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Some aspects of the robustness of climate change mitigation policies

Julie Rozenberg

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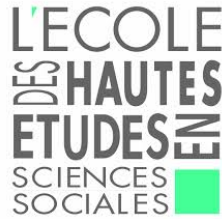
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ÉLÉMENTS SUR LA ROBUSTESSE DES POLITIQUES CLIMATIQUES

SOME ASPECTS OF THE ROBUSTNESS OF CLIMATE CHANGE
MITIGATION POLICIES

THÈSE PRÉSENTÉE PAR
JULIE ROZENBERG

POUR OBTENIR LE GRADE DE DOCTEUR
DE L'ÉCOLE DES HAUTES ÉTUDES EN SCIENCES SOCIALES

DISCIPLINE : ÉCONOMIE

Soutenue le 18 Juin 2014 devant un jury composé de

Valentina Bosetti:

Professeur d'économie à l'Université Bocconi, Milan

rapporteur

Lionel Ragot:

Professeur d'économie à l'université Paris Ouest Nanterre La Défense

rapporteur

Marianne Fay:

Economiste en chef du groupe Changement climatique, Banque Mondiale

examineur

Jan Corfee-Morlot:

Directrice du programme climat, environnement et développement à l'OCDE

examineur

Keywan Riahi:

Directeur de recherche à l'IIASA

examineur

Jean-Charles Hourcade:

Directeur de recherche CNRS

directeur de thèse

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A LA MÉMOIRE DE MARGAUX.

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Eléments sur la robustesse des politiques climatiques

RÉSUMÉ

Cette thèse s'attache à améliorer la robustesse des techniques d'évaluation des politiques d'atténuation du changement climatique, ainsi que la robustesse des instruments implémentés. En explorant des centaines de scénarios qui capturent l'incertitude sur les évolutions technologiques, sociologiques et démographiques futures, ainsi que sur la disponibilité des ressources fossiles et l'implémentation des politiques d'atténuation, elle révèle les déterminants des émissions futures et des coûts de l'atténuation. Cette méthodologie permet de filtrer les informations pertinentes pour la décision et de concentrer le débat sur les questions et politiques centrales pour le succès des politiques de réduction d'émissions de gaz à effet de serre. La thèse propose également de focaliser le débat sur des instruments robustes aux contraintes politiques car ayant peu d'impacts négatifs à court-terme. Des politiques permettant de rediriger les investissements vers du capital bas-carbone – par exemple les normes d'efficacité énergétique ou des instruments financiers – nous rapprochent des objectifs d'émissions de long-terme sans affecter les propriétaires du capital polluant déjà installé.

Some aspects of the robustness of climate change mitigation policies

ABSTRACT

This thesis looks for robustness in climate change mitigation policies assessment and implementation. Exploring the uncertainties surrounding future technologies, fossil fuel resources, policy instruments, consumption preferences, population and economic growth with an Integrated Assessment model, it disentangles the future drivers of future carbon emissions and of mitigation costs. Such methodologies improve the understanding of models, filter out the issues that do not really matter, help policymakers focus on critical factors and develop consensus about where the focus should be. The thesis also proposes to focus on instruments that are robust to political constraints thanks to their lower short-term impacts. Such instruments include performance standards or financial instruments that redirect the bulk of investments towards clean capital without affecting the owners of existing polluting capital.

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Chapter 2: Rozenberg, J., C. Guivarch, R. Lempert, and S. Hallegatte (2013). Building SSPs for climate policy analysis: a scenario elicitation methodology to map the space of possible future challenges to mitigation and adaptation. *Climatic Change*.
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Introduction

This thesis contributes to the analysis of the uncertainty surrounding the evaluation and implementation of climate change mitigation policies. In the scientific community, this uncertainty – around the future drivers of climate change impacts or mitigation costs – has raised criticism about the use of Integrated Assessment Models for finding what policy to implement. Some accusers argue that the models are too obscure when they incorporate many complex mechanisms (Henriet et al., 2014) or others that they are too simple when they reduce those mechanisms to cost curves (Pindyck, 2013).

It can be argued that in the field of climate change, the complexity of models is inevitable since a variety of stakeholders need to understand by which lever they will be affected by policies. One can then imagine at least two directions for improving the use of models as supports for policy decisions: (i) changing the methodology and exploiting computational capacity to improve the understanding of models, filter out the issues that do not really matter, help policymakers focus on critical factors and develop consensus about where the focus should be; (ii) coming back to compact models for in-depth analysis and theoretical grounding of the central mechanisms.

The thesis argues that in context of deep uncertainties, finding the optimal instrument is illusory but other approaches can inform robust decision-making frameworks for climate mitigation. Mitigation policies can for instance be evaluated in a robust way against hundreds of different baseline scenarios, in which we have a precise understanding of emissions drivers. Large databases help finding the trade-offs between different metrics of mitigation costs and the drivers of each metric. They also allow concentrating on the determinants of GDP in policy scenarios in-

stead of the relative cost with regards to a highly uncertain counter-factual baseline. Also, an analysis of the co-benefits of climate mitigation, e.g. in terms of protection against oil scarcity, can be very valuable to many decision makers, in particular when there are trade-offs between the cost metrics. Eventually, the thesis analyzes instruments that mitigate the inter- and intra-generational distributional impacts of climate policies.

BASELINES ARE KEY IN ASSESSING CLIMATE MITIGATION COSTS

The usual approach to assess climate mitigation costs requires defining a “baseline” scenario that gives the emissions of greenhouse gases (GHG) in the absence of a climate policy. This baseline is then compared to a climate-stabilization scenario in order to evaluate the impacts of mitigation instruments on various indicators (e.g. GDP, welfare, investment) — everything else being equal. The definition of the baseline therefore determines both the potential for future GHG emissions reduction and the costs of meeting a given climate stabilization target.

The baseline includes assumptions on future consumption preferences, technical change, fossil fuel resources, and economic policies at the macroeconomic and sectoral levels. These assumptions shape future development pathways, notably growth rates, structural change and resource intensity. For developing countries, an economy following development policies that emphasize greater investments in infrastructure, such as rail transport or energy efficiency improvements, is likely to follow a low GHG emission trajectory. Conversely, an economy with substantial coal resources and scarce capital can be pushed towards a development path with high emissions.

These assumptions are compromised by pervasive uncertainties that make the conception of one baseline irrelevant. Two main types of uncertainty can be distinguished when using the models that assess climate mitigation costs: conceptual uncertainty and parametrical uncertainty (Oreskes and Belitz, 2001). Conceptual uncertainty arises from the different mechanisms represented in models (e.g. partial vs general equilibrium effects), and the equations used to do so. Some of the dynamic linkages between technical choices and consumption patterns and, in turn, how these interact with economic signals and policies are indeed poorly un-

derstood (IPCC, 2001, chapter on costing methodologies). On the other hand, parametrical uncertainty comes from the wide range of possible values for input parameters of the equations. These include *inter alia* uncertainties on the costs and future availability of low-carbon technologies, unconventional fossil fuels resources, growth and wealth distribution, consumption patterns and social changes.

These considerations call for several alternative baseline scenarios characterized by different assumptions regarding development patterns and innovation. Mitigation (or adaptation) costs assessments across these different baselines would thus give estimate ranges rather than a single number and would help understand better the impact of different uncertainties on emissions and cost measures.

Building contrasted baseline scenarios for climate change policies is a difficult endeavor. It requires both a qualitative vision of possible futures and a quantitative translation of their corresponding trajectories. In the usual approach, that was used for instance for the SRES scenarios (?) the qualitative exploration precedes the quantitative translation. More precisely, the first step necessitates identifying *ex-ante* the key drivers of future emissions, selecting a few contrasted set of assumptions, and building comprehensive storylines out of these sets of assumptions. These storylines must be — as far as possible — internally consistent and be representative of the scope of possible scenarios. The storylines are then translated into model inputs, leading eventually to quantitative scenarios.

The first part of the thesis starts with a chapter on this process, illustrated by the Shared Socio-Economic Pathways, the new IPCC socio-economic scenarios built for climate change research. In order to integrate the research communities working on adaptation and mitigation, the SSPs must be contrasted along two axes: challenges to mitigation, and challenges to adaptation. Defining appropriate indicators for these challenges and selecting both contrasted and internally-consistent scenarios is a difficult task. This first chapter points the methodological issues met when using the usual approach and proposes different methodologies.

Now that calculation capacity has significantly improved, the scenario construction process may indeed be reversed. Both the complexity of the issues decision-makers and scientists are dealing with and the uncertainty surrounding for instance future economic, technological or climatic conditions could be better comprehended. The existence of many links and feedbacks between the drivers that need

being considered may lead to counter-intuitive trajectories: even though input drivers are chosen to be representative of the uncertainty, the scenarios created as output of the models may not be representative of the scope of possible futures.

This thesis proposes new methodologies to improve the assessment of future climate and energy policies. It demonstrates that the calculation power now available for socio-economic scientists can help reveal new insights on complex problems if a large number of scenarios is systematically considered before evaluating policies.

Instead of selecting *ex-ante* a few sets of hypotheses, models can be run hundreds or thousands of times to explore a scenario ensemble as large as possible. Choices can then be made in the output space (that of scenarios) instead of the input space (that of the input hypotheses). Such alternative methodologies help better apprehending the deep uncertainty surrounding future economic forces relevant for the study of climate change adaptation and mitigation and help assess policy costs in a more robust way. Understanding and ranking uncertainties indeed allows finding the important levers for policy action and reducing some of these uncertainties.

In this thesis, scenario databases will be built with only one model, for practical reasons. First, we had only the IMACLIM-R model at our disposal. Second, analyzing the underlying drivers of scenarios generated with a single model is much easier than doing so for the outputs of many models.¹

Chapter 2 proposes a methodology to develop Shared Socio-Economic Pathways (SSPs) with a “backwards” approach, based on (i) an *a priori* identification of potential drivers of mitigation and adaptation challenges; (ii) a modeling exercise to transform these drivers into a large set of scenarios; (iii) an *a posteriori* selection of a few SSPs among these scenarios using statistical cluster-finding algorithms. This backwards approach helps inform the development of SSPs to ensure the storylines focus on the driving forces most relevant to distinguishing between the SSPs. This illustrative analysis shows that, in our database, consumption behaviors, equity concerns and convergence of developing countries prove

¹Key challenges arise from using a variety of models with differences in model focus, structure and assumptions. However, a promising direction for future research is to find ways to systematically analyze the large scenario databases that have been produced for the IPCC fifth assessment report.

most important towards explaining future difference in challenges to adaptation and mitigation.

Chapter 3 identifies the main drivers of future CO₂ emissions using a scenario database built with the IMACLIM-R model. Starting with an analysis of the Kaya components across the database, we find that the main driver of future emissions is GDP per capita, offset by improvements in energy efficiency. The carbon content of energy, conversely, barely changes between 2010 and 2050, and this is true in all scenarios. We also find that GDP per capita and energy efficiency are anti-correlated, such that they cancel each other's effects on emissions and reduce the overall uncertainty on future emissions. We then look for the drivers of emissions among the exogenous parameters of the model and find that assumptions on the availability of coal and unconventional oil mainly determines future CO₂ emissions. The influence of this parameter is however not channeled through increased carbon intensity of energy, or through increased GDP per capita (GDP per capita depends on assumptions on behaviors and energy efficiency potentials). To go further, the chapter is completed by a Structural Decomposition Analysis (SDA) to disentangle structural change from increases in activity. Correlations between factors are lower with such decomposition, and we show that the activity effect (increase in production per capita) is the main determinant of future emissions and it is mainly driven by the availability of coal and unconventional fuels. This effect is offset by structural and energy intensity effects, which are caused by energy efficiency and behaviors hypotheses. SDA therefore proves very useful for explaining future emissions as it decorrelates the factors and explains why future fossil fuels availability is the main driver of emissions in this particular database.

MITIGATION COSTS METRICS AND CO-BENEFITS

The previous chapter found that baseline emissions strongly depend on assumptions on the future availability of coal and unconventional fuels. Chapter 4 and 5 find that depending on the metrics considered, these parameters also play an important role in mitigation costs through their impact on the baseline.

Chapter 4 addresses the co-benefits of climate policies by assessing in a common framework both the costs of climate policies and oil scarcity, taking into ac-

count macroeconomic feedbacks. It shows that both costs are of the same order of magnitude, and that mitigation costs are lower when oil is scarce in the baseline (this result is consistent with the previous chapter). Moreover, a robust result across the database suggests that, in the context of a limited and uncertain amount of ultimately recoverable oil resources, climate policies reduce the world vulnerability to peak oil. Climate policies, therefore, can be considered as a hedge against the potential negative impact of oil scarcity on the world economy. This hedge parallels the climate-related hedge of early climate policies, and may appear as a significant side-benefit of climate policies to many decision-makers.

Chapter 5 takes a step back and shows that when assessing mitigation costs, one stumbles over the irreducible socio-economic uncertainties at play, but also on the several cost metrics that co-exist and are conceptually different (e.g. carbon price and macroeconomic cost of the policy). Using a scenario database and analyzing scenarios with statistical methods, it finds that the two issues are linked. Our results first highlight the quantitative importance of findings from the theoretical literature: the political choices behind the implementation of mitigation policies, namely here the use of carbon pricing revenues, have a major influence for the costs of the policy. A substitution of the carbon tax for pre-existing distortive taxes also entails a trade-off: it reduces macroeconomic costs and its range of possible values, but it increases the carbon price and its range of possible values. Moreover, our results give new insights. The macroeconomic cost of a mitigation policy strongly depends on baseline assumptions on the availability of fossil fuels, while these parameters have no impact in the stabilization scenario (this is analyzed in depth in chapter 4). The macroeconomic cost is thus not a good proxy for absolute GDP per capita reached in mitigation scenarios. The latter is strongly determined by assumptions on energy efficiency and behaviors, two drivers that do not influence significantly the macroeconomic cost. Framing therefore matters when assessing mitigation costs and their determinants. The importance of behaviors and energy efficiency for the cost-efficiency of mitigation policies is a remarkable result, given that most mitigation studies focus on technologies and policy design, and disregard the uncertainty surrounding future consumption behaviors. This chapter calls for caution in costs results interpretation, presentation and communication and emphasize the need to pursue efforts to develop and apply methods that quantify

the effects of socio-economic uncertainties for climate policy decisions. Chapter 5 also suggests that baselines are misleading in the assessment of mitigation costs. These assessments could instead concentrate on finding the parameters and policy levers that maximize welfare under a climate constraint.

These last two chapters illustrate the fact that the sub-optimality of the baseline growth path (in the absence of the climate externality) is also crucial in assessing mitigation costs. The presence of rigidities or market imperfections — such as unemployment or imperfect foresight — in the baseline may increase mitigation costs but allows highlighting some co-benefits of climate mitigation policies. For instance, in the presence of a complex fiscal system the implementation of a carbon tax recycled through a decrease of distortionary taxes (e.g. labor taxes) can generate a double dividend (Chapter 5). Also, mitigation policies can reduce the adverse impacts of oil scarcity on economic growth if in the baseline agents do not anticipate oil depletion (Chapter 4).

Such considerations are very important for the implementation of mitigation policies, given the uncertainty surrounding mitigation costs. In particular, when there are trade-offs between the different metrics of mitigation costs, evaluating the potential co-benefits of a climate mitigation policy may strengthen the case for action and help reach a consensus.

The rest of the thesis focuses on a different issue, namely the intra and inter-generational impacts of mitigation instruments. It argues that the short-term impacts of a climate mitigation policy may hamper its political implementation and call for alternative instruments able to tackle both the equity and efficiency aspects of a policy.

THE INTRA AND INTER-GENERATIONAL IMPACTS OF MITIGATION INSTRUMENTS

Short-term impacts of mitigation instruments is another central point for performing a sound assessment of mitigation options and for providing policy-relevant information to decision-makers. Most cost assessments rely either on a cost-benefit analysis that compares the economic costs of a mitigation policy to its benefits in terms of avoided climate change damages, or on a cost-efficiency approach that

looks for the least-intertemporal-cost option allowing to reach a given climate target.

According to these criteria, the carbon tax is the best instrument to maximize intertemporal welfare in a climate-stabilization scenario. But public policy is especially difficult in contexts where costs are immediate, concentrated and visible; and benefits are spread over time and over citizens (Olson, 1971). There will necessarily be losers in an intertemporal-efficient transition to a clean economy. Among them, the owners of the most carbon-intensive long-lived capital will see their assets instantaneously lose value and become “stranded assets.” Since the owners of polluting capital – and the workers whose job depend on this capital – were playing by the rules when they made their investment, before any carbon pricing had been decided, they may become strong opponents to a carbon tax. If this equity issue is not tackled, it is very unlikely that a carbon tax can become politically-acceptable and thus be implemented.

In order to provide policy-relevant information, mitigation instruments could therefore be assessed with both efficiency criteria (they reduce emissions) and equity criteria (they compensate losers). Instead of using a uniform carbon tax as a benchmark against which other instruments should be evaluated, one could use a carbon tax completed by measures that compensate the losers. The thesis thus looks for robustness in the design of mitigation instruments by looking at their inter- and intra-generational distributional impacts.

Chapter 6 investigates how the transition to clean capital is modified when using *investment-based* instruments such as performance standards or feebate programs instead of a carbon price. It uses a Ramsey model with two kinds of capital and irreversible investment, and focuses on the short-term asset price variations caused by different instruments and on the repartition of abatement efforts over time. The cost of climate mitigation decomposes as a technical cost of using clean instead of polluting capital and a transition cost due to the irreversibility of pre-existing polluting capital. With a carbon price, the transition cost can be limited by under-utilizing polluting capital, at the expense of a loss in polluting assets value (i.e. stranded assets) and a drop in income. By removing this option, instruments that focus on redirecting investments increase the intertemporal cost of the transition but reduce short-term losses and increase the short-term value of polluting

assets. These results highlight a trade-off between the optimality of a climate mitigation policy and its short-term impacts, which may influence political acceptability. When comparing the instruments in terms of welfare maximization, the carbon tax alone is always the best policy. When looking at criteria such as short-term impacts, however, investment-based instruments may appear preferable to some decision-makers and voters. In particular, the impact on asset prices would primarily affect the owners of polluting capital and the workers who depend on them, transforming them into strong opponents to the mitigation policy.

Chapter 7 then proposes instruments that can help redirect investments towards low-carbon capital in the absence of a carbon price. It argues that such redirecting can be done with “carbon certificates” that can be accepted as part of commercial banks legal reserves. These certificates can be distributed to low-carbon projects, and be exchanged by investors against concessional loans, reducing capital costs for low-carbon projects. Within this scheme, mitigation expenditures are compensated by a reduction in regular investments, so that immediate consumption is maintained. This framework is not as efficient as a carbon tax but may be politically easier to implement. Eventually, the key message of this thesis is that optimality is not a good framework for the evaluation of mitigation policies: mitigation costs are too dependent on uncertain exogenous drivers. Instead, robust approaches can be used both for the evaluation and the design of mitigation policies.

