing efficiency of outputs over intermediate inputs. There is empirical evidence for the importance of efficiency of energy use and other material inputs in accounting for GDP growth (Baptist & Hepburn, 2013; De Bruyn, 2013). In a neoclassical aggregate production function, intermediate inputs drop out of the growth equation. Aggregate production functions could add intermediate inputs productivity to the aggregate neoclassical production function, as Baptist and Hepburn (2013) propose. But, as explained in Chapter 2, in a multi-sectoral model with dual accounting of quantities and values of economic flows, one can work – in a production engineering style – with gains in output productivity of one sector over intermediate inputs, which effectively means: over factor inputs of other sectors. If this is the case, then one has to speak of productivity (efficiency) gains in intermediate inputs.

An example below shows how for a 2-sector model intermediate input productivity gains differ from single sector growth, and how they are an essential part of the explanation for GDP growth. This example also illustrates that beyond the physical productivity gains of the production factors labour and capital (whose income is value added), it is a decrease in “real” costs of total supply thanks to intermediate input efficiency gains that causes “real” income gains.

The latter finding also explains that if we add the aspect of international trade, one can observe that an increase in import prices relative to domestic prices increases the aggregate real costs of total supply, with GDP growth below average factor productivity gains (all other things equal). In theory, something like this might have happened during the oil crises of 1973 and 1979. Possible objections that sectoral boundaries are arbitrary and thus not useful for aggregate growth accounting are besides the point: The only issue is the right allocation of aggregate factor productivity gains to intra-sectoral factor productivity gains and inter-sectoral intermediate input efficiency gains.

When working with a multisectoral CGE model with dual accounting of quantities and values, like in IMACLIM-ZA, the relevance of intermediate input intensity for growth-accounting can be easily shown through the following simple quantitative example of a 2 sector model:

Consider a two-sector model of country A, which has a closed economy consisting of an Agriculture sector (A) and a Restaurants sector (R). The Agriculture sector supplies to Restaurants and to Final

²⁵ In theory these heterogenous consumption preferences can influence macro-economic outcomes in a multisectoral model through intermediate consumption in the same way as shown here for final consumption.

Consumption of one aggregate household (FC), while the Restaurants sector supplies its services to the Agriculture sector and also to FC. The total volume of IC and FC in this Base Year is indexed at the arbitrary value of 1.00. Assume that its economic I-O table, volume indexes for quantities of output and consumption by sector, and thus its matrix a matrix for prices and of intensities of inputs over outputs are given by Table E.5.

Table E.5 Base Year statistics for imaginary Agriculture - Restaurants economy

Values, 0	A	R	IC total	FC	Total Uses
A	0.0	5.0	5.0	5.0	10.0
R	2.0	0.0	2.0	8.0	10.0
IC total	2.0	5.0	7.0		
L	8.0	5.0		13.0	
Y	10.0	10.0			20.0

Volu- mes, 0	A	R	IC total	FC	Total Uses
A	0.0	5.0	5.0	5.0	10.0
R	2.0	0.0	2.0	8.0	10.0
L	8.0	2.0		10.0	
Q	10.0	10.0			20.0

Prices, 0	A	R	IC total	FC	Total Uses
pA		1.00	1.00	1.00	1.00
pR	1.00		1.00	1.00	1.00
pL	1.00	2.50		1.30	
pY	1.00	1.00			1.00

Inten- sity, 0	A	R	IC total	FC	Total Uses
IC_A/Q		0.50			
IC_R/Q	0.20				
L/Q	0.80	0.20	L/Q avg 0.57	L/ GDP 0.77	L/ supply 0.50
Q/Q	1.00	1.00	Supply/GDP:	1.54	

Suppose now that physical productivity gains are introduced, because some people had illuminous ideas about how to increase productivity: In the Agriculture sector some people had good ideas about how to increase labour productivity by 25%. Thanks to the increase in labour productivity, the amount of Restauration service per physical unit of output can be reduced, but maybe a bit less than the productivity gain, e.g. with 15%, because the now more productive workers like to enjoy better lunch brakes. In the Restaurants sector people had good ideas about how to reduce food waste by 10%, which reduces the need for Agricultural inputs equivalently – but there are no improvements of labour productivity in terms of output (e.g. meals served) over workers.