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1

The Shared Socio-Economic Pathways in perspective

BUILDING SCENARIOS FOR CLIMATE CHANGE RESEARCH

When Broecker popularized “Global Warming” in *Science* in 1975 (Broecker, 1975), he built a projection of future CO₂ atmospheric concentration and temperature increase based on predicted fuel consumption until 2010. Shortly after that, Nordhaus (1977a) and Nordhaus (1977b) projected future changes in global temperature until 2080, and analyzed the costs of three different climate mitigation scenarios compared to this “uncontrolled” scenario. In 1989, the IPCC started preparing emissions scenarios to provide climate scientists with a basis for estimating future possible climate changes up to 2100, under the hypothesis that no mitigation policy is implemented by then. A first set of scenarios was published in 1990 (IPCC, 1990), followed by the six IS92 scenarios in 1992 (Leggett et al., 1992; Alcamo et al., 1994).

A scenario can be thought of as a “coherent, internally consistent, and plausible description of a possible future state of the world” (McCarthy, 2001). Most published analyzes of climate change mitigation policy, and many investigating climate change impacts and adaptations, have been based on long-term socioeconomic scenarios. Since the turning point between the second and third IPCC assessment report,¹ construction of scenarios has been recognized as a means for organizing and communicating the many uncertainties associated with climate policy support. By illuminating the span of possible futures, consideration of diverse scenarios has the potential to highlight the interaction of complex uncertainties that would otherwise be difficult to analyze (Groves and Lempert, 2007).

In climate change research, scenarios have mostly been produced by “story and simulation” methods (Garb et al., 2008). Groups of experts first work collaboratively to build a few storylines that qualitatively describe plausible, internally consistent outcomes for deeply uncertain processes, such as future population change, economic growth, and technological progress. These storylines are informed by experts’ intuition regarding the most important driving forces of these trends. Storylines are then translated into representative quantitative projections, which are used as inputs to Integrated Assessment Models (IAMs) or different sectoral models. IAMs then produce key outputs such as energy technology market shares, greenhouse gas emissions, and atmospheric CO₂ concentration.

The gap between qualitative storylines and quantitative trajectories creates many methodological challenges that are disconnected from modeling difficulties. Among them is the different levels of consistency that are required within storylines and quantifications, and between them. One can describe a storyline as consistent if it embodies influences that are self-reinforcing (Schweizer and Kriegler, 2012). On the other hand, IAMs trajectories are consistent if the model can find solutions to the set of equations, given initial conditions. The consistency between storylines and quantifications is however one of the biggest challenges of the story and simulation approach and will be discussed in this chapter.

Up to now, most analyzes have used the Special Report on Emissions Scenar-

¹The second IPCC assessment report was strongly based on econometrics and prevision, while from the third report on, IPCC assessments were built around a multiplicity of future scenarios.

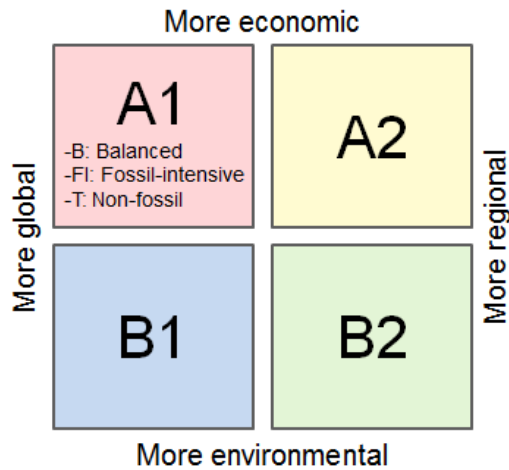


Figure 1.1: The SRES space.

ios (SRES, see Nakicenovic et al., 2000). These scenarios describe possible world evolutions in demographic, social, economic, and technological terms, up to 2100. To construct the SRES, experts adopted the scenario axis method as in Schwartz (1991), which uses quadrants of a two-dimensional space to define four scenarios (fig. 1.1). In the SRES, the axes were defined by degree of globalization and degree of sustainable development. The quadrants were used to sketch four storylines and quantify four sets of projected exogenous variables, which were used as model inputs for many climate policy studies (see Parry et al., 2004, for one of the many examples). The SRES scenarios were thus developed using a forward-looking logic that started by first describing driving forces, and then modeling the resulting emissions and atmospheric concentrations of greenhouse gases and aerosols. In this sequential approach, climate models were used last to project the magnitude and pattern of climate change under the different SRES scenarios.

The SRES assume that there are no climate change impacts and no mitigation policies. They have been used as “baselines” to assess the performance of adaptation and mitigation policies and to investigate residual impacts from climate change. For instance, the costs and benefits of climate mitigation policies can be estimated by comparing the change in global mean temperature in a SRES scenario and in the same scenario in which specific climate policies are implemented (see a review in IPCC, 2007). Also, the potential impacts of climate change can be assessed by

comparing a SRES scenario with the same scenario in which climate impacts are included (e.g., Arnell, 2004).

The modeling community however indicated that the scenario axis and sequential methods often hindered effective use of scenarios (Moss et al., 2010; Parson et al., 2007). The sequential approach took more than ten years before climate modelers could use SRES to simulate different climate changes. Also, because storylines were decided on separately from model construction, it was often difficult for the models to completely reflect the storylines (Wang et al., 2013).

Since the SRES were published, new information has accumulated in demographic and socioeconomic projections, in impact, adaptation, and mitigation analyzes. The SRES demographic and socioeconomic assumptions are aging and new scenarios are needed to address more effectively the questions surrounding adaptation and mitigation policies (Ebi et al., 2013; Hallegatte et al., 2011). Such scenarios also need to cover a wider range of greenhouse gas concentrations (including those that can be reached by implementing mitigation measures) and to facilitate the integration of mitigation, adaptation, and impact analyzes (Ebi et al., 2013).

The scientific community has thus developed a new set of scenarios to replace the SRES (Moss et al., 2010; van Vuuren et al., 2012; Kriegler et al., 2010; Arnell et al., 2012; O'Neill et al., 2011; Ebi et al., 2013), following a different logic. Instead of a sequential approach, the new process builds climate and socioeconomic scenarios in parallel, starting from a set of four future pathways for anthropogenic impact on the climate system, measured using "radiative forcings." These four pathways are known as representative concentration pathways (RCPs) and cover a very wide range of possible future radiative forcing: they range from ambitious climate stabilization at 2.6 W/m^2 forcing to 8.5 W/m^2 forcing, which correspond, respectively, to atmospheric greenhouse gas concentrations of about 430 and 1230 ppm $\text{CO}_2\text{-eq.}$ in the year 2100. In contrast to the SRES, RCPs are first defined by GHG concentration outcomes instead of driving forces, and they don't incorporate any socio-economic information.

Such a process gives a high relative autonomy between the IPCC groups I (on the physical aspects of the climate system) and II-III (on the socio-economic aspects of climate change) for purely technical reasons. While climate modelers have

assessed the climate response to these RCPs for the IPCC fifth assessment report,² in IAM modelers are building socioeconomic scenarios, called Shared Socioeconomic Pathways (SSPs), consistent with the RCPs. As with the earlier SRES scenarios, the new SSPs describe different socioeconomic characteristics, different vulnerabilities, and different GHG emissions.

The key point of the new scenarios architecture is that the four RCPs are not associated to a unique GHG emissions pathways or socio-economic pathway (van Vuuren et al., 2012; Guivarch and Rozenberg, 2013). Each RCP can result from different combinations of economic, technological, demographic or institutional evolutions.

The SSPs will also be combined with climate mitigation policies called Shared Policy Assumptions (SPAs). Indeed, even though some of the RCPs can be reached in “baseline” scenarios, i.e. with no mitigation policy, others will most likely require to implement specific economic instruments to reduce GHG emissions.

The SSPs, combined with SPAs, will thus allow creating a correspondence between the four RCPs and different combinations of socio-economic and policy assumptions.

To assist with the exploration of both adaptation and mitigation questions with the same scenarios, Arnell et al. (2012) proposed to develop SSPs that are contrasted along two axes: socio-economic challenges to adaptation and socio-economic challenges to mitigation (Figure 1.2). In this challenges space, three domains correspond to futures where mitigation and adaptation challenges co-vary (SSP₁, SSP₂, SSP₃), while two domains are mixed futures where adaptation challenges dominate (SSP₄) or mitigation challenges dominate (SSP₅). This new framework will allow two distinct research communities working on the same scenarios and highlighting the synergies and trade-offs between adaptation and mitigation issues.

To build the scenarios, experts adopted a “story and simulation” approach (as for the SRES) and gathered in Boulder in November 2011 to build five storylines for the SSPs. Building narratives for each of the SSPs required imagining five coherent, internally consistent, and plausible future states of the world defined in terms of challenges to adaptation and mitigation. Those five narratives that depict

²for instance RCP2.6 maintains global temperature increase below 2C by the end the century while RCP8.5 can lead to temperature increases of 4C by 2100.

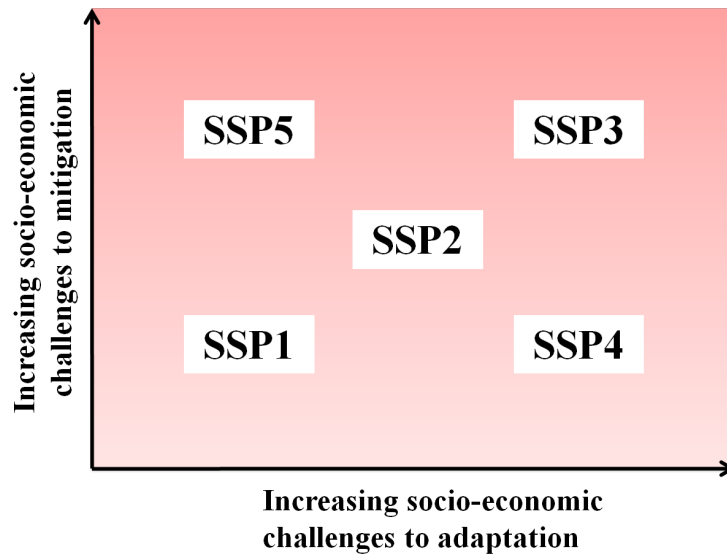


Figure 1.2: The challenges space.

five future states of the world are different in nature from those of the SRES, which were built around future identified trends (e.g. consumption preferences, globalization). Here, since the classification of any particular scenario as representative of any of the five domains depends upon its outcomes, the socio-economic driving forces of future challenges remained to be identified.

The concepts of “challenges to adaptation and mitigation” are broad and were not clearly defined in the scenario framework. Each expert could thus interpret these challenges with their own indicators (e.g. CO₂ emissions or cost of low carbon technologies for mitigation challenges, GDP per capita or exposure to climate change for adaptation challenges). Also, no structured discussions were organized to agree on the socio-economic driving forces of future challenges to adaptation and mitigation.

Experts therefore started from five future states of the world defined implicitly by some indicators of future challenges to adaptation and mitigation, and leaning on the drivers they had intuitively identified as relevant for these indicators, they built the narratives representative of the five SSPs. The narratives can be found in O’Neill et al. (2011).

After the Boulder meeting, a few teams interpreted the SSP storylines in terms

of quantitative projections for population, GDP and urbanization (the “drivers”), which will be used as inputs to Integrated Assessment Models. These models will then produce key outputs such as energy technology market shares or greenhouse gas emissions for each SSP.

In a second step, these same models calculate, for each SSP, the costs of reaching a given stabilization target. The quantified drivers will also be used for local adaptation studies and sectoral models.

LIMITATIONS OF THE “STORY AND SIMULATION” APPROACH

This innovative process met some methodological challenges in its practical implementation.

Given the uncertainty surrounding all possible drivers of future challenges to adaptation and mitigation, and given the feedbacks and correlations that exist between these different drivers, relying on intuition to build storylines may hamper the process of building internally-consistent storylines, or storylines that will be consistent with model outputs. For instance, there are many links between the evolution of population and GDP growth — e.g. high birth rates can reduce GDP growth through investments effects or “capital dilution” (Brander and Dowrick, 1994), population aging has strong effects on labor supply and induces large structural changes that impact growth (Borsch-Supan, 2003), education spending, which is correlated to wealth levels, have strong impacts on population and economic growth (Mankiw et al., 1992; Lutz and Kc, 2011) — and many of them are not captured quantitatively when both pathways are determined by separate models.

Two limitations of the “story and simulation” approach for building SSPs are discussed in this thesis: (i) this approach does not guarantee that the final scenarios will be contrasted enough to cover a wide range of challenges to mitigation and adaptation; (ii) there may be an important consistency gap between the storylines and the quantifications.

The first concern materialized in The Hague in May 2012 when IAM teams presented the first quantifications based on the population and GDP projections that were produced by IIASA and the OECD respectively. When they interpreted the SSP narratives, the OECD modeling team constructed very contrasted projec-

tions. Growth is very high in SSP5 – high challenges to mitigation and low challenges to adaptation – with 3% global mean GDP per capita growth rate per year between 2010 and 2100, while it is very low growth in SSP3 – high challenges to adaptation and mitigation – with 0.9% global mean GDP per capita growth rate per year between 2010 and 2100. In 2100, GDP per capita is thus more than six times higher in SSP5 than in SSP3. As a result, although it may look surprising at first glance, the IAMs that used these GDPs as inputs produced outcomes that did not match the SSP storylines in terms of GHG emissions. For instance, GHG emissions were low in SSP3 while this scenario is defined by high challenges to mitigation. Indeed, in SSP3 GDP per capita is so low in some regions of the world that in IAMs emissions are limited by the lack of economic activity after 2050.

Of course, other indicators of challenges to mitigation could be high in SSP3, for instance bad governance or very expensive low-carbon technologies. However, building SSPs coherent with the RCPs and the corresponding climate projections requires that some scenarios meet RCP8.5 concentration levels.

The second concern in the construction of SSPs is the internal consistency of the storylines, and their consistency with the quantifications. The internal consistency issue of the narratives is addressed by Schweizer and O'Neill (2013), who use a systematic technique for the development of storylines called the cross-impact balance (CIB) method and find that most of the internally-consistent scenarios lie on the SSP1-3 diagonal in the challenges space.

Here, we are concerned by another consistency issue. The narratives assume, with very few theoretical justification, that GDP growth is higher in SSP5 – which is very energy-intensive – than in SSP1 – which is energy-sober. The numerical interpretations thus lead to a GDP per capita that is 1.7 times higher in SSP5 than in SSP1 in 2100 (3% against 2.4% mean GDP per capita growth rate per year between 2010 and 2100). This view that an environmentally-friendly world creates less wealth than an energy-intensive world was already anchored in the SRES scenarios. In the A1B1 scenario (energy intensive), GDP per capita is $74.9 \cdot 10^3$ 1990US\$ in 2100 while it is only $46.6 \cdot 10^3$ 1990US\$ in the B1 scenario (environmentally-friendly). These numbers amount to a 2.7% mean growth rate per year between 1990 and 2100 in A1 against 2.25% per year in B1. This opposition between growth and the environment is not grounded on solid scientific evidence and can lead to

mis-interpretation and misuse of scenarios. For instance, Lomborg claimed in his book (Lomborg, 2001; Hourcade and Journé, 2003) that this lower GDP growth in the B1 scenario was the cost of climate mitigation. This interpretation is wrong since SRES are defined by different preferences and values, making the comparison of GDPs irrelevant. Also, all SRES scenarios are baselines, i.e. they do not model climate mitigation policies. Mitigation costs can only be assessed within each scenario, comparing GDP in the baseline scenario with that of a similar scenario in which a policy is implemented to reach a climate stabilization target.

Such interpretation of the scenarios can be detrimental to the climate change community as it can give the impression that there is trade-off between energy efficiency and development potentials. Lessons were not learned from the SRES in that regard, and scientists keep implying that an environmentally-friendly world creates less wealth than an energy-intensive one when they build scenarios, even though there is no evidence of such a strong assumption. In chapters 3 and 5 and in appendix C we find that when using an IAM with endogenous GDP, that is which represents the feedbacks of energy consumption and fossil fuels depletion on economic growth, GDP tends to be higher in scenarios with low energy intensity than in energy-intensive ones. In chapter 2 we find that when using GDP and CO₂ emissions as indicators to future challenges to adaptation and mitigation, very few scenarios end up in the SSP5 domain (high challenges to mitigation low challenges to adaptation, Fig. 1.2). This suggests that with our model, the quantifications of SSP5 are not consistent because high GDP growth is most of the time associated with high energy efficiency. In Chapter 3 and Appendix C we show that when using an IAM with endogenous GDP, computing a higher GDP in SSP5 than in SSP1 implies changing assumptions on future coal availability. Indeed, in a fossil energy-intensive scenario, high GDP growth (that is, one possible interpretation of SSP5) can only be achieved with large availability of coal and unconventional oil.

These results suggest that the assumption of an opposition between growth and the environment is not only misleading but also possibly wrong. For future research, it is thus worth investigating the links between energy consumption and economic growth in depth and incorporating these mechanisms in IAMs.

BUILDING DATABASES WITH INTEGRATED ASSESSMENT MODELS

The dominant approach consisting in choosing a small number of scenarios and treating each as a distinct “parallel universe” made sense when computer time was scarce. However, a general shortcoming of this approach is that the wide variety of future uncertainties is inspected *ad hoc* leaving many uncertainties and potential risks un-investigated. Some authors suggest that the *ad hoc* nature of these scenarios constrains their policy relevance, since it can easily be argued that such studies are not comprehensive (Lloyd and Schweizer, 2013; Schweizer and Kriegler, 2012), and many stakeholders do not recognize themselves in the analysis.

Now that computational capacity has greatly improved, more reliable methodologies than the “story and simulation” approach could be used. For instance, more value may come from adopting risk analytic perspectives, where the conditions for policy failure are identified (e.g. Lempert, 2013), or the analysis is tasked with uncovering less biased scenarios (this from a statistical perspective, e.g. Morgan and Keith, 2008; Shlyakhter et al., 1994). In the case of SSPs, experts could analyze scenario databases that cover a wide range of uncertainties for the possible drivers of future challenges to adaptation and mitigation, and choose *ex-post* the most relevant and consistent scenarios. Such a methodology would be all the more relevant as SSPs are defined by their outcome (challenges to adaptation and mitigation) and not by their drivers.

METHODOLOGY

As in any quantitative scenarios exercise, building a scenario database requires structuring the problem, i.e. carefully defining the question or the decision, with clear distinctions drawn between alternative outcomes for a single decision maker. It also requires identifying key decision metrics in consultation with that decision maker and key uncertainties (Lempert et al., 2003).

Problem structuring leads to choose — or develop — one or several numerical models that represent the exogenous uncertainties, the policies levers and the relationships between them.

Once in possession of one of several appropriate models, the next step is the construction of a database. There are an infinite number of combinations of plau-

sible values of the model(s) input parameters. Depending on the number of uncertainties that need being considered and of the size of the model, different methods can be used.

In this thesis, we will use the IMACLIM-R model, an Integrated Assessment Model developed at CIRED, since it is this only one at our disposal. It also simplifies the work, as analyzing the underlying drivers of scenarios generated with a single model is much easier than doing so for the outputs of many models that vary in model focus, structure and assumptions.

With IMACLIM-R, we choose two or three possible values for each parameter (based on the literature) and we group the parameters into a few subsets of parameters (between 5 and 10 generally) to avoid combinatory explosion. Combining the two or three possibilities for each subset leads to the simulation of several hundred scenarios that cover the uncertainty space a priori important for the issue we are analyzing.

DATABASES OPEN UP NEW PERSPECTIVES

Working with a large ensemble of quantitative scenarios opens up new perspectives illustrated in this thesis and related working papers. It can help select ex-post a small number of scenarios relevant for a given question, identify emerging behaviors across all scenarios, assess the sensitivity/robustness of a result to uncertainty or analyze the ensemble dynamically to identify shifts in pathways.

With only a small number of scenarios, one cannot possibly know whether the mechanisms or numbers assessed are robust to a variation of key parameters or if they are looking at a special case. With a scenario database, quantifications are associated to the margins of error due to the uncertainties considered. This helps discriminating robust results from those that are sensible to key parameters.

Also, a scenario database allows analyzing the result distribution and applying probabilistic reasoning if one is capable of building (subjective) probability distributions for the input parameters or the resulting scenarios. The scenario ensemble can then be analyzed to identify emerging behaviors. For instance, looking for correlations between different measures enlightens multi-criteria decisions and highlights the possibilities for synergies or trade-offs. To go further, it is also possible

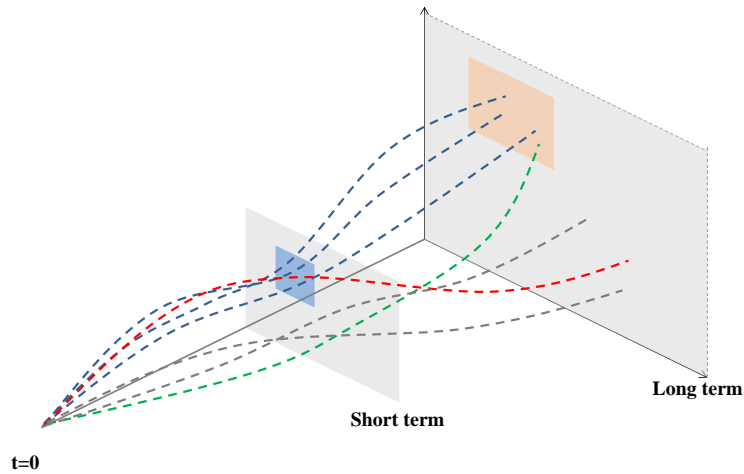


Figure 1.3: Windows of opportunity

to evidence the conditions that lead to these synergies. Statistical techniques are used to discover the main drivers of a group of scenarios, i.e. the combination of input parameters that lead to certain results in the output space.

Furthermore, the database can be analyzed in a dynamic way, in order to link the short and the longer-run and discover windows of opportunity (fig. 1.3 and Guivarch et al., 2014). A dynamic approach indeed moves away from the “parallel universes” approach and allows answering questions such as “where should I be in the short-run to be able to reach this particular long-term objective?” (it is complementary to sequential decision-making such as in Ha Duong et al., 1997). Given the diversity of possible long-run trajectories, such a question is only relevant for a large number of scenarios.

Finally, in situations where a small number of scenarios is required (for instance to communicate the results or harmonize different studies that will rely on the same scenarios), a database can help choosing the scenarios that will be most relevant to the question we are asking.

Systematic scenario techniques can assist the construction of consistent storylines and bring transparency to the usual story and simulation methodologies. As an example, the quantitative results for SSP2 in chapter 2 illuminate the difficulties that were met during the Boulder meeting when storylines had to be built (O’Neill et al., 2011). These demonstrate that a scenario elicitation methodology that starts

from indicators of future challenges to adaptation and mitigation cannot easily find relevant drivers for a middle scenario (SSP₂). The “middle of the road” SSP – SSP₂ – was indeed problematic in Boulder as the endpoint was not well defined: medium challenges for both adaptation and mitigation was hard to depict in an unanimous way. In particular, it was unclear whether SSP₂ was in the middle because many indicators of future challenges to adaptation and mitigation were in the middle, or because the scenario was a combination of opposite extreme (e.g. high availability of low-carbon technologies but very bad governance may generate middle challenges to mitigation). When using the quantitative methodology in chapter 2, the endpoint is well defined (quantitative indicators of challenges are in a “middle” state) but there is no unique set of drivers that put scenarios in the SSP₂ domain (or out of this domain). These results show that SSP₂ cannot be defined properly. As a consequence, in place of the backwards approach used for other SSPs, experts adopted a forecast approach and defined the SSP₂ as a “continuation of current trends” scenario.

Accordingly, thinking that models can solve all issues in scenario building is illusory. Models are helpful tools to help organize the experts’ thoughts but they are limited. We do not discuss the relevance of existing models in this thesis, and the interested readers can refer to Crassous (2008) for a detailed discussion on the IAM modeling community. Here, we use scenario databases to put scenario building methodologies into perspective (chapter 2), improve the utilization of complex models for climate change mitigation and highlight robust behaviors or policies (chapters 3 and 5).

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2

A scenario elicitation methodology to map the space of possible future challenges to mitigation and adaptation

2.1 A NEW GENERATION OF SCENARIOS

Most published analyzes of climate change mitigation policy, and many investigating climate change impacts and adaptations, are based on long-term socioeconomic scenarios. Up to now, most analysis have used the Special Report on Emissions Scenarios (SRES, see Nakicenovic et al., 2000), that describe possible world evolutions in demographic, social, economic, and technological terms, up to 2100. They assume that there are no climate change impacts and no mitigation policies, and thus have been used as “baselines” to assess the performance of adaptation and mitigation policies, and to investigate residual impacts from climate change. For instance, the costs and benefits of climate mitigation policies can be estimated by

comparing the change in global mean temperature in a SRES scenario and in the same scenario in which specific climate policies are implemented (see a review in IPCC, 2007). Also, the potential impacts of climate change can be assessed by comparing a SRES scenario with the same scenario in which climate impacts are included (e.g., Arnell, 2004).

The scientific community is now developing a new set of scenarios (Shared Socioeconomic Pathways or SSPs) to replace the SRES (Moss et al., 2010; van Vuuren et al., 2011; Kriegler et al., 2010; Arnell et al., 2012; O'Neill et al., 2011). As with the earlier SRES scenarios, the new SSPs will describe different socioeconomic characteristics, different vulnerabilities, and different GHG emissions. To assist with the exploration of both adaptation and mitigation questions with the same scenarios, Arnell et al. (2012) propose to develop SSPs that are contrasted along two axes: socio-economic challenges to adaptation and socio-economic challenges to mitigation.

Using “story and simulation” methods (Garb et al., 2008), similar to those used for SRES, groups of experts would build the SSPs working collaboratively to choose a common set of qualitative storylines, informed by experts’ intuition regarding the most important driving forces leading to different vulnerabilities to climate change and different abilities to mitigate (see O'Neill et al., 2011, for an illustration with the SSP process). Analysts would then use computer simulation models to develop quantitative projections based on these storylines.

But this process may fail to yield storylines that focus on the most important driving forces for each SSP, and avoid focusing on the less important drivers. For some driving forces, the direction of the influence can be ambiguous ex-ante. For instance, it is likely that climate change vulnerabilities in an urban world are different from those in a rural world; but it is difficult to guess whether one is more or less vulnerable than the other. Cities are vulnerable to floods, air pollution and heat waves while rural zones are vulnerable to drought (falling yields), famines and migration. There is an obvious difference in the nature of vulnerability but not in the magnitude of the vulnerability. Moreover, some mechanisms (feedbacks, rebound effects, etc.) might appear negligible a priori but reveal themselves to be crucial in a more careful analysis. This is why an ex-ante selection of the likely drivers of the capacity to mitigate and adapt appears insufficient to us, and could

be completed by an analysis that validates the most important drivers ex-post.

Furthermore, since future socioeconomic and environmental changes are highly uncertain, policies need to be tested against a variety of scenarios that cover a large range of possible futures (Lempert, 2013; Hallegatte, 2009). It would indeed be dangerous to implement a climate policy that performs well in one given scenario but completely fails in another, for instance if the population is larger or technological change slower than expected. Although the “story and simulation” process creates coherent scenarios through the storylines, it does not guarantee that the scenario outcome in terms of GDP or GHG emissions for instance will cover the uncertainty spectrum expected by users.

To address these challenges, we suggest here developing SSPs using a “backwards” approach. Our methodology is based on (i) an identification of potential drivers of challenges to mitigation and adaptation, (ii) a modeling exercise to explore the uncertainty space and select scenarios, and (iii) an a posteriori confirmation of which drivers matter and of the sign of their influence on adaptation and mitigation challenges, using statistical cluster-finding algorithms.

In recent years, several research groups have employed similar approaches, in which cluster-finding algorithms applied to databases of multiple simulation model runs are used to suggest scenarios relevant for specific policy questions with less potential ambiguity than can arise from story and simulation methods (Gerst et al., 2013; Lempert et al., 2006; McJeon et al., 2011; Haasnoot et al., 2013; Hamarat et al., 2012). For example, one such “scenario discovery” analysis focused on mitigation strategies, evaluating the costs and benefits of a Renewable Energy Portfolio standard in the U.S. It found that the availability of low-cost biomass feedstock and low-cost sites for wind energy were the most important drivers for whether or not the policy produced high cost outcomes (Toman et al., 2008). The concept of “backwards” analysis is similar to the “tolerable window” approach (Petschel-Held et al., 1999) that identified policies consistent with defined guardrails for climate evolution, though the current approach can be used with any forward-running model (Lempert et al., 2006). The concept of defining scenarios relevant to specific decision-relevant criteria is also consistent with the Global Business Network’s “strategic scenarios” approach, although we do not start with a specific decision but with the broader issue of defining scenarios that are contrasted

in terms of future challenges to adaptation and mitigation, similarly to recent work on defining scenarios for climate adaptation studies (Birkmann, 2013). While the structural form of our model limits the results described in this paper, our approach could usefully be generalized to employ multi-model analysis (Barker et al., 2002, 2006; Peace and Weyant, 2008).

To build a database of many cases in this study, we first identify potential drivers of future challenges to adaptation and mitigation and translate some of our potential drivers into different model parameters (e.g., the amount of ultimately recoverable oil resources). Other drivers cannot be accommodated in the model and are considered part of a narrative, accompanying model parameters and results (e.g. quality of governance). Combining the different states of these drivers (e.g., the amount of oil is low or large), we build a database of model runs (as in Rozenberg et al., 2010). We then obtain several hundreds of scenarios¹ by combining the model outputs with additional external drivers that cannot be included in the model, but that are essential for an analysis on future challenges to adaptation and mitigation.

Once we have constructed the database, we distinguish the scenarios using criteria measuring future challenges to adaptation (e.g., the share of people living below the poverty line) and mitigation (e.g., baseline CO₂ emissions). The scenario discovery algorithms then identify the common characteristics (e.g., the demographic changes, the extent of globalization) that best predict the scenarios where the challenges to adaptation or mitigation are high or low. They help us select a few SSPs that are contrasted along these criteria. For SSPs, the selected scenarios have to be sufficiently general, since they need to be applicable to a large set of research questions and decisions. Therefore, instead of starting from a specific decision, we look to find contrasted scenarios in terms of adaptation and mitigation challenges. But this “scenario elicitation” methodology can be used to build different sets of scenarios, each decision maker choosing the drivers relevant to a particular policy issue and selecting his or her own scenarios from a common database.

To summarize, we propose the following approach for developing SSPs:

¹Note that there is no consensus of the terminology used in scenario analysis. Here, we label each of our model runs a “scenario.” The Robust Decision-Making tradition (Lempert and Groves, 2010) labels these runs “cases” and considers a “scenario” as a set of “case” particularly relevant to the analysis of a given decision.

- (i) We first identify *ex-ante* the main driving forces of the world future challenges to mitigation and adaptation to climate change, based on existing literature (Section 2.2).
- (ii) We then translate these driving forces into model parameters for a global energy-economic model, and we combine these parameters to build a large number of model runs. We also combine model outputs with external drivers (that are not included in the model) to create a large set of scenarios (Section 2.3).²
- (iii) We analyze the resulting database using indicators measuring future challenges to mitigation and adaptation, and we identify *a posteriori* the main driving forces of these future challenges. Then we select five contrasting combinations of drivers to cover the range of possible challenges to adaptation and mitigation (Section 2.4).

The last section discusses how this could define a new approach to the use of scenarios by the climate community. Noting that the most relevant scenarios are often crafted explicitly for specific communities facing specific climate-related decisions (European Environment Agency (EEA), 2009; Parson et al., 2006), this new concept envisions providing data and tools that would allow each user to construct his or her own scenarios as needed, while ensuring broad consistency among users with the underlying base of scientific knowledge.

2.2 THE EX-ANTE DRIVERS OF CHALLENGES TO ADAPTATION AND MITIGATION

Hallegatte et al. (2011) propose three dimensions to explore climate change vulnerability and adaptation challenges, that are described in details in Appendix B.2: (i) Globalization: a “converging” world vs. a “fragmented” world; (ii) Equity: inclusive development vs. “growth and poverty” development; and (iii) Environmental stress: an “environment-oriented” world vs. an “environmentally-stressed”

²The scenario discovery literature generally refers to the entries in the database of model results as cases. Here we use the term scenarios because we have added to the database entries information associated with narratives in addition to the results of model runs.

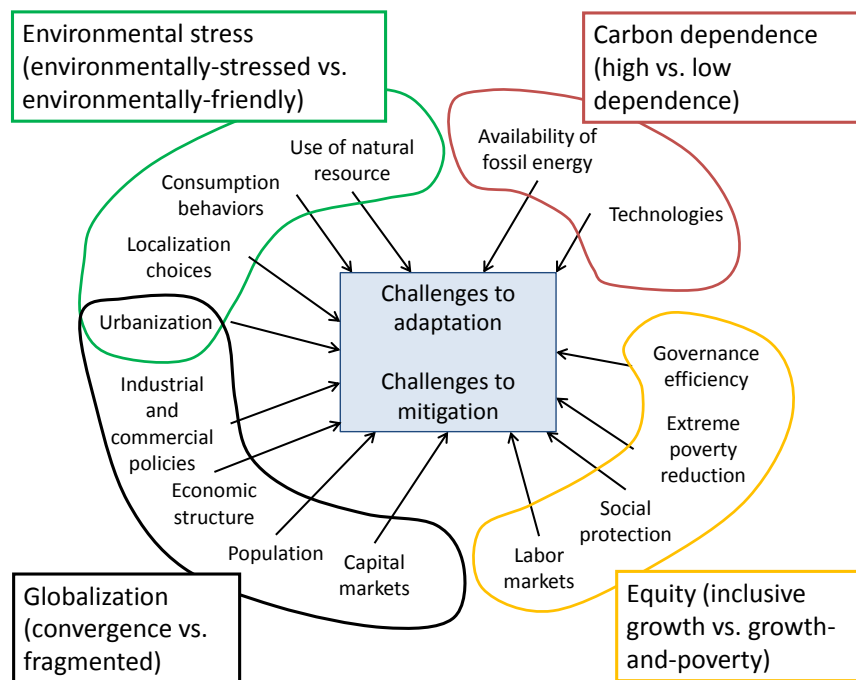


Figure 2.1: Identified drivers of the challenges to mitigation and adaptation, in the four main dimensions.

world. As described in Appendix B.2, these dimensions, along with dependency on fossil fuel, also appear highly relevant to challenges to mitigation.

The resulting four dimensions are shown in Figure 2.1, giving an idea of which parameters can be included in each dimension. The figure suggests that some of these parameters can be included in different dimensions (e.g., urbanization can be included in the environmental/lifestyle dimension or in the convergence dimension), showing that there will always be some flexibility and subjectivity in how our approach is applied. Note also that the literature is not the only place to look for ex-ante drivers of future adaptation and mitigation challenges. Other sources such as expert elicitation surveys (Schweizer and O’Neill, 2013) could also prove valuable. Nonetheless, the drivers considered here should prove more than sufficient for the illustrative purposes of this paper.

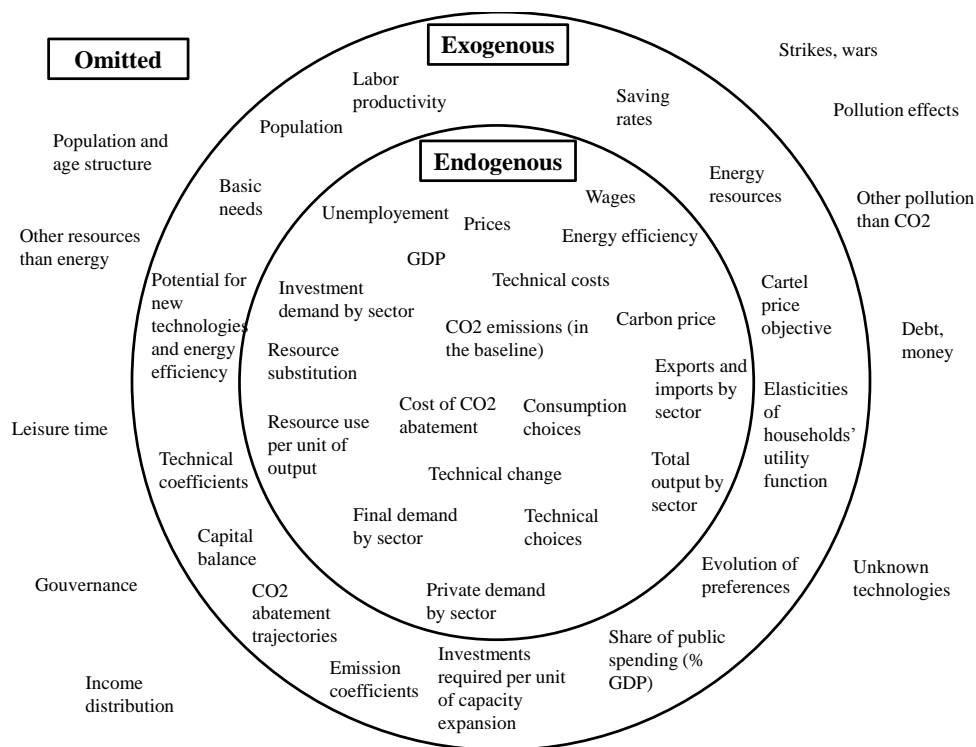


Figure 2.2: Endogenous, exogenous and omitted drivers in the IMACLIM-R model.