A model can be constructed to predict what will happen economically (not culinary). Firstly, there are no savings and investment which implies that all output is allways consumed, and we assume no valued capital, making labour the only factor of production. Furthermore, prices are assumed to be same for all users. Implying for each good (and sector) a balance in values and in quantities. For consumed product $i = A$ or R , and production of sector $j = A$ or R , these balances are (Eq. 6-9):

$$Q_i = \sum_{j=A,R} IC_{ij} + FC_i \quad (4)$$

$$Y_i = Q_i * p_i = \sum_{j=A,R} IC_{ij} * p_i + FC_i * p_i \quad (5)$$

$$Y_j = Q_j * p_j = \sum_{i=A,R} IC_{ij} * p_i + L_j * p_{L,j} \quad (6)$$

$$\sum_{j=A,R} L_j * p_{L,j} = \sum_{i=A,R} FC_i * p_i \quad (7)$$

, with:

Q_i quantity of products of sector i (is A or R) being used (consumed);

Q_j quantity of products produced by sector j (is A or R);

(for $i = j$, $Q_i = Q_j$, and the same is true for Y and p)

IC_{ij} quantity of products i consumed in intermediary consumption by sector j ;

FC_i quantity of products i consumed in final consumption by the aggregate household;

Y_i value of products of sector i which are consumed (= total Uses);

Y_j value of products produced by sector j (= total Resources *or* Supply);

p_i, p_j prices of products consumed or produced;

L_j amount of labour (workers or time) used in the production of sector j ;

$p_{L,j}$ the price of labour (wage) in sector j ;

Equation 4 says that all wage earned is used for Final Consumption. Equation 3 says that all costs are recovered by the price of products. Equation 2 defines the total value of consumption Y_i , and implies that all production costs are recovered by sales, while Eq. 1 implies that all quantities produced are consumed (for $i = j$).

Following the assumption that all production is consumed for its production value (*meaning: no mismatch = no savings \neq investment*), there must be full employment. To model the change between the base year 0 , and projection year t after productivity changes, we assume that the labour force per sector remains constant (labour specialisation), and add the following rules (Eq 10-13):

$$L_{j,t} = \overline{L_{j,0}} \quad (8)$$

$$Q_{j,t} = L_{j,t} * \frac{\overline{Q_{j,0}}}{L_{j,0}} * LPF_j = \overline{Q_{j,0}} * LPF_j \quad (9)$$

$$p_{L,j,t} = \overline{p_{L,j,0}} * LPF_j \quad (10)$$

$$IC_{ij,t} = \frac{\overline{IC_{ij,0}}}{\overline{Q_{j,0}}} * IPF_{ij} * Q_{j,t} \quad (11)$$

, with:

$\overline{L_{j,0}}, L_{j,t}$ respectively employed labour force of sector j in base year (0) and projection year t ;

LPF_j, IPF_{ij} respectively sector j 's physical labour output productivity factor (multiplier), and the intermediate input productivity factor (multiplier) of output j over input i .

To solve this model for projection year t the only requirement is to correctly set the price $p_{i,t}$ of one of the two sectors in such a way that all constraints are respected (the price of the other sector will automatically follow from the former).²⁶ In our case we decide to solve for the price of the Restaurants sector, p_R .

The solver finds an average decrease in real prices. To present results more realistically, we choose a Fischer GDP price index as the numéraire and deflate all values by its value. This gives the I-O tables in values and quantities for projection year t , as well as the matrices for prices and physical intensities, shown in Table E.6.

The projection year's GDP (15.9) is 22.3% higher than in the base year (BY): 13.0.²⁷ Real income of labour increases beyond average labour productivity, which, weighted by BY share of GDP is only +15%, and therefore insufficient to explain total GDP growth. To explain total GDP growth, intermediary inputs, to which we attributed productivity growth too, enter the scene.