2.3 HOW TO BUILD SCENARIOS

There are good reasons to think that these factors represent the major drivers of challenges to adaptation and to mitigation, but this is only an informed guess. Complex mechanisms, interactions, and feedbacks can act on these drivers, and a more sophisticated analysis is possible. To test whether these drivers are well chosen, we translated some of them into model parameters.

To do so, we used the IMACLIM-R model (Rozenberg et al., 2010; Waisman et al., 2012, and Appendix A), which projects the long-term evolution of the world economy and allows us to explore the uncertainty that arises from unknown exogenous trends (e.g., future population) and parameter values that are debated.

For a given model, not all drivers can be translated into input parameters. Indeed, some of the drivers are direct inputs of the IMACLIM-R model (e.g., population), some are the result of upstream hypotheses (e.g., the availability of fossil

energy is the result of hypotheses on oil resources and inertia in the development of production capacities), and some are model outputs (e.g., economic structure). Note that some potential technological breakthroughs such as hyper efficient micro grids or black swans like epidemics are not modeled here.

Figure 2.2 represents the parameters that are endogenous, exogenous or omitted in the IMACLIM-R model. To build a database, parameters must be chosen among the exogenous parameters of the model.

For this exercise, we selected the following drivers to be translated into input parameters of the IMACLIM-R model and considered several alternative values for these parameters to reflect uncertainty on future challenges to adaptation and mitigation:

2.3.1 DIMENSION1: GLOBALIZATION

Population. We use the three UN scenarios (low, median, and high). In a next step, population data defined specifically for the SSPs could be used.

Economic structure. Even though this driver is an output of the IMACLIM-R model, we influence it by introducing three assumptions on the speed of labor productivity convergence (Appendix B.2.2). This parameter influences economic growth in each region, but note that GDP growth is endogenous in IMACLIM-R.

Capital markets. The IMACLIM-R model treats capital balances as exogenous, so we consider two assumptions about global financial imbalances reduction: in the first assumption financial imbalances are phased out exponentially in two decades, whereas in the second assumption they remain constant for the whole simulation period.

2.3.2 DIMENSION2: ENVIRONMENTAL STRESS

Energy sobriety. We make two assumptions (i.e. two groups of hypotheses affecting many different variables) regarding energy sobriety:

- Development patterns: We introduce two assumptions on the evolution of households' preferences (environmentally-inclined or energy-intensive) in transportation and housing (evolution of the number of cars per capita, maximum dwelling surface per capita in developing countries) as well as

on the saturation level of households' industrial goods consumption (Appendix B.2.2).

- **Production choices:** We introduce two alternatives on the freight content of economic growth through alternative evolutions of the input-output coefficient representing the transportation requirement per unit of good produced (Appendix B.2.2).
- **Induced energy efficiency:** Even though energy efficiency is driven by energy prices, we introduce two alternatives for the parameters describing its maximum annual improvement in the leading country and the catch-up speed of the others (Appendix B.2.2).

2.3.3 DIMENSION3: CARBON SUPPLY

Availability of fossil energy. We introduce two assumptions about oil resources (parameters include the amount of ultimately recoverable resources, inertia in the deployment of non conventional oil, the maximum growth rate of Middle-East production capacities), the gas price indexation on the oil price, and the elasticities of coal price growth to demand changes (Appendix B.2.2). Each of these variables can take two different values depending on the assumption.

Availability of low-carbon technologies. We build two assumptions for parameters describing the market penetration of nuclear energy, renewable resources, carbon capture and storage, and electric vehicles. These parameters include learning rates and maximum market shares throughout the simulation period. More details are given for each technology in III.3 in Appendix B.2.2.

2.3.4 DIMENSION4: EQUITY

Dimension 4 has to be treated differently, because IMACLIM-R in its current form cannot include its drivers (inequality within countries). Since the model is based on a representative consumer-worker, it cannot take into account income distribution among consumers-workers. Considering the importance of this driver, it cannot be disregarded. We thus introduce it through an external driver, i.e. that is

not included in the model and does not modify the model outputs, but adds numerical information to the model results to build a scenario. In other words, we add to the model a variable that does not have any feedback on the other variables.

In the current case, we add quantitative information on “equity.” Some of the scenarios are built assuming a global reduction of within-country inequality (an “inclusive growth” set of scenarios), in which the share of income of the 20% poorest in countries increases by 33% by 2090 (e.g., in a country where the 20% poorest receive an income corresponding to 6% of total GDP in 2010, this share increases to 8% in 2090). Others are built assuming a global increase in within-country inequality, with a share of income of the 20% poorest that decreases by 33% by 2090. We therefore create an additional output variable, namely the income of the 20% poorest, which is built from model outputs (GDP per capita in less developed countries) and from this “external” driver.

The result is a set of 286 scenarios³ (see Figures 2.3 and 2.4), each being the combination of (1) a set of model parameters describing the drivers, (2) a model run with these parameters, and (3) additional quantitative information that does not have feedbacks on the other variables but is relevant for challenges to adaptation and mitigation (e.g., in our case, inequalities within countries).

2.4 HOW TO SELECT RELEVANT SCENARIOS

The definition of SSPs as given by the Boulder meeting (O’Neill et al., 2011) is imprecise as to the metrics of climate change adaptation and mitigation challenges, but also as to the range of possible values for these metrics.

To select SSPs using our approach, we must however define indicators for measuring the challenges to mitigation and adaptation. Given the number of possible indicators, this is a difficult task. While much work has been devoted to the question of how to choose such indicators, little agreement exists on how best to do so. For example, Fussel (2010) reviews the many indicators that have been proposed for the challenges to adaptation. He shows that alternative indicators can

³Combining all assumptions creates 288 model runs, but one baseline did not run until the end of the simulation period. Thus, two scenarios are excluded from the database (derived from this model run and the two hypotheses on equity).

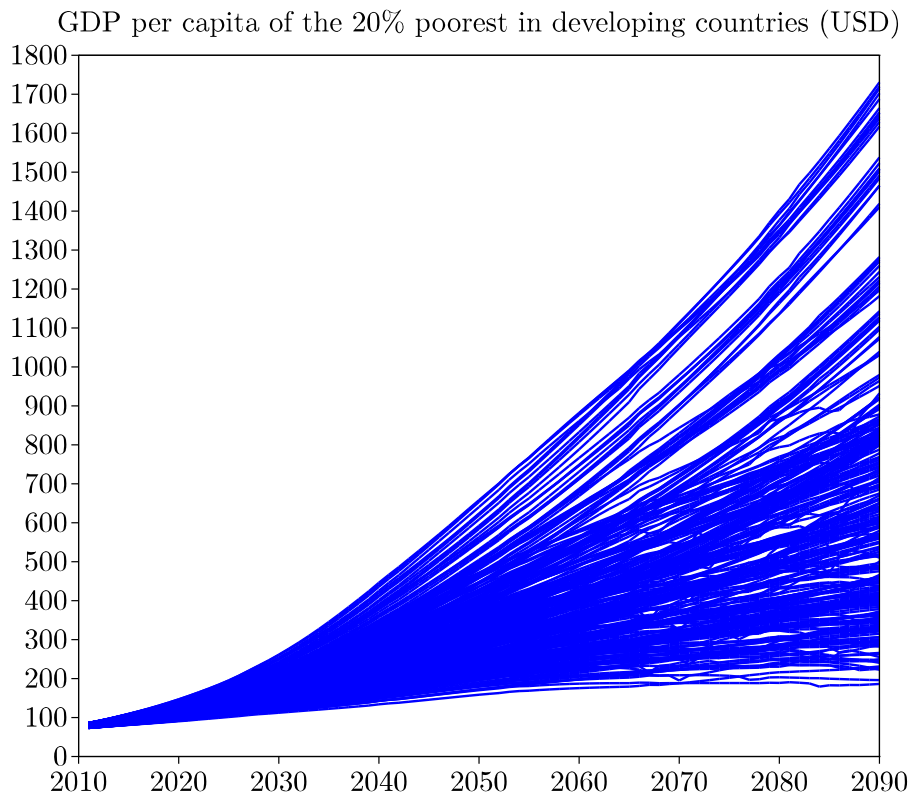


Figure 2.3: GDP per capita of the 20% poorest in a selection of developing countries in 286 scenarios resulting from 143 model runs with IMACLIM-R and two hypotheses on the share of income of the 20% poorest.

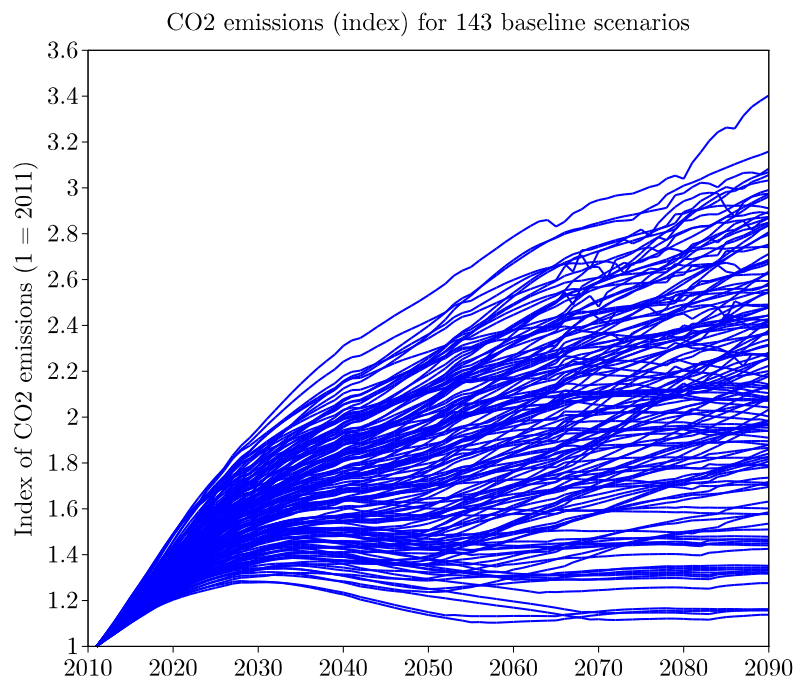


Figure 2.4: CO2 emissions resulting from 143 model runs with the IMACLIM-R model.

lead to very different prescriptions and vulnerability hot spots. He also shows that political considerations, value and ethical judgments strongly influence the choice of indicators related to vulnerability and adaptive capacity. Mindful of these challenges, our analysis adopts very simple indicators, two for mitigation and two for adaptation, which seem sufficient for the illustrative purposes of this study. We note, however, that our proposed methodology can in principle accommodate a large set of alternative indicators.

As one indicator for challenges to mitigation, we chose baseline CO₂ emissions. We are well aware that this measure does not include all components of such challenges. For instance, good governance and reduced inequalities are likely to make it easier to implement mitigation policies, regardless of CO₂ emissions. As a second indicator, we use the GDP losses that would result from a mitigation policy that stabilized radiative forcing at a given level.

For adaptation, no easy indicator is available. Still well aware of the limits, we decided to use the income of the 20% poorest in a selection of developing countries (African countries, India, South America [except Brazil] and South East Asia). Of course, this is a very partial indicator, and it is well known that challenges to adaptation will depend on many other factors, such as governance and technologies (see the review in the Appendix B.2 and in Hallegatte et al., 2011). In the current analysis, we use this simple indicator only to illustrate our methodology and make a first proposal for SSPs. In a second step, we use the share of jobs in agriculture in developing countries.

We next normalize our two indicators (the sum of global emissions over the 2011-2090 period for challenges to mitigation and the discounted income of the 20% poorest in developing countries, over the same period, for challenges to adaptation) and map our 286 scenarios over the resulting space. As shown in Figure 2.5, the scenarios span most combinations of challenges to mitigation and adaptation as defined by these indicators. We then define five regions in this space that correspond to the five SSPs.

In the selection of SSP spaces, we emphasize contrast, i.e., on having scenarios with different challenges to mitigation and adaptation. We do not focus on the “probability” of these scenarios. The “plausibility” is supposed to be ensured in the first phase of this analysis, when the determinants have been chosen and trans-

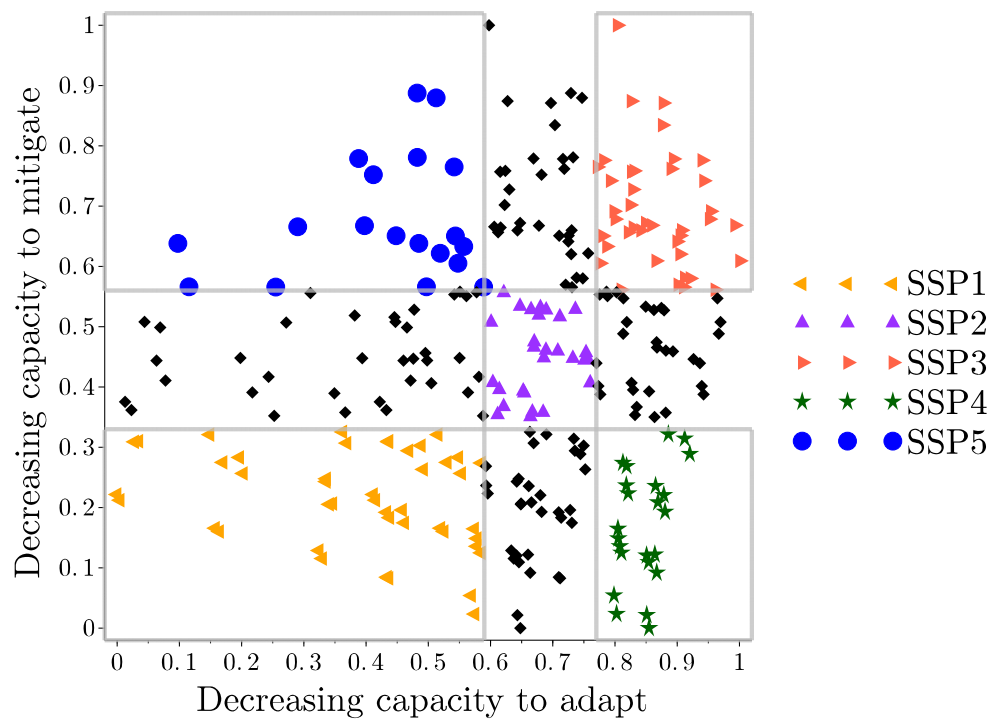


Figure 2.5: Capacities to adapt and to mitigate that define the five SSP spaces and the results of our 286 model runs arrayed in this space.

formed into model parameters. We do not want to focus on probabilities because the ability to assess them appears out of reach and because focusing on the most likely scenarios would lead to disregarding low-probability high-impact scenarios, which might be the most relevant in a risk-management approach. Since we think that the analysis of climate policies is an analysis of climate risks more than anything else, the inclusion of low-probability scenarios in SSPs appears essential.

As previously noted, even though many indicators are available to measure future challenges to adaptation and mitigation, in (O'Neill et al., 2011) the range of uncertainty for these indicators is not defined for each SSP. In our analysis, the range of model outputs depends on the uncertainty we considered on the input parameters, and on the interactions that are modeled between the different drivers. Chapter 3 will indeed show that the endogenization of many drivers sometimes reduces the uncertainty on certain outputs (e.g. CO₂ emissions).

We thus define the SSP space relatively to the resulting uncertainty on model outputs. In other words, the SSP space is delimited by the minimum and maximum values for our indicators across the database (0 and 1 when they are normalized).

To select the five SSP boxes, we choose numerical thresholds for the challenges to mitigation and adaptation indicators that characterize each SSP. Here we choose the two thresholds so that one-third of the scenarios lie below the first and one-third lie above the second (Figure 2.5). This choice results in a significant number of scenarios in each SSP region. One could, however, set thresholds independently of the scenarios distribution, for instance by requiring that all SSP regions have the same area. As described below, we find that in this particular example our results are relatively insensitive to the choice of thresholds. More generally, the choice of threshold and scenario space shapes might usefully be assisted by approaches such as the hierarchical cluster methods used by Gerst et al. (2013).

Having chosen thresholds to define the SSP regions, we can then use a “scenario discovery” cluster analysis to identify the main drivers of each scenario group. “Scenario discovery,” often used to support robust decision making (Lempert and Kalra, 2011; Lempert et al., 2003), provides a computer-assisted method of scenario development that applies statistical or data-mining algorithms to databases of simulation model results to characterize the combinations of uncertain inputs

parameter values most predictive of specified classes of results. Importantly, scenario discovery also suggests which uncertain input parameters have less influence. We apply a modified version of the PRIM (Patient Rule Induction Method) (Friedman and Fisher, 1999) to the 286 scenarios spanning the range of adaptation and mitigation indicators shown in Figure 2.5. A variety of classification algorithms have been used for scenario discovery. PRIM often proves useful in this context because it facilitates users' ability to trade between the accuracy of the scenario descriptions and their interpretability, that is, the ease with which decision makers can understand the information contained in the scenarios (see for example, the comparison between PRIM and the Classification and Regression Tree (CART) algorithm in Lempert et al., 2008).

An SSP is defined by a range of values for the adaptation and mitigation indicators. PRIM seeks a set of drivers that maximize the matching between those drivers and the model scenarios that have the indicator values associated with each SSP. For instance, for SSP₅, we want to find the drivers such that a scenario with these drivers has a high likelihood of being in the upper-left-hand corner of Fig 5 and such that a scenario is in the upper-left-hand corner has a high likelihood of having these drivers. To measure this match, we use three criteria (see Bryant and Lempert, 2010). *Coverage* is the fraction of scenarios consistent with the indicators (e.g. that lie in the SSP₅ corner of Fig 2.5) that are also consistent with the drivers. *Density* is the fraction of all scenarios consistent with the drivers that are also consistent with the indicators.⁴ *Interpretability* represents that ability of decision makers to understand the information by the combinations of drivers and is measured by having a small number of drivers.

Since these three measures are generally in tension with one another, PRIM provides the user a set of options representing different trade-offs among density, coverage, and interpretability.

Table 2.1 shows our results. Each column shows an SSP and the middle eight rows list its potential drivers. A cell filled with black text indicates that a driver plays a significant role in that SSP whereas grey italics text indicates that the driver plays

⁴Coverage is analogous to "sensitivity" or "recall" in the classification and information retrieval literatures. Density is analogous to "precision" or "positive predictive value" in those literatures.

Table 2.1: Combinations of future challenges to adaptation and mitigation in our five SSP spaces as identified by the scenario discovery analysis described in the text. Black/grey italics text indicates more/less important drivers. Coverage and density (rounded) measure the explanatory power of the drivers for each SSP.

	SSP ₁ (15% cases)	SSP ₂ (10% cases)	SSP ₃ (14% cases)	SSP ₄ (8% cases)	SSP ₅ (7% cases)
Equity (2 options)	improved	improved	worsen	worsen	improved
Convergence (3 options)	<i>medium or fast</i>	medium or slow		slow	fast
Energy sobriety (2 options)	high	low	low	high	low
Availability of low C technologies (2 options)			<i>low</i>		
Availability of fossil fuels (2 options)					
Population (3 options)	medium or low	<i>low</i>	high or medium	or medium or low	
Capital markets (2 options)					reduced imbalances
Coverage/Density	70%/65%	45%/40%	80%/65%	90%/90%	50%/75%

a partial role. We distinguish the former from the latter using the resampling test described in Bryant and Lempert (2010). This test runs PRIM on multiple subsamples of the original dataset and notes the fraction of subsamples for which each parameter emerges as an important driver of the scenario definition. We consider a driver that scores greater than 50% in the test as significant and less significant otherwise.

The final row shows the explanatory power of these combinations of drivers, as measured by their coverage and density (rounded at 5%). For instance, the SSP4 column shows that low equity, slow convergence, and high energy sobriety contribute most significantly to SSP4 while medium or low population plays a partial role. The last row says that ninety percent of the cases in the region of Figure 2.5 noted as SSP4 meet these conditions (coverage) and ninety percent of the cases that meet these conditions are SSP4 (density).

Some drivers, such as equity, contribute strongly to all the SSPs. Indeed, this driver has a direct impact on the challenges to adaptation axis, since it was used to calculate the indicator; this driver splits the income of the 20% poorest into two groups, with a compression to the right as GDP per capita decreases. In the same way, the “energy sobriety” driver has a strong impact on challenges to mitigation, since it directly influences CO₂ emissions in the baseline. It also influences the challenges to adaptation because energy sobriety leads to higher GDP, i.e. to less poverty.⁵

The impact of population on the indicators is ambiguous and not always significant. Although one might think that a higher population would reduce GDP per capita in a world with finite resources, a higher population growth rate implies higher potential economic growth in the model, so that challenges to adaptation might decrease. Moreover, higher economic growth accelerates capital turnover and increases the share of low-carbon technologies, thus decreasing challenges to mitigation. The results show, however, that a high population is inconsistent with SSP1 and that a low population is inconsistent with SSP3.

⁵The “energy sobriety” driver contains hypotheses on behaviors, localization choices, and the potential for energy efficiency (energy efficiency is endogenous and driven by energy prices). In scenarios with high energy sobriety, energy prices are lower, accelerating GDP growth. This result warns against the use of exogenous GDP scenarios, developed independently from natural resources and energy modeling.

Other drivers, such as fossil fuel availability and capital markets, contribute to few if any SSPs. The non-significant impact of fossil fuel availability is due to two contradictory effects: on the one hand, a constrained oil supply induces substitution toward coal, which emits more CO₂ for the same energy service. On the other hand, it also induces higher energy prices, which trigger faster energy efficiency. In the same way, low-carbon technologies contribute to only one SSP because they tend to slow down energy efficiency through lower energy prices, which lessens their effect on carbon emissions.

An interesting result of this analysis is the difficulty in finding scenarios corresponding to SSP₅ (i.e., scenarios with both high baseline emissions and high GDP growth). Indeed, to include one-third of all scenarios above the first threshold for adaptation challenges, we had to define it at a high value, around 0.6 (Figure 2.5). As already mentioned, GDP growth is affected by energy consumption and sobriety. If energy consumption is too high — and energy efficiency too low — energy prices are so high that GDP growth is significantly reduced, especially in developing countries. This explains why there are few scenarios with high economic growth and high baseline emissions. This result however depends on the indicator considered, and taking a different indicator for challenges to mitigation helps finding SSP₅ scenarios (section 2.4.2).

Another conclusion of the analysis is the difficulty to define a unique SSP 2. Indeed, coverage only reaches 45%, which means that 55% of the scenarios identified as potential SSP₂ in Figure 3 corresponds to other drivers than those identified in Table 2.1. In other terms, there are other sets of drivers that could lead to scenarios with medium challenges to adaptation and mitigation. This quantitative result is consistent with discussions in the Boulder meeting in November 2011 (O'Neill et al., 2011) and the proposition to have several versions of SSP₂.

Eventually, this representation allows testing the ex-post relevance of our drivers on our indicators. The hypotheses that we made about financial markets and the future reduction of imbalances are not a posteriori main drivers of the world challenges to adaptation and mitigation, except for SSP₅. These results must be moderated, however, because they depend significantly on the choice of indicators and on the delimitation of the SSP spaces.

2.4.1 SCENARIO DISCOVERY ANALYSIS WITH DIFFERENT SSP DOMAINS

As previously discussed, in our analysis the SSP space is defined around the minimum and maximum values for the indicators across the database. The definition of each SSP domain within this space is however debatable, and to test sensitivity to the choice of threshold for the SSP regions, we repeated the analysis a third time using same-sized SSP domains with a diamond-shaped domain corresponding to SSP₂⁶ (Fig. 2.6 and table 2.2).

This definition of the domains is independent of the scenario distribution inside the SSP space. Such a definition would make more sense if the whole SSP space was defined in absolute terms. Also, defining the space in absolute terms would allow comparing scenarios from different models and databases. Since it not the case, for an illustrative purpose we make the heroic assumption that the range of uncertainty resulting from our scenario database covers the uncertainty that the scientific community wants to consider for the SSPs.

The results share many similarities with those of the first analysis: convergence, availability of low-carbon technologies and capital markets explain all SSPs in the same way as in the first analysis. SSP₁ is explained by the same drivers as in the first analysis, except that population does not matter anymore. Similarly, the results for SSP₅ are constant except that low energy sobriety is replaced by high availability of fossil fuels. Note that both drivers increase CO₂ emissions, but may have opposite impacts on GDP: low energy sobriety may reduce GDP (see chapter 3) while high availability of fossil fuels increase GDP (see chapter 4).

As they contain much more scenarios than in the first analysis, SSP₃ and SSP₄ domains are explained by a smaller number of drivers: SSP₃ is only explained by low energy sobriety and low availability of low-carbon technologies while SSP₄ is explained by a medium or slow convergence and high energy sobriety.

Moreover, since the scenario distribution is compressed to the right of the domains, the equity driver is no longer significant for SSP₃ and SSP₄. In other words, SSP₃ and SSP₄ domains include scenarios with both high and low equity assumptions.

⁶We credit the idea for a diamond-shaped domain corresponding to SSP₂ to Jae Edmonds of the GCAM modeling group at the Joint Global Change Research Institute.

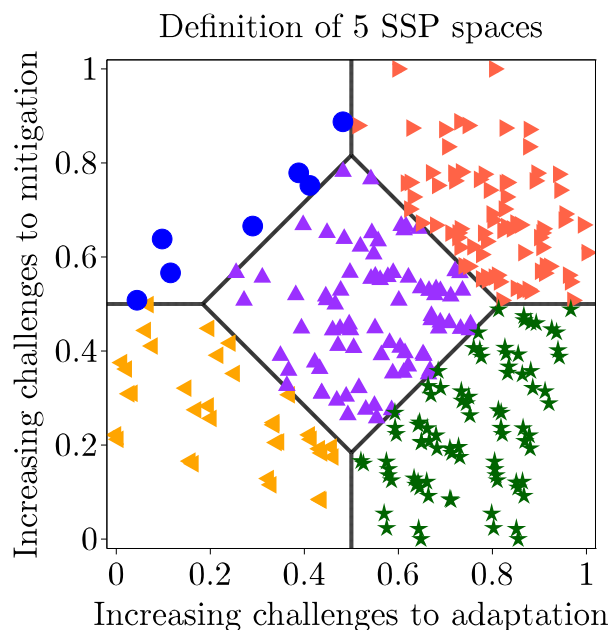


Figure 2.6: Delimitation of five SSP spaces using different thresholds and the same indicator as in the first analysis. The boundaries between the domains for SSP3 and SSP5, as well as SSP1 and SSP4, are demarcated by the midpoint of the normalized interval ($x = 0.5$ and $y = 0.5$). The boundaries of the SSP2 domain were chosen such that all five domains would have the same area.

Table 2.2: Combinations of future challenges to adaptation and mitigation for our five SSP spaces as identified by different SSP domains. Framed results are the similarities with Table 2.1. *The small red italicized text recalls the results in Table 2.1 when there is a difference.* Coverage and density measure the explanatory power of the drivers for each SSP.

	SSP ₁ (12% cases)	SSP ₂ (28% cases)	SSP ₃ (27% cases)	SSP ₄ (30% cases)	SSP ₅ (2% cases)
Equity (2 options)	improved	worsen <i>(improved)</i>	<i>(worsen)</i>	<i>(worsen)</i>	improved
Convergence (3 options)	medium or fast	medium or slow		medium or slow <i>(slow)</i>	fast
Energy sobriety (2 options)	high	<i>(low)</i>	low	high	<i>(low)</i>
Availability of low C technologies (2 options)			low		
Availability of fossil fuels (2 options)					high
Population (3 options)	<i>(medium or low)</i>	<i>(low)</i>	<i>(high or medium)</i>		
Capital markets (2 options)					reduced imbalances
Coverage/Density	95%/70%	45%/95%	70%/75%	75%/70%	85%/50%

This movement of the domains leads to a contradictory result for SSP₂: improved equity was a significant driver in the first analysis while worsened equity is now significant. Note that this is the only contradictory result and that here again, coverage is bad (45%) for SSP₂, which confirms that it is very difficult finding a storyline for this SSP.

Eventually, we find that in this particular example our results are relatively insensitive to the choice of domain definition. To improve the methodology, approaches such as the hierarchical cluster methods used by Gerst et al. (2013) might be useful to identify the thresholds between scenario groupings. This may help identify more natural breakpoints and alternative shapes for scenario domains. Such an approach will be investigated in chapters 3 and 5.

2.4.2 SCENARIO DISCOVERY ANALYSIS WITH DIFFERENT INDICATORS

Using the same threshold definition as in the first analysis, we repeat the analysis using a different set of indicators. As an indicator of future challenges to mitigation, we calculate the GDP losses from a mitigation policy reducing emissions to stabilize radiative forcing at a given level (we retain a target at 3.7 Wm^{-2}). For adaptation challenges, we use the share of jobs in agriculture in developing countries.

The results of this third analysis share some similarities with those of the first one (table 2.3); for example, convergence is slow for SSP₄ and fast for SSP₅; energy sobriety is high for SSP₁ and low for SSPs 3 and 5. But significant differences can also be noted. For instance, low-carbon technologies become significant in SSPs 1, 3, 4 and 5. This is due to the mitigation challenges indicator (i.e., the cost of a mitigation policy): low-carbon technologies help meet the climate objective at a lower cost without slowing down energy efficiency, which is triggered by the carbon tax in all scenarios. In this third analysis, capital markets are significant in three SSPs because they have an impact on the adaptation challenges indicator: a reduction of financial imbalances (as in SSP₁ for instance) induces developing countries to invest more locally. This accelerates structural change and reduces the share of jobs in agriculture.

Table 2.3: Combinations of future challenges to adaptation and mitigation for our five SSP spaces as identified by different indicators (share of jobs in agriculture in developing countries and GDP losses from a mitigation policy). Framed results are the similarities with Table 2.1. *The small red italicized text recalls the results in Table 2.1 when there is a difference.* Coverage and density measure the explanatory power of the drivers for each SSP.

	SSP ₁ (9% cases)	SSP ₂ (6% cases)	SSP ₃ (14% cases)	SSP ₄ (7% cases)	SSP ₅ (13% cases)
Equity (2 options)					
Convergence (3 options)	<i>(medium or fast)</i>	medium <i>(medium or slow)</i>		slow	fast
Energy sobriety (2 options)	high	<i>(low)</i>	low	<i>(high)</i>	low
Availability of low C technologies (2 options)	High		low	high	low
Availability of fossil fuels (2 options)					
Population (3 options)	<i>(medium or low)</i>	medium <i>(low)</i>	high or medium		
Capital markets (2 options)	reduced imbalances			Constant imbalances	<i>(reduced imbalances)</i>
Coverage/Density	50%/80%	30%/60%	55%/90%	90%/85%	60%/45%

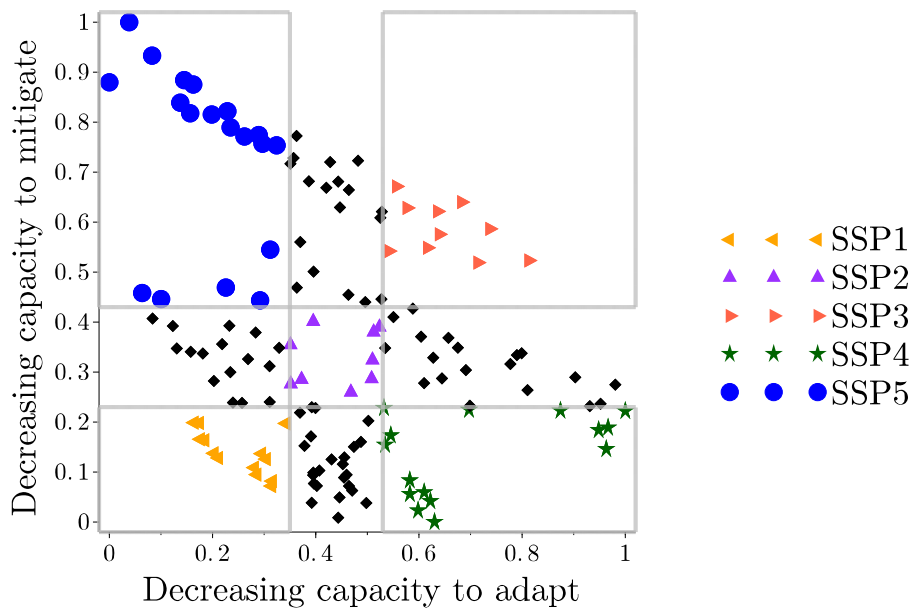


Figure 2.7: Delimitation of five SSP spaces using different indicators (share of jobs in agriculture in developing countries and GDP losses from a mitigation policy reducing emissions in order to stabilize radiative forcing at a given level).

2.4.3 STABLE SCENARIOS ACROSS INDICATORS

The similarities and differences in the two analyzes with different criteria for challenges to mitigation and adaptation constitute a first indication of the robust results for SSPs development. To go further, we consider only scenarios that are in the same SSP domain for both sets of indicators. For each SSP domain, only about ten scenarios are stable to a change of indicators, and they have a few drivers in common:

- **SSP1 (11 scenarios):** these scenarios are characterized by a high availability of low-carbon technologies, energy-sober behaviors and a reduction in financial imbalances. Low-carbon technologies reduce challenges to mitigation by allowing emission reductions at a relatively low cost, while energy-sober behaviors reduce the total amount of emissions that need being abated. At the same time, these sober behaviors release financial resources for growth in low-energy sectors. This is amplified in developing countries by a reduction of financial imbalances, which increase growth and accelerate structural

chance towards the tertiary sector.

- SSP₂ (5 scenarios): there is no common characteristic to those scenarios.
- SSP₃ (7 scenarios): these scenarios are the exact opposite of the SSP₁ scenarios, and are characterized by a low availability of low-carbon technologies, energy-intensive behaviors and maintained financial imbalances. Energy-intensive behaviors and maintained financial imbalances constrain economic growth in low income countries, making them vulnerable to climate change. Globally, energy-intensive behaviors create high carbon emissions and the high cost of low-carbon technologies increase challenges to mitigation.
- SSP₄ (11 scenarios): these scenarios are characterized by low equity, low convergence and maintained financial imbalances. A conjunction of bad macroeconomic conditions (low convergence and maintained financial imbalances) leads to low economic growth in developing countries and very slow structural change (low income countries still rely heavily on the agricultural sector). As a consequence, carbon emissions are low globally and mitigation costs remain relatively low. A slow reduction of inequalities worsen the condition of the poorest in developing countries, who are very vulnerable to climate change.
- SSP₅ (10 scenarios): these scenarios all have a high convergence, nine of them have a low availability of low carbon technologies and nine of them have reduced financial imbalances. High convergence and reduced financial imbalances create high GDP growth in developing countries, and therefore quick structural change and low adaptation challenges but also relatively high emissions. In addition to high emissions, the high cost of low-carbon technologies make it costly to mitigate climate change.

These results confirm that it is difficult to find a unique set of drivers defining SSP₂; this intermediate scenario can be represented by very different futures. They also show that the relevant set of drivers depend on which SSP is considered. Interestingly, SSP₁ and SSP₃ are defined by the same set of drivers — but with opposite values — that mainly describes the energy system (technologies and energy

intensity). Conversely, SSP₄ and SSP₅ are characterized by assumptions on socioeconomic aspects, and particularly equity and economic convergence.

This analysis remains preliminary and the robustness of its results would be increased by the inclusion of additional driver values, additional drivers, alternative selection criteria, and more models. In particular, combining different models with different designs would be key to improve our confidence in the SSP determinants, because it would help assess the uncertainties surrounding the model structures. Indeed, the coherence that we find for a certain set of drivers depends on modeling choices and might be called into question by other models. For instance, Wang et al. (2013) look for the drivers of future CO₂ emissions and find that the three variables selected empirically as strong predictors are the population size in 2100, the relative efficacy of R&D with respect to labor productivity to produce consumer goods and the relative efficacy of carbon free energy technology.

2.5 CONCLUSION AND FURTHER CHALLENGES

A central goal of scenario exercises is to inform the development of robust strategies, that is, strategies that perform better than the alternatives over a wide range of plausible future states of the world. When this process is successful, it can be surprising that uncertain factors do not affect the relative performance of a robust strategy.

Such context dependence of the most important scenarios for decision making presents both an opportunity and a challenge for the choice of socioeconomic scenarios. The opportunity is that it provides a clear definition of the most policy-relevant scenarios - those that most directly inform the trade-offs among strategies. But it also suggests the need for different sets of scenarios for different decisions.

But as a first step, we propose in this paper an illustration of how this methodology could be applied to define a first set of SSPs, appropriate for a broad range of decisions concerning climate policies, including mitigation and adaptation. We show that this approach allows for the development of five baseline SSPs that have very different challenges to adaptation and mitigation (at least according to the very simple indicators we used in this study).

Most importantly, the development of SSPs will not be a one-shot exercise. In-

stead, it will be a continuous process of refinement. The methodology that is proposed here could be applied to an increasingly large set of scenarios produced using different methods and models. The methodology would indeed be particularly relevant if a large number of diversified models are used to construct the scenario database in which SSPs are selected. Also, it would be particularly useful to develop a large set of selection criteria, which could be used to select SSPs that are particularly adapted to a specific problem.