Table E.6 Projection year statistics for imaginary Agriculture - Restaurants economy

<i>Values, t</i>	A	R	IC total	FC	Total Uses
A	0.0	4.6	4.6	8.1	12.7
R	2.1	0.0	2.1	7.8	9.9
IC total	2.1	4.6	6.7		
L	10.6	5.3		15.9	
Y	12.7	9.9			22.6

<i>Volumes, t</i>	A	R	IC total	FC	Total Uses
A	0.0	4.5	4.5	8.0	12.5
R	2.1	0.0	2.1	7.9	10.0
L	8.0	2.0		10.0	
Q	12.5	10.0			22.6

<i>Prices, t</i>	A	R	IC total	FC	Total Uses
pA		1.02	1.02	1.02	1.02
pR	0.99		0.99	0.99	0.99
pL	2.50	0.00		1.59	
pY	1.02	0.99			1.00

<i>Intensity, t</i>	A	R	IC total	FC	Total Uses
IC_A/Q		0.45			
IC_R/Q	0.17				
L/Q	0.64	0.20	L/Q avg 0.47	L/GDP 0.63	L/supply 0.44
Q/Q	1.00	1.00	Supply/GDP:		1.42

It can be shown that the value of total income increases relative to the non-income component of total supply: In the Base Year, total supply was valued at 20, whereas total income (GDP in our closed economy) was valued at 13, meaning that supply equals 1.54 times GDP. In the projection year total supply is valued at 22.57, or 1.42 times the new GDP (15.9). In other words, the new costs of total supply relative to GDP are $(1.42 / 1.54) = 0.923$ times BY costs of supply relative to BY GDP. This decrease of “real costs of total supply” is equal to an increase in the real value of income. Its inverse can be considered to multiply GDP growth, in our example by $(1 / 0.923) = 1.084$ times (Table E.7).

To finally arrive at the GDP growth obtained in our model one only needs to calculate the growth of

²⁶ This can for instance be done with the discrete solver in MS Excel.

²⁷ In a closed economy model without a government sector nor investment, on the “Uses” side of the economy, GDP equals the real value (GDP price deflated) of Final Consumption (FC).

supply relative to the (constant) labour factor input: To start this calculation we index total supply in BY at the value 1.00. Next, we calculate year t 's volume of supply at the value of real (deflated) GDP prices. We thus multiply our index by the real value growth of total supply: $(22.57 / 20.0 =) 1.129$.

Table E.7 Productivity changes between BY and year t for the Agriculture-Restaurants economy

<i>0-t</i> <i>prod-</i> <i>uctivity</i>	A	R	IC total	FC	Total Uses
Q/IC_A		1.111			
Q/IC_R	1.176				
			<i>Q/L</i> <i>avg</i>	<i>GDP /L</i>	<i>Supply</i> <i>/L</i>
Q/L	1.250	1.000	1.154	1.223	1.129
			GDP/ Supply:		1.084

Multiplying the multiplier for real supply by the multiplier for real income over costs of supply gives the multiplier for growth of real income: $1.129 * 1.084 = 1.223$, in other words: GDP growth.

Of course, the same value equals GDP deflated factor income²⁸ (value added), but this notion does not offer any insight into why GDP growth is higher than growth in (physical) factor productivity. Calculating the decrease of real (unit) costs of supply does offer such an explanation, because it also accounts for productivity (or efficiency) improvement for intermediary inputs. Furthermore, in an open economy this decomposition approach allows to incorporate changes in the real costs caused by changing real import prices, and – by calculating the increase of supply over domestic output – changes in the trade-off between imports and domestic production.

An objection which could be made is that the values for intermediary inputs depends on the chosen sectoral disaggregation and therefore cannot play a role in growth accounting. But, it might be better to consider intermediary input productivity (or efficiency) gains as productivity gains of one sector's output over the factors of production of other sectors', whose inputs it uses. In our example: Suppose Agriculture and Restaurants would have been part of not only the same sector but even the same company, and that intermediary inputs are therefore not accounted for in the I-O table. In this case one has a a single-sector closed economy without IC. If we assume that aggregate economic numbers (wages and final consumption) increase in the same way as in our 2-sector model: Instead of having intermediary input productivity gains, one can assume that the restauration and agriculture divisions within the same company require less of each others labour. Labour productivity gains will now equal 22.3%. Changing the sectoral disaggregation will therefore change physical factor and input intensities of sectors, but it will not change overall GDP growth, as long as sectoral classifications are held constant.

The lesson which can be drawn from the A-R economy example is that a change in real costs of total

²⁸ GDP deflated factor income in our closed economy example equals the weighted average increase in (physical) labour (output) productivity deflated by the GDP price index.

supply matters for GDP growth. It is now also clear that a discussion of drivers of growth should discuss intermediate input efficiency of production, import prices²⁹ and relevant trade-offs which determine choices of substitution in intermediary consumption, final consumption, and trade.