Over the long term, one can imagine a large multi-model scenario database and a diversity of selection criteria that can be used to identify which scenarios are most relevant for a given category of decisions. A web-based tool could then be proposed to allow decision makers to select the few scenarios that they need to consider in their decision making process. Such a tool would benefit from the multiplicity of models available in the literature. It would also avoid the difficult selection of a few marker scenarios, which will inevitably oversimplify the reality and result in the discarding of a lot of useful information.

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3

The determinants of future CO₂ emissions

The persistent increase in global CO₂ emissions since the beginning of the twentieth century is the result of many driving forces that include *inter alia* population growth, fossil fuels discoveries or technical change. Decomposition methods have proved very useful for analyzing the drivers of past CO₂ emissions and are now accepted as an analytical tool for policymaking on national energy and environment issues (Raupach et al., 2007; Ang and Zhang, 2000). In particular, they are used to understand the driving forces behind energy demand and supply, material flows and dematerialization, and allow interpreting CO₂ emissions growth rate as a function of several “determinants” that can be influenced by policies. The Kaya decomposition, for instance, decomposes emissions growth as the product of population times GDP per capita times the energy intensity of GDP times the carbon content of primary energy (Kaya, 1990). Such decomposition shows that since 2000 global emissions growth was driven by a slowing down or reversal of earlier

declining trends in the energy intensity of GDP and the carbon intensity of energy, coupled with continuing increases in population and GDP per capita (Raupach et al., 2007).

When it comes to building scenarios about future emissions growth, one must be careful with the use of decomposition techniques. The Kaya components should not be considered as the fundamental driving forces of emissions, that may include for instance natural resources, consumption behaviors, localization choices or technical change. Also, it is important to keep in mind that the four components are not independent from each other. For instance, Duro and Padilla (2006) show that in high-income countries the energy intensity of GDP has been anti-correlated with per-capita GDP growth for the past decades. There is no such thing as a linear link between population and CO₂ emissions growth, and this link depends instead on the real (or modeled) interactions between demographics, economic growth, technology and economic structure (Nakicenovic et al., 2000).

As a consequence, the Kaya decomposition cannot be used to build scenarios about future energy consumption or CO₂ emissions, but it can be applied to the results of scenario exercises, as in the SRES exercises (Nakicenovic et al., 2000).

Building scenarios of future emissions growth requires modeling the many interactions between CO₂ emissions and their potential drivers, including population, economic growth, technical change and fossil resources. Integrated Assessment Models (IAMs) have been built with this objective in mind, and feature detailed representations of technical systems and their interaction with the economy, including endogenous technical change (Kohler et al., 2006; Scricciu et al., 2013).

With increasing complexity in the representation, however, increasing uncertainty is dragged in the process. IAMs include hundreds of exogenous parameters that describe unknown trends (e.g., future population) or encompass poorly understood mechanisms (e.g., the evolution of consumption preferences), therefore resulting in a wide range of possible future CO₂ emissions between models (Nakicenovic et al., 2000) and within models (Webster et al., 2002). Yet, it is difficult to know if this wide range of results overestimates or underestimates the plausible range of future emissions. On the one hand, only known technologies and fossil resources are included in emissions scenarios (e.g., in the early 2000's no model would include shale gas in their projections) and projected GDP or labor produc-

tivity trends do not radically deviate from the past. On the other hand, it is possible that some non-modeled mechanisms would reduce the range of results if included (e.g. an omitted negative feedback loop between some elements of the system).

Here, we claim that reducing this uncertainty by finding the “best guess” value for uncertain parameters or finding the most appropriate representation of controversial mechanisms is counter-productive. Instead, considering all possible scenarios and using statistical data analysis techniques to identify the most important determinants of future emissions as modeled by IAMs brings useful insights (Gerst et al., 2013).

This chapter builds a database of future emissions scenarios using an IAM called *IMACLIM-R*. This model is particularly relevant to our exercise as it endogenizes three of the four Kaya components: per-capita GDP, the energy intensity of GDP and the carbon intensity of energy. It has a hybrid structure in the sense that energy is explicitly represented in both money metric values and physical quantities, and it combines bottom-up information with a general equilibrium framework. This dual vision of the economy is a precondition to guaranteeing that the projected economy is supported by a realistic technical background and, conversely, that any projected technical system corresponds to realistic economic flows and relative prices. The *IMACLIM-R* model thus produces scenarios with a strong consistency on the interplay between development patterns, technology and growth.

The scenario database is computed from the combination of hypotheses on selected exogenous parameters representative of technical choices in the supply side and in the end-use equipments, structural changes in the final demand for goods and services (dematerialization of growth patterns), microeconomic behaviors with imperfect foresight and macroeconomic dynamics.

As a first step the database is analyzed in terms of Kaya components. We find that on average across the database, population and per-capita GDP contribute to emissions growth, offset by a decrease in the energy intensity of GDP. The carbon content of primary energy, however, barely varies between 2010 and 2050 in our scenarios. This result is very robust over the database, as the carbon content of primary energy stays almost constant in all scenarios. Conversely, the growth of per-capita GDP and energy intensity of GDP are very uncertain across the database and contribute to the uncertainty surrounding future emissions. Nevertheless,

the growth rates of GDP per capita and of the energy intensity of GDP are anti-correlated, thus reducing the overall uncertainty on future emissions.

Data-mining techniques are then used to find the combinations of exogenous parameters that best determine future CO₂ emissions in the model. We find that the exogenous parameters driving the future availability of coal and unconventional oil are the main drivers of future CO₂ emissions in our model. Surprisingly enough, these parameters do not increase CO₂ emissions through an increase in the carbon content of energy (since we have shown that this Kaya component barely varies during the first half of the 21st century in our scenarios), but through higher activity growth.

To better understand the results, we apply the same statistical data analysis techniques to the Kaya components and show that per-capita GDP and energy intensity are both driven by exogenous assumptions on energy efficiency and consumption behaviors. The main driver of CO₂ emissions – coal and unconventional availability – is however absent from the Kaya analysis.

To go further, the chapter is completed by a Structural Decomposition Analysis (SDA) to disentangle structural change from increases in activity. Correlations between factors are lower with such decomposition, and we show that the activity effect (increase in production per capita) is the main determinant of future emissions and it is mainly driven by the availability of coal and unconventional fuels. This effect is offset by structural and energy intensity effects, which are caused by energy efficiency and behaviors hypotheses.

SDA therefore proves very useful for explaining future emissions as it decorrelates the factors and explains why future fossil fuels availability is the main driver of emissions in this particular database.

Identifying the main drivers of future emissions – among all the interactions that are accounted for in IAMs – can help focus policymakers' attention on reducing the uncertainty surrounding these drivers. With the *IMACLIM-R* model, we have shown that the availability of coal and unconventional fuels was the main driver of future emissions through an increase in activity (and not in the carbon content of energy). This effect can however be mitigated by structural change and energy efficiency. In the absence of a carbon price, one way of reducing future emissions would thus be to limit the access to new sources of fossil fuels, while

implementing structural policies and promoting energy efficiency.

The remainder of this chapter is structured as follows: section 3.1 briefly recalls the past evolution of Kaya components and describes the construction of the database. Section 3.2 looks for the main drivers of CO₂ emissions and of the Kaya components among the model exogenous parameters. Section 3.3 performs a Structural Decomposition Analysis and section 3.4 concludes.

3.1 HISTORICAL TRENDS AND OVERVIEW OF THE DATABASE

The Kaya identity is frequently used to analyze the drivers of past carbon emissions. It decomposes emissions as follows:

$$\text{CO}_2 = \text{pop} \times \frac{\text{GDP}}{\text{pop}} \times \frac{\text{TPES}}{\text{GDP}} \times \frac{\text{CO}_2}{\text{TPES}} \quad (3.1)$$

It is derived from the more general IPAT identity, which states that Human Impact (I) on the environment equals the product of P= Population, A= Affluence, T= Technology. GDP per capita is thus often referred to as “affluence” in the literature (Waggoner and Ausubel, 2002).

In the Kaya identity, technology is decomposed into the energy intensity of GDP and the carbon content of primary energy. The energy intensity of GDP encompasses both the structure of the economy (whether it is mainly based on services or on energy-intensive industrial and manufacturing sectors) and the energy-efficiency of each sector. The carbon content of primary energy depends on the technical choices that have been made for energy production.

If we define x as the average growth rate of CO₂ emissions between 2010 and 2050 ($x = \left(\frac{\text{CO}_2(2050)}{\text{CO}_2(2010)}\right)^{1/40} - 1$) we can write:

$$\log(1 + x) = \log(1 + x_p) + \log(1 + x_g) + \log(1 + x_e) + \log(1 + x_c) \quad (3.2)$$

Where the x_i are the average growth rates of the different factors. Equation 3.2 can be approximated, for small variations of the x_i , by $x = x_p + x_g + x_e + x_c$. The Kaya decomposition therefore allows easily interpreting future CO₂ growth rates as the sum of the factors growth rates.

Even though the Kaya decomposition is useful to interpret future CO₂ emissions, its components should not be considered as the fundamental driving forces of emissions, that may include for instance natural resources, consumption behaviors, localization choices or technical change.

Also, it is important to keep in mind that the four components are not independent from each other. For instance, an increase in working population can directly increase GDP per capita while an improvement in education can reduce fertility rates but accelerate growth through a higher labor productivity. An acceleration of growth can lead to faster resources depletion and higher emissions, but can also accelerate technical change and therefore improve the energy intensity of GDP, as well as the carbon content of primary energy. On the other hand, high energy intensity of GDP can increase energy prices if resources are limited, thus reducing GDP growth.

3.1.1 HISTORICAL DATA

Globally, emissions have been growing at about the same pace as GDP per capita for the last twenty years: they have increased by 50% between 1992 and 2010 while GDP per capita has increased by 45% (Fig. 3.1). The carbon content of energy has barely moved between 1992 and 2010, while the energy intensity of GDP has decreased by 20% in 20 years. These results however hide large discrepancies between income groups and regions.

In high income countries, emissions grow slower than GDP per capita thanks to high energy efficiency improvements that reduce the energy intensity of GDP and a relatively small decrease in the carbon intensity of primary energy. GDP growth and energy intensity of GDP are anti-correlated in those countries (Duro and Padilla 2006): higher GDP growth induces accelerated investment in new efficient technologies while improvements in energy efficiency reduce energy costs and increase GDP. As a result, in high income countries emissions grow as the same pace as population (they have increased by 7% between 1992 and 2010) while GDP has increased by 36% between 1992 and 2010.

In low and middle income countries, emissions and GDP per capita have more than doubled between 1992 and 2010, while the energy intensity of GDP has been

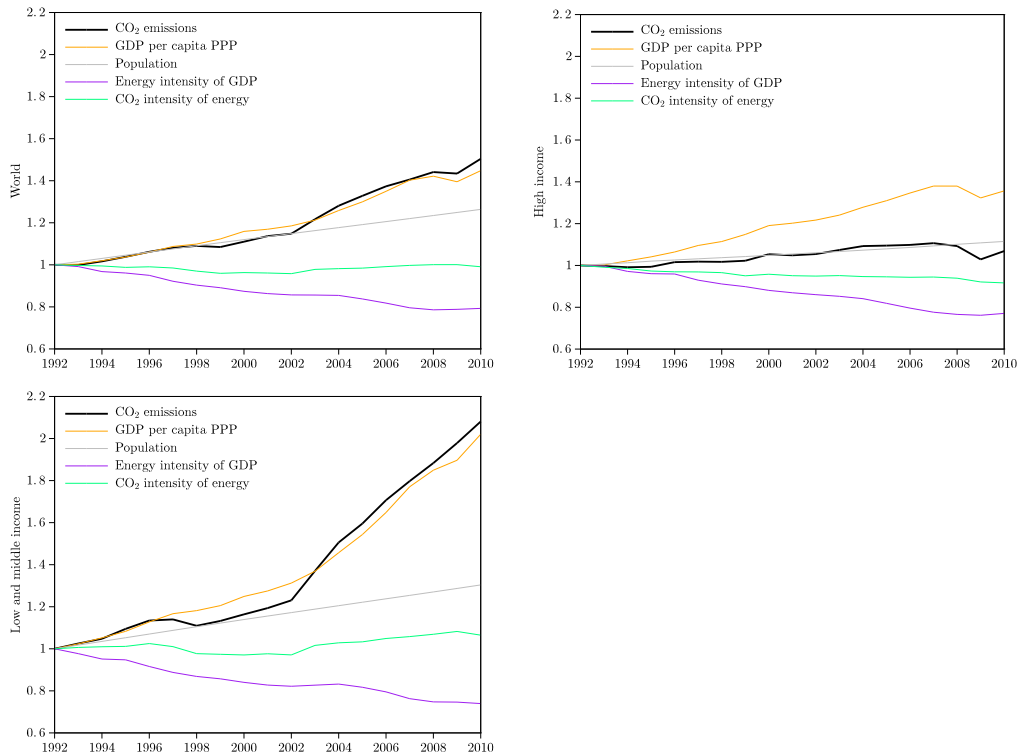


Figure 3.1: Historical Kaya components indexes (1=1992). Source: World Bank data.

reduced by 27%. This results are mostly due to the large share of India and China in developing countries' emissions. Middle-East, North Africa and Latin America have seen their CO₂ emissions increasing faster than GDP per capita in the past ten years, while Eastern Europe and Central Asia have been decarbonizing their economy since the beginning of the 1990s, thus increasing GDP per capita faster than emissions.

3.1.2 CONSTRUCTION OF THE DATABASE

To explore the determinants of future CO₂ emissions, a database of several hundred scenarios is built with an IAM called *IMACLIM-R* (?). Hundreds of uncertain parameters are selected and grouped in seven categories: (i) leader growth, which prescribes evolutions of labor productivity growth and population growth in the US; (ii) low-income countries' catch-up, which gives catch-up speed towards the

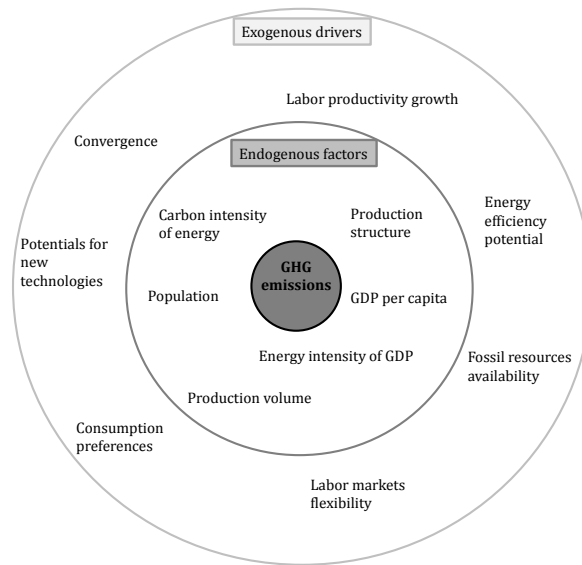


Figure 3.2: Exogenous drivers and endogenous factors determining CO₂ emissions within the IMACLIM-R framework.

leader’s labor productivity level and population growth in low-income regions; (iii) consumption behaviors, which describe households’ preferences and basic needs for transportation and living surfaces, and the freight content of the economy, a proxy for localization choices; (iv) energy efficiency, which groups the parameters governing the evolution of energy input per unit of goods and services produced and its reaction to energy prices; (v) the availability of low carbon technologies, which describes potentials and learning-by-doing curves for new generation of nuclear plants, renewables, CCS and electric vehicles; (vi) the availability of unconventional fossil fuels, such as shale oil and gas and coal-to-liquids; (vii) labor markets flexibility. Within each group, two or three alternative values are selected for each parameter based on existing literature. These sets of alternatives are then combined to run 288 baseline scenarios. No climate policy is modeled, in particular not those that were implemented after 2001.

Figure 3.2 summarizes the different kinds of CO₂ determinants considered in this chapter, and whether they are endogenous or exogenous given the model and database we are using. In a different framework other exogenous drivers or endogenous factors could be included (or would be excluded).

For the sake of simplicity, only world aggregates are considered for emissions

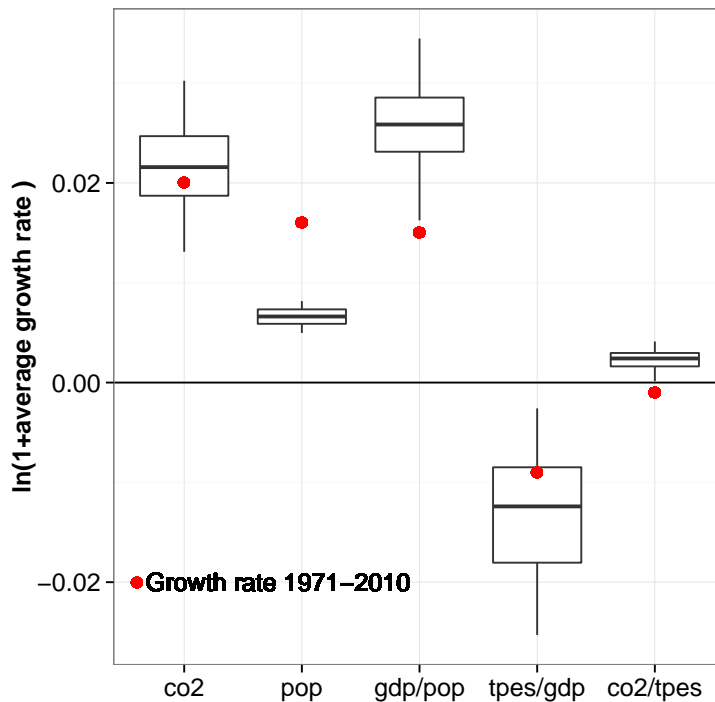


Figure 3.3: Box plot for the average yearly growth rate over 2010-2050 for the emissions and the four Kaya components, for all scenarios. The box displays the first and third quartiles while the whiskers extend to the maximum and minimum data values. Red dots show the historical average growth rate between 1980 and 2010.

and their drivers. Accordingly, global analysis is incomplete because of the great heterogeneity among populations with respect to GHG emissions, and a thorough assessment would necessitate to decompose emissions and drivers by country or main region.

3.1.3 OVERVIEW OF THE SCENARIO DATABASE

Figure 3.3 summarizes the four Kaya components growth rates for the 288 scenarios, between 2010 and 2050. It displays the historical average growth rates between 1971 and 2010 for comparison.

In these scenarios global population always increases by hypothesis, at a slower rate than historical trends (0.66% per year on average).

Consistently with past trends (Hamilton and Turton, 2002; Raupach et al., 2007), on average in our scenarios, GDP per capita is the main contributor to the emissions growth rate, offset by the energy intensity of GDP.

On average over the database, global GDP per capita increases by 2.6% per year between 2010 and 2050, while energy intensity decreases by 1.3% per year. Note that these rates are higher than historical trends, thanks to high growth and energy efficiency improvements in China and India in the first decades of the simulations.