E.4. Labour market models in other IMACLIM models

Following the analysis by Guivarch *et al.* (2011), the IMACLIM-R *Monde* model (Crassous, Hourcade, & Sassi, 2006; Waisman, Guivarch, Grazi, & Hourcade, 2012) and IMACLIM-S/P models (Combet, 2013; Ghersi, 2015; Lefevre, 2016), of which IMACLIM South Africa is an example, generally use a wage curve to model wage setting in the labour market.

There are other studies with IMACLIM modelling which focus on the labour market besides Guivarch *et al.* (2011). For instance, Darmendrail (2008) explores the possibility to use different labour market models as discussed in Pissarides (1998) in an early version of the IMACLIM-S/P France model. She found that, next to the already used *wage curve* labour market model in IMACLIM-S France, only the “Competitive” and the “Search” model could be tested. The “Union bargaining” model only makes sense in case a model is multi-sector, whereas calibration data lacked to apply the Efficiency wage model. With these different labour market models, Darmendrail tests the impacts of a carbon tax combined with recycling of tax revenues through lowering social contributions (charges) on wages, or through a lump-sum transfer to households. In the end, her analysis shows that the different labour market models do not lead to fundamental differences in the results for main macro-economic indicators: GDP, unemployment, wage, and CO₂ emissions. The only difference is the extent to which these indicators are affected. With the competitive model (expectedly) salaries decrease more than in the other two models, but with a lower decrease in unemployment, and GDP growth remaining higher than for the other two models. Darmendrail (2008) remarks that having a multiple level skill model with inter-sector skill mobility would be an interesting aspect of labour market rigidities to be captured for a macro-economic analysis of the interaction between energy transition and employment.

Using a more recent version of IMACLIM-S France – with a Blanchflower and Oswald type wage curve – Combet (2013) analyses the interaction between carbon taxation, economic growth, the labour market and income distribution. He finds positive impacts for France’s economic development from recycling carbon tax revenues into reducing social contributions (charges) on wages. An important feature of his model is that it has 20 household income/expenditure classes, with different levels of household class sensitivity, and adaptability, to the price of energy. His model, however does not differentiate for different levels of skills, one of the main perceived problems for the South African labour market.

Differentiation by skill with the use of a wage curve is used by Wills and Lefevre (2012) and Lefevre

²⁹ This model suggests that GDP growth will be lower if import prices suddenly increase – as for instance happened during the oil crises.

(2016) who distinguish three levels of skill of labour, each representing a unique factor of production, thus leading to a segmented (non-competing groups) labour market. For them, labour supply by level of skill, and distribution of wages by level of skill over six household classes is determined exogenously, whereas labour demand by level of skill is determined in a CES KLEM production function, with the three skill levels at an equal level, and their aggregate at an equal level with capital.

The conclusion is that these different IMACLIM models already capture rigidities in the labour market through a wage curve, as proposed by Blanchflower and Oswald (1995), but that there has not yet been very elaborate model development on the role of levels of skill of labour.

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Titre : Croissance, chômage et compétences en Afrique du Sud : Analyse de plusieurs plans de recyclage des revenus d'une taxe carbone

Mots clés : croissance verte; Afrique du Sud; prospective de long terme; énergie; marché du travail; transformation structurelle

Résumé : Cette thèse fournit une illustration numérique de la façon dont une taxe carbone pourrait affecter le PIB, l'emploi, les émissions de CO₂ et les inégalités socio-économiques en Afrique du Sud. Elle utilise un modèle d'équilibre général calculable « hybride » en économie ouverte par projection en un seul pas de temps de 2005 à 2035. Le modèle représente des économies de second rang, notamment des rigidités sur le marché du travail liées aux niveaux de qualification et dans la production électrique. Sept scénarios basés sur des modalités différentes de recyclage de la taxe carbone sont analysés, plus une option d'investir une partie des revenus de la taxe dans l'amélioration des qualifications de la force de travail.