The carbon content of primary energy, interestingly, barely changes for all scenarios: in the fastest scenario it increases by 0.41% per year, and on average over the database it increases by 0.23% per year. This means that in the absence of climate policies the world is not likely to decarbonize its energy supply by 2050, consistently with past trends (Raupach et al., 2007). Indeed, in our model low-carbon technologies for energy production do not gain large market shares in the absence of a carbon price.

3.1.4 UNCERTAINTY

Figure 3.3 shows that the uncertainty (i.e. the variance of the components) is not homogeneous among the different Kaya components. The exogenous uncertainty around future population growth is small as regard to the endogenous uncertainty surrounding future per-capita GDP growth and energy intensity growth. As for the carbon intensity of energy, its growth is similar in all scenarios, meaning that the stability of carbon intensity is a robust result across the database.

Interestingly, combining the uncertainty on various input parameters with the IMACLIM-R model leads to large uncertainty on future per-capita GDP growth rates, but very small uncertainty on the carbon content of energy. This means that the uncertainty considered on the availability of low-carbon technologies is canceled by the model behavior in those scenarios. Indeed, the parameters describing the availability of low-carbon technologies include the development potential of these technologies and their learning rate. However, if fossil energy prices remain relatively low, agents do not invest in those technologies, which therefore never penetrate the markets on a large scale even though they have large potentials and high learning rates. In our set of baseline scenarios, it seems that fossil resources (oil,

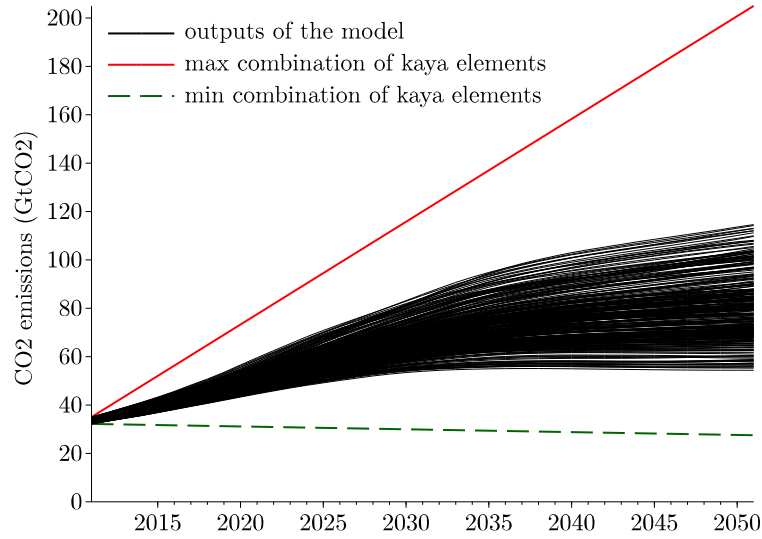


Figure 3.4: CO₂ emissions for the scenario database, and emissions levels in 2050 using the maximum and minimum growth rates given by Kaya components. The model significantly reduces the uncertainty on CO₂ emissions.

gas and coal) are sufficient to sustain the profitability of fossil-fueled technologies as regards to low-carbon technologies whatever the hypotheses on supply and demand.

As already mentioned, it is important to recall that given the interdependences between Kaya components, the uncertainty on CO₂ emissions is not a combination of the uncertainty on Kaya components (and in particular of per-capita GDP and energy intensity of GDP). We illustrate this in Fig. 3.4. Combining the maximum and minimum average growth rates for all four components, we compute CO₂ emissions in 2050 using the Kaya decomposition and show that it overestimates the range of emissions resulting from model runs. Indeed, the maximum emissions that would be obtained in 2050 when combining the Kaya elements are around 200 GtCO₂, while the actual maximum emissions found by the model are around 110 GtCO₂, i.e. nearly 50% lower. The feedbacks between Kaya components that are modeled in the IMACLIM-R model thus decrease the uncertainty around future emissions.

	pop	gdp/pop	tpes/gdp	eco2/tpes
pop	1.00			
gdp/pop	-0.24	1.00		
tpes/gdp	0.02	-0.80	1.00	
eco2/tpes	0.00	-0.06	0.29	1.00

Table 3.1: Correlation coefficient between the average annual growth rates of the different Kaya factors.

3.2 ANALYSIS

3.2.1 CORRELATIONS

To have a better understanding of the links between the Kaya components in the IMACLIM-R model, we compare their growth rates two by two over the whole scenario database. We find that the growth rate of population and of carbon intensity of primary energy are mostly independent from the other components growth rates (table. 3.1). The impact of population on other components is indeed complex. Although one might think that a higher population would reduce GDP per capita in a world with finite resources, a higher population growth rate implies higher potential economic growth in the model. The correlation coefficient between population and GDP per capita growth rates is indeed negative (-0.24) but it is therefore rather small. Moreover, even though higher energy intensity requires to use more carbon-intensive energy resources (such as coal and unconventional fuels), the correlation coefficient between energy intensity of GDP and carbon content of energy is only 0.29.

On the other hand, the growth rates of GDP per capita and the energy intensity of GDP are strongly anti-correlated across the database (the correlation coefficient is -0.80): the faster energy intensity of GDP decreases, the faster GDP per capita increases.

This relationship between both components growth rates explains why the range of emissions coming out of the model is smaller than the combination of Kaya components.

The factors explaining the correlation between energy intensity growth and GDP growth are however not straightforward, as there is a two-way relationship between decreasing energy intensity and growing GDP: on the one hand, energy efficiency, which decreases the energy intensity of GDP, can increase GDP per capita through a reduction of production costs (lower energy expenses). On the other hand, a high labor productivity growth increases GDP per capita and creates a quicker capital turnover, therefore triggering faster technical and structural change towards energy-efficient technologies and high value-added sectors that are less energy-intensive than industry.

3.2.2 EXOGENOUS DRIVERS OF EMISSIONS

To understand the uncertainty on future emissions, the influence of each set of exogenous parameters on CO₂ emissions is analyzed with an analysis of variance (ANOVA). The exogenous parameters are the ones in the outer circle in Fig. 3.2. The results are displayed in table 3.2, and show that the variance of CO₂ emissions growth rates between 2010 and 2050 can be mostly attributed to the set of assumptions on the availability of coal and unconventional fossil fuels. This set is followed by energy efficiency and behaviors assumptions, that also contribute to the variance of CO₂ emissions.

Accordingly, these results depend on the assumptions that were made on the input parameters. The higher the contrast between the possible values of a parameter, the higher the impact on the model outputs variance. Also, the results depend on how parameters were grouped. If energy efficiency and behaviors parameters had been grouped, for instance, this bigger group may have had a higher impact than the availability of coal on the emissions variance. These limitations are inherent to the methodology. However, the rest of the chapter will show that an analysis of variance gives different results according to the output considered, suggesting that the impact of a given set of parameters on the outputs does not only depend on the inputs variance.

The fact that the availability of coal and unconventional fossil fuels matters for future CO₂ emissions is not very surprising. The higher the availability of fossil fuels, the lower their price and therefore the higher the demand. Interestingly,

	Sum Sq	F value	Pr(>F)
Wages	0.0000060	8.034	0.00493 **
Leader growth	0.0002082	280.226	< 2e-16 ***
Convergence	0.0000003	0.394	0.53059
Behaviors	0.0007741	1042.000	< 2e-16 ***
Energy efficiency	0.0012664	1704.538	< 2e-16 ***
Technologies	0.0001766	237.702	< 2e-16 ***
coal and XTL	0.0023652	3183.593	< 2e-16 ***
Residuals	0.0002080		

Table 3.2: ANOVA for CO₂ emissions mean growth. Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. In red are the drivers that explain more than 75% of total variance.

although the variance in CO₂ emissions is mainly explained by the availability of carbon-intensive fossil fuels, the analysis of the Kaya components showed that this effect is not channeled through the carbon intensity of primary energy. Indeed, we have found in the previous section that the carbon intensity of energy barely varies between 2010 and 2050, in all scenarios.

The availability of coal and unconventional fuels thus possibly increase CO₂ emissions through accelerated per-capita GDP growth or a smaller decrease in the energy intensity of GDP. To understand the mechanisms at stake, we then perform an ANOVA on each of the Kaya components.

3.2.3 THE CARBON CONTENT OF ENERGY DEPENDS ON FOSSIL FUELS AVAILABILITY

Table 3.3 displays the results of analyses of variance for the three endogenous Kaya factors.

The variance of the carbon content of primary energy growth rate is first explained by the availability of low-carbon technologies, followed by the availability of coal and unconventional fuels. This result is not surprising as the carbon content of energy depends on the relative cost of fossil-fueled vs low-carbon technologies, which triggers investments and structural change towards more or less

	Sum of squares		
	CO ₂ /TPES	TPES/GDP	GDP/POP
Wages	7.200e-07 ***	0.000071 ***	0.0001462 ***
Leader growth	4.700e-07 ***	0.000097 ***	0.0003727 ***
Convergence	1.200e-07 .	0.000037 ***	0.0005582 ***
Behaviors	1.800e-05 ***	0.002310 ***	0.0006974 ***
Energy efficiency	5.280e-06 ***	0.006086 ***	0.0018520 ***
Technologies	1.215e-04 ***	0.000158 ***	0.0001210 ***
Coal and XTL	8.642e-05 ***	0.000707 ***	0.0001358 ***

Table 3.3: ANOVAs for Kaya factors. Signif. codes: ‘***’ 0.001 ‘.’ 0.1. In red are the drivers that explain more than 75% of total variance.

carbon-intensive pathways. In the IMACLIM-R model, the (exogenous) potential for technical change is driven by the “low-carbon technologies” parameters and actual substitution from fossil to low-carbon technologies is triggered by high fossil energy prices, which depend on the “availability of coal and unconventional fuels” parameters.

As it was previously mentioned (section 3.1.3), the carbon content of primary energy is however not crucial in explaining CO₂ emissions in baseline scenarios since it increases by 0.23% per year on average. It is thus more interesting to focus on GDP per capita and the energy intensity of GDP, which are the Kaya components that mainly explain CO₂ emissions growth.

3.2.4 THE ENERGY INTENSITY OF GDP AND PER-CAPITA GDP DEPEND ON THE SAME DRIVERS

The growth rate of the energy intensity of GDP first depends on the parameters driving energy efficiency, then on the parameters driving consumption behaviors. As the parameters behind the energy efficiency and behaviors drivers directly influence energy consumption, this result is not surprising.

Interestingly, GDP per capita growth rate also depends first on energy efficiency and then on behaviors. Labor productivity growth (leader productivity and con-

vergence) only discriminate GDP per capita in third and fourth position. This result demonstrates that the correlation between GDP growth and energy intensity decline can be explained by these common factors: energy efficiency and energy-sober behaviors reduce the energy intensity of GDP and increase GDP per capita through a reduction of production costs.

High energy efficiency in productive sectors reduces the pressure on non-renewable resources and lowers energy prices, thus reducing production costs and increasing output. If consumption behaviors are energy-intensive (e.g. households have high basic needs for heat and transport services), these lower energy prices might trigger higher energy consumption in the rest of the economy and thus generate an important rebound effect. Conversely, if behaviors are energy-sober, the effect on GDP growth is twofold: first, it has a supply effect with lower production costs, which lead to lower final goods prices and increases demand and production. Second, lower energy prices allow households to consume more final goods for a given budget, amplifying the effect on GDP through increased total demand.

3.2.5 A TWO-WAY RELATIONSHIP

Going further, it can be shown that labor productivity growth also creates a correlation between the energy intensity of GDP and GDP per capita growth rates. Figure 3.5 represents the energy intensity of GDP and per-capita GDP growth rates, each dot in this figure being one of the 288 scenarios in the database. The orange arrow represents the influence of energy efficiency and behaviors on GDP intensity and per capita GDP: the bottom of the arrow starts from the average of both variables among scenarios that have high energy-efficiency potentials and energy-sober consumption behaviors; the end of the arrow reaches the average of both variables for scenarios with energy-intensive consumption behaviors and low energy-efficiency potentials. The combination of energy efficiency and behaviors clearly increases per-capita GDP growth while it decreases the energy intensity of GDP.

The green arrows represents in the same way the influence of hypotheses on labor productivity growth (leader growth+catch-up speed) on the database. It shows that labor productivity growth strongly increases per-capita growth rate (even though less than energy efficiency parameters), and that it also has an effect on the

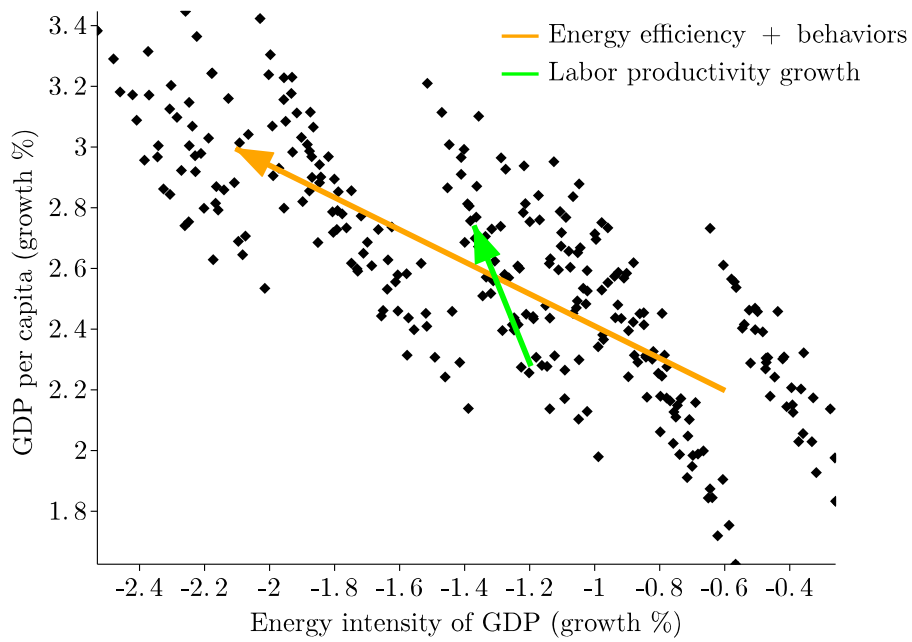


Figure 3.5: Energy intensity of GDP and per-capita GDP growth rates for the database. The orange arrow represents the influence of energy efficiency and behaviors on both axes as the difference between the two centers of mass. The green arrows represents the influence of hypotheses on labor productivity growth (leader growth+catch-up speed) in the same way.

energy intensity of GDP: a high labor productivity growth — and thus high GDP growth — reduces the energy content of GDP through accelerated technical and structural change.

Eventually, the Kaya decomposition highlights drivers and dependences that cancel each other out, at the expense of the mechanisms that explain future emissions. Even though the Kaya decomposition is useful to understand some of the different forces behind future carbon emissions growth, it does not highlight the “elephant in the room” i.e. fossil resources, as the main driver of future emissions in the IMACLIM-R model.

3.3 STRUCTURAL DECOMPOSITION ANALYSIS (SDA)

The analysis of emissions determinants is improved with a Structural Decomposition Analysis (SDA). This decomposition allows accounting separately for structural changes and increase in the production volume. Such decomposition is used on the EMF28 scenario database in Forster et al. (2013), to compare the drivers of emissions in reference scenarios and mitigation scenarios. This paper shows that in mitigation scenarios, energy efficiency improvements and structural change are the main driver of emissions reductions in the short-run while decarbonization becomes more important towards the end of the century. The paper also compares intensity, structure and activity effects in different sectors among different models and show that carbon intensity mainly declines in the electric sector while energy efficiency mainly concerns energy-intensive sectors and the transportation sector.

The hybrid structure of the IMACLIM-R model facilitates such decomposition, as it endogenizes both the produced added-value per sector and physical energy consumptions. CO₂ emissions are expressed as follows (*s* are economic sectors):

$$\text{CO}_2 = \text{pop} \times \frac{\text{GDP}}{\text{pop}} \times \sum_s \left(\frac{\text{GDP}_s}{\text{GDP}} \times \frac{\text{TPES}_s}{\text{GDP}_s} \times \frac{\text{CO}_{2s}}{\text{TPES}_s} \right) \quad (3.3)$$

The 12 economic sectors modeled in the IMACLIM-R model are coal, oil, gas, electricity, refined products, construction, air transportation, marine transportation, other transports, agriculture, industry and a composite sector with services and small industries. Following Ang (2005), the variation of CO₂ emissions between

2050 and 2010 can then be expressed as:

$$\Delta\text{CO}_2 = \text{CO}_2^{2050} - \text{CO}_2^{2010} = \Delta\text{pop} + \Delta\text{act} + \Delta\text{struct} + \Delta\text{intensE} + \Delta\text{intensC} \quad (3.4)$$

$$\text{with } \Delta X = \sum_s \frac{\text{CO}_2_s^{2050} - \text{CO}_2_s^{2010}}{\log\left(\frac{\text{CO}_2_s^{2050}}{\text{CO}_2_s^{2010}}\right)} \times \log\left(\frac{x_s^{2050}}{x_s^{2010}}\right)$$

with s the sectors and x either population, production per capita, the share of each sector in production, the energy intensity of each sector or the carbon intensity of energy in each sector.

3.3.1 EMISSIONS ARE MOSTLY DUE TO ACTIVITY INCREASE, OFFSET BY STRUCTURAL CHANGE AND AN ENERGY-INTENSITY DECLINE

The activity effect is the one that mostly drives CO₂ emissions growth. As in the Kaya decomposition, population growth and the increase in the carbon intensity of energy contribute relatively little to emissions growth. These positive effects on emissions are offset by structural change and a decreased energy intensity of production that reduce CO₂ emissions growth. Structural change is mostly characterized by a decline in the share of industry in favor of the composite goods.

Table 3.4 displays correlations between SDA factors. It is found that the activity effect is weakly anti-correlated to the structure effect (-0.48) and weakly correlated to the carbon intensity effect (0.65). Otherwise, the SDA factors are not correlated.