L'analyse montre que sous hypothèse standard de changement technique, une taxe carbone de 100 ZAR par tonne de CO₂ environ a peu d'impact négatif sur le PIB et l'emploi lorsqu'elle est associée à un mode de recyclage des revenus approprié : subventionner le facteur travail et réduire les taxes sur les profits des entreprises pourrait conduire aux meilleurs résultats macroéconomiques, mais ne réduit pas les inégalités. Des mesures supplémentaires sont nécessaires pour réduire la « pauvreté énergétique ». Pour atteindre le NDC d'Afrique du Sud au titre de l'Accord de Paris, un taux de taxe d'environ 300 ZAR ou 55\$ par tonne de CO₂ serait nécessaire. Toutefois, un tel taux pourrait avoir un impact significatif sur la croissance du PIB. En même temps, sans changement de la tendance de croissance de la productivité du travail, ce PIB plus faible conduirait à un chômage plus élevé que dans le cas de référence.

Une politique d'investissement de 7.5 milliards de ZAR de revenus carbone dans les qualifications de la main d'œuvre, avec l'objectif d'augmenter l'accès à la formation de haut niveau et de réduire le manque de salariés très qualifiés, pourrait avoir un effet très positif sur la croissance du PIB. Néanmoins, de meilleures données de calibration sont encore nécessaires.

Les conclusions de cette thèse appellent par ailleurs à un examen approfondi du type de changement technologique qui pourrait se produire en Afrique du Sud. Le progrès technologique, les préférences des consommateurs et le contexte international, limitent la capacité de l'économie à se restructurer et se décarboner et incidemment à réduire les impacts négatifs de la taxe carbone sur la croissance du PIB. Une véritable évaluation du changement technologique futur serait pertinente pour tous les secteurs et facteurs de production. Nous donnons des exemples qui montrent que l'efficacité énergétique et matières jouent un rôle important pour la croissance du PIB sous contrainte carbone, car elles déterminent la flexibilité de l'économie à réduire la consommation d'énergie et à la substituer au facteur travail par exemple. Ces conclusions sont a priori valables pour l'Afrique du Sud mais également pour le reste du monde. Ces résultats impliquent aussi que la politique climatique internationale doit traiter la question des transferts de technologie et celles des potentiels différents de décarbonation sérieuse à l'échelle nationale.

Title : Economic growth, unemployment and skills in South Africa: Analysis of different recycling schemes of carbon tax revenue

Keywords : green growth; South Africa; long-term forecasting; energy; labour market; structural change

Abstract : This PhD thesis gives a numerical illustration of how a carbon tax affects South African GDP, employment, CO₂ emissions and socio-economic inequality. It uses a "hybrid" computable general equilibrium model of an open economy in a one-step projection from 2005 to 2035. It models second-best economies, notably skill-related rigidities in the labour market and in production of electricity. Seven scenarios for recycling of carbon tax revenue are analysed, plus an option to invest a part of tax revenue in improvement of skills of labour.

The analysis shows that under conventional assumptions about technological change, a carbon tax of around 100 ZAR₂₀₀₅ (18 USD₂₀₁₃) per tonne of CO₂ will have little negative consequences for GDP and employment, when combined with the right type of tax revenue recycling: Labour subsidies and company profit tax reduction likely lead to the best macro-economic outcomes, though do not reduce inequality. Additional measures are needed to reduce "energy poverty". To achieve South Africa's NDC of the Paris Agreement, a carbon tax rate of around 300 ZAR₂₀₀₅ or 55 USD₂₀₁₃ per tonne of CO₂ is necessary. However, this could have serious impacts on GDP growth. Also, without a change in the trend of increasing labour productivity, such lower GDP will lead to higher unemployment than in the reference case.

An investment in skills of 7.5 billion ZAR₂₀₀₅ of annual Ctax revenue, with the objective of increasing access to high quality education and reducing the high skill labour shortage, is found to have a positive impact on GDP growth. However better calibration data is required.

The findings of this PhD thesis furthermore call for a thorough examination of what type of technological change could be expected for South Africa. Technological progress, consumer preferences and international circumstances limit the economy's capacity to restructure and decarbonise and therefore to reduce negative consequences of carbon taxation for GDP growth. Proper assessment of future technological change is relevant for all sectors and inputs. Examples are given that show that energy and materials efficiency have an important role in future GDP growth under carbon constraints, because they determine the economy's flexibility to reduce energy consumption and to substitute it, e.g. by labour. This finding normally holds not only for South Africa, but also for the rest of the world. These results also imply that international climate policy must coordinate technology transfer and that it has to take different potentials of nations to decarbonise into account.