3.3.2 THE SDA FACTORS ARE NOT DETERMINED BY THE SAME DRIVERS

Similarly to the Kaya factors, the main drivers of SDA factors among the exogenous drivers of the scenario database are highlighted (fig. 3.7). Strikingly, except for activity, each of the SDA factor is determined by one set of exogenous parameter. Fig. 3.7 shows that 85% of the energy-intensity variance is explained by energy-efficiency parameters, 77% of the carbon intensity variance is explained by the availability of coal and 76% of the structure variance is explained by behav-

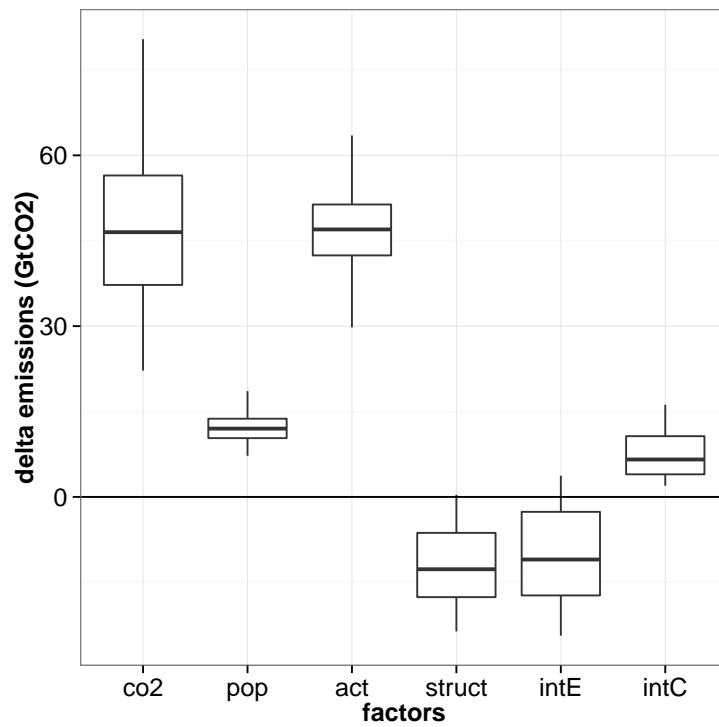


Figure 3.6: Box plot for the SDA decomposition. The structure effect is negative, meaning that structural change decreases CO₂ emissions. co2= Emissions, pop=Population, act=Activity, struc=Structure, intE=Energy intensity, intC=Carbon intensity.

	pop	act	struct	intensE	intensC
pop	1.00				
act	0.03	1.00			
struct	0.25	-0.48	1.00		
intensE	0.34	0.00	-0.12	1.00	
intensC	0.38	0.65	0.01	0.12	1.00

Table 3.4: Correlation coefficients between the SDA factors. pop=Population, act=Activity, struc=Structure, intensE=Energy intensity, intensC=Carbon intensity.

iors.

Activity is explained by the cost of production factors: lower energy prices, higher labor productivity (and to a lesser extent more flexible wages) increase activity. Interestingly, its main explanatory driver is the availability of coal and unconventional fuels.

This last result may be surprising since in the Kaya decomposition, per-capita GDP was mainly explained by energy efficiency and consumption behaviors. Here, when disentangling the structural effects from the intensity and activity effects, the image becomes clearer: energy-sober behaviors and localization choices create structural change in favor of low-energy sectors; energy efficiency investments reduce the energy intensity of production; lower energy prices increase global activity and therefore, everything else being equal, CO₂ emissions.

Eventually, the structural decomposition clarifies the determinants of future CO₂ emissions and could be more easily used for scenario building. Indeed, all factors are roughly independent and the activity effect explains why CO₂ emissions are mainly driven by the coal and unconventional fuels parameters.

3.4 CONCLUSION

This chapter looked for the drivers of future CO₂ emissions among a database of scenarios built with an Integrated Assessment Model that represents the links between economic growth and energy consumption. It used the Kaya identity, which states that CO₂ emissions are the product of population times GDP per capita times the energy intensity of GDP times the carbon content of primary energy. This identity is useful to understand the main forces behind carbon emissions growth, but it may be misleading if not used carefully.

First, the Kaya decomposition must be used as an *ex-post* analysis of emissions, but must not be used *ex-ante* as a combination of emissions main driving forces. Doing so would overestimate (by a factor of 2) the uncertainty surrounding future emissions, as it would not account for the links between the different components.

Second, analyzing the Kaya components, it is found that the GDP per capita growth rate and the energy intensity of GDP growth rates are the main contributors to carbon emissions growth up to 2050. Comparing the two components

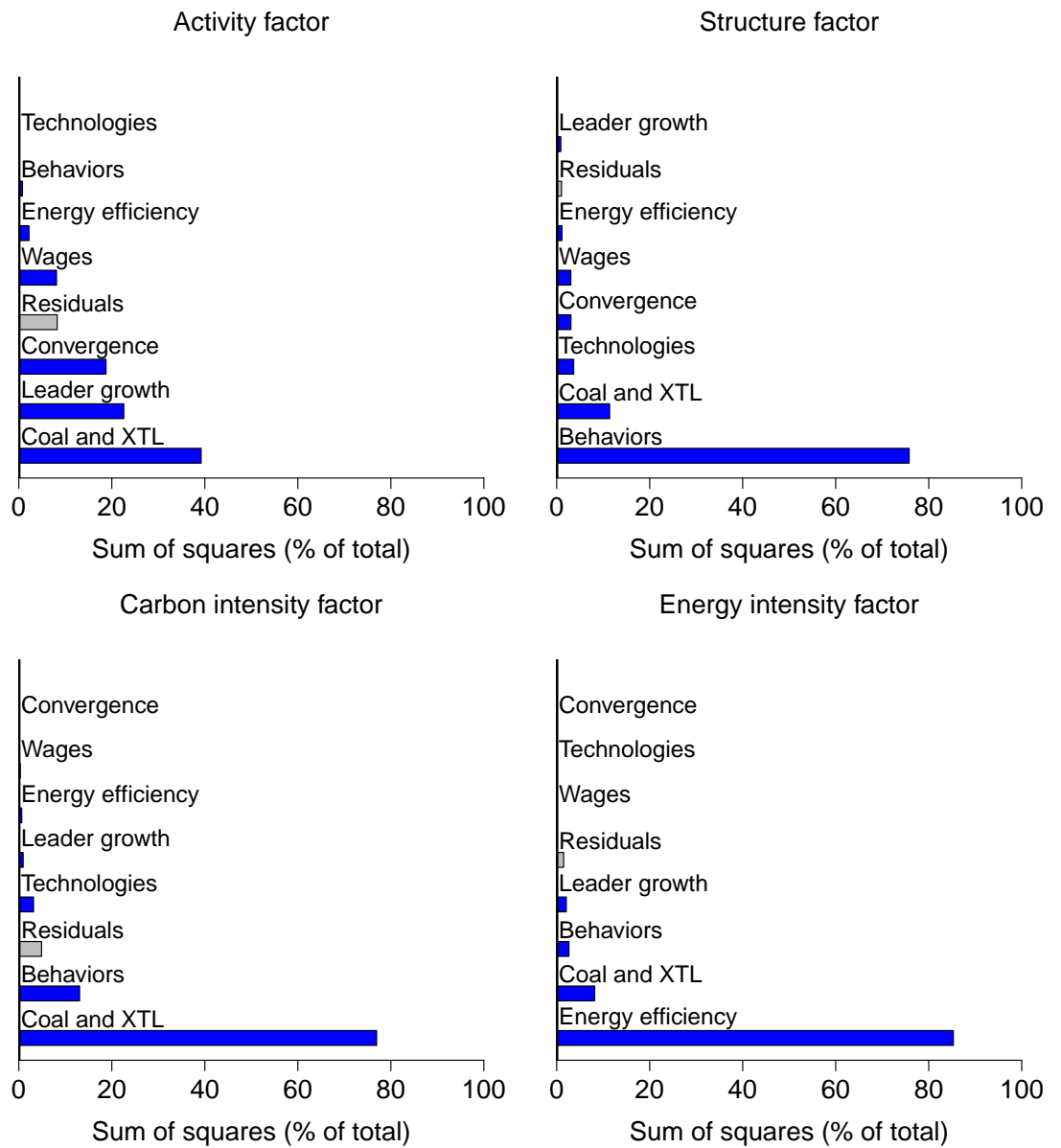


Figure 3.7: ANOVA results for SDA factors.

over a scenario database, it is shown that these two components are strongly anti-correlated. To explain the correlation, the main exogenous driving forces of each component are thus highlighted.

Both components are determined by the hypotheses on energy efficiency potentials and by consumption behaviors and localization choices. This demonstrates that optimistic assumptions on consumption behaviors and on the elasticity of energy savings to increasing energy prices had a strong positive impact on GDP growth. In other words, both a reduction of energy services through sober behaviors and a reduction of the energy needed for a given service through energy efficiency increase GDP growth. Moreover, assumptions on labor productivity growth create a second-order correlation between GDP growth and the energy intensity of GDP growth. Accelerated GDP growth thanks to higher labor productivity creates a quicker capital turnover and allows investing in energy-efficient technologies sooner.

However, the Kaya decomposition hides the fact that future emissions are mostly determined by the availability of coal and unconventional fuels in the database. Even though the Kaya decomposition is useful to understand the different forces behind future carbon emissions growth, it does not highlight the channel through which the “elephant in the room” i.e. fossil resources, increase CO₂ emissions.

The chapter is thus completed by a Structural Decomposition Analysis to disentangle structural change from increases in activity. SDA proves more useful than the Kaya decomposition to understand the main drivers of CO₂ emissions. Correlations between factors are lower with such decomposition, and it is shown that the activity effect (increase in GDP per capita) is a strong determinant of CO₂ emissions and that it is mainly driven by the availability of coal and unconventional fuels. The availability of unconventional fossil fuels increases activity and therefore emissions. This effect on emissions is however mitigated by structural change and energy efficiency which depend on consumption behaviors and energy-efficiency investment.

These results suggest that in the absence of ambitious mitigation policies — for instance because of political unacceptability — careful attention should be given to unconventional fuels. For instance, Pasqualini and Bassi (2013) show that even under the American Clean Energy and Security Act of 2009, the American oil shale

industry would be highly profitable by 2040. Instead of considering the amount of fossil fuels as given, i.e. that no policy can influence its availability, fossil fuel supply could be considered as a lever to reduce CO₂ emissions. Harstad (2012) makes the case for supply-side environmental policies, arguing that it eliminates leakage issues and can lead to the first-best optimum even if only a limited number of countries participates in the climate coalition.

Even though this chapter shows that fossil fuel resources increase economic activity, it also shows that the main drivers of per-capita GDP are energy efficiency and consumption behaviors, as they trigger structural change towards low-energy-high-value-added sectors. This result also suggests that energy efficiency investment create a macro-rebound effect, as they induce higher (but less energy-intensive) growth.

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4

Climate policies as a hedge against the uncertainty on future oil supply

Despite the inextricable link between oil scarcity and climate change (Toman, 2002; Brown and Huntington, 2008; Huntington and Brown, 2004; Turton and Barreto, 2006), the interplay between these two issues is paradoxically lacking a quantified analysis within a macroeconomic framework. This chapter uses the global energy-economy model IMACLIM-R to address this gap by assessing in a common framework both the costs of climate policies and oil scarcity, taking into account macroeconomic feedbacks. It shows that both costs are of the same order of magnitude. Moreover, our results suggest that, in the context of a limited and uncertain amount of ultimately recoverable oil resources, climate policies reduce the world vulnerability to peak oil. Of course, specific policies could also reduce this vulnerability. But by shifting energy use toward coal, they would lead to soaring greenhouse gases emissions. Climate policies, instead, can yield benefits from both sides: avoiding dangerous climate change (Mastrandrea and Schneider,

2004) and hedging against the uncertainty on oil resources.

The amount of recoverable oil is extremely uncertain, and yet the world economy highly depends on it. Nevertheless, it is barely the only uncertain factor that may have a significant impact on all economies in the future. Major sources of uncertainty include, *inter alia*, future investments to sustain oil production; the strategy of Middle-East oil producers that have a significant market power in the oil market; future coal prices; the ability of synfuels (biofuels and coal-to-liquid) to penetrate energy markets; the existence and penetration of carbon-free power generation technologies and of low-carbon end-use technologies in the transportation and residential sectors (Pacala and Socolow, 2004); and future development patterns in the developing world. From a methodological point-of-view, this assessment has two consequences : first, the climate–energy issue should not be investigated assuming a Hotelling–like framework in which the final amount of recoverable oil is known and oil prices are perfectly anticipated by all actors (see for instance Pindyck, 1978; Devarajan and Fisher, 1982). A modeled world in which all actors know how and when oil production will decrease and energy prices will increase is qualitatively different from the real world, in which all actors have to make decisions in a context of high uncertainty on these important world-economy drivers. It may thus be useful to introduce the effect of imperfect anticipations in the analysis, in order to take this difference into account. The second consequence is that it appears as inadequate to assess climate policies in a modeled world assuming that only one baseline scenario is possible. Today, any investment has to be assessed taking into account many uncertainties, including the one on future energy prices. Investing in climate policies is no different.

Designing climate policies requires decision-making methods that go beyond deterministic cost-benefit analysis and account for uncertainty and progressive arrival of new information, like sequential decision-making (Ha-Duong et al., 1997) or robust decision-making (Lempert, 2000). Informing such decision process demands quantifying the level of uncertainty associated to long-term scenarios. This chapter presents an approach to address this requirement, through a sensitivity analysis of our energy-economy model, IMACLIM-R.

IMACLIM-R is a hybrid simulation model of the world economy (Hourcade, 1993). A more developed description is available online in the Electronic Supplementary

Material, and the model is fully detailed in (?). IMACLIM-R represents in a consistent framework the macro-economic and technological world evolutions. The growth engine is composed of exogenous demographic trends and of technical progress that increases labor productivity, as in Solow's neoclassical model of economic growth (Solow, 1956). Demography simply follows UN median scenario and labor productivity is represented as an exogenous trend based on the convergence assumption, as it is common practice in the energy-environment modeling community. The two sets of assumptions on demography and labor productivity only prescribe potential growth. Actual economic growth then results endogenously from the interaction of these driving forces with short-term constraints: (i) available capital flows for investments¹ and (ii) under-utilization of production factors (labor and capital) due to the inadequacy between flexible relative prices (including wages) and inert capital vintages characteristics. Importantly, the model is not based on perfect expectations, but on adaptive expectations reacting on current price signals and past trends. IMACLIM-R, therefore, represents a "second-best" economy, *i.e.* a suboptimal economy in which resources can be under-utilized.

IMACLIM-R produces long-term scenarios of the world economy evolution and allows to explore the uncertainty that depends on unknown exogenous trends (e.g., future population) and parameter values that are debated or encompass poorly understood mechanisms. To get a better understanding of this uncertainty, we carried out a sensitivity analysis on selected exogenous parameters.

One difficulty arises from the multiplicity of parameters; we identified hundreds of parameters on which a sensitivity analysis can be useful, and each parameter can take an infinite number of values. To avoid combinatory explosion, the parameter domain has been simplified. First, the selected parameters are aggregated into a few consistent parameter sets. For instance, all parameters describing the future availability of oil and gas are aggregated into an "oil and gas markets" parameter set. Then, two or three sets of values are associated to each parameter set. For instance, the "oil and gas market" parameter set has three sets of possible values corresponding to increasing scarcity for both oil and gas; these sets of values

¹The amount of investment in each sector drives the pace of productive capacity expansion and the pace of embodied technical change.

are hereafter labeled as “Assumptions.”

In this analysis, we selected eight sets covering the major drivers of macroenergetic contexts with assumptions on natural resources, technologies and international economic trends. These sets have been built based on expert opinion² in such a way that the eight sets are as independent as possible. In this analysis, we assume also that the different possible values of each set are of equal probability. All sets are described in details in the Electronic Supplementary Material ; the two most important for this study are:

Oil and gas markets: this set describes (i) the amount of ultimately recoverable resources; (ii) the amount of Middle-East investment to sustain oil production at the oil field scale and to explore for new fields; (iii) the inertia in non conventional production development; and (iv) the indexation of gas prices on oil prices. In “Assumption 1” scenarios, these parameters are combined so that resources are abundant and easily extracted: oil production can reach 115 Mb per day. In “Assumption 3” scenarios, oil and gas supplies are very constrained: production peaks below 95 Mb per day. “Assumption 2” represents an intermediate situation with a production plateau around 95 Mb per day.

Implementation of climate policies: the model simulates (i) a “Business As Usual” (BAU) world with no constraint on emissions, or (ii) a “stabilization” world in which a carbon price reduces emissions such that CO₂ concentration is stabilized at 450 ppm in the long run. In stabilization scenarios, revenues from carbon tax or auctioned emissions allowances are either entirely given back to households, or recycled following a lump-sum principle in which each sector receives back what it paid.

We carried out an exhaustive exploration of all the combinations for the eight sets, leading to 576 scenarios. Of course, our parameter set does not cover all the uncertainty in scenarios. For instance, no population or productivity growth parameter has been included in the sensitivity analysis, for we want to focus on the uncertainty arising from the energy system and climate policies.

In our exercises, we measure the costs of oil scarcity and of climate policies using

²Expert opinion includes *inter alia* data from bottom-up models such as POLES (LEPII-EPE, 2006), and data from the IEA (Fulton and Eads, 2004; IEA, 2008) and private business experts on technological potentials. See Electronic Supplementary Material for more information.

the same metric, namely the sum of the Gross World Product (GWP) over the 2010-2050 period, discounted at a 3% discount rate. The costs are measured as the relative difference (in percent) between the discounted summed GWP in two scenarios (e.g., with vs. without climate policies, everything else being equal; with more or less oil scarcity, everything else being equal).

We find that, in our model, the cost of oil scarcity is significant (see figure 7.1). In the BAU scenarios, for instance, oil scarcity has a large impact on Gross World Product (GWP), and the 3%-discounted GWP over the 2010-2050 period is reduced on average by 2.6% in Assumption 3 scenarios (oil is scarce) compared with Assumption 1 scenarios (oil is largely available). Depending on assumptions on the other parameter sets (see Electronic Supplementary Material), these BAU losses range from 1.8% to 3.7%. They are due to changes in oil price trajectories, which affect production costs and purchasing power. The additional rent transfer from oil-importers to oil-exporters due to higher oil prices is indeed not only a transfer of resources. This higher rent has a negative impact on economic activity at the global scale because of various macroeconomic effects (exchange rates appreciation, changes in investment decisions, modification of capital and goods international flows, and technologies) and thus reduces GWP. The impact of climate policies is significant as well, since they cost 1.2% GWP on average.

Most importantly, oil scarcity and climate policy interact with each other. Our results demonstrate that GWP losses from the combination of climate policies and strong oil scarcity are smaller than the sum of both effects taken separately (see Tab. 4.1). The cost of climate policies is indeed strongly correlated with oil resources: with large resources (Assumption 1) this cost is much higher (1.7% on average) than when oil resources are scarce (0.7% on average in assumption 3). It is important to note that this lower cost when oil is scarce does not arise from lower baseline emissions. Even in the scenario of highest oil scarcity, baseline emissions in 2050 are well above the 450 ppm target, in particular because coal consumption replaces oil through coal-to-liquid. Consequently, the reduction in emissions between the baseline and the stabilized scenario is about the same in the three options of the oil and gas parameter set, and tighter oil scarcity does not necessarily help meet the CO₂ concentration target.

In fact, climate policies are less costly when oil is scarce because, in addition

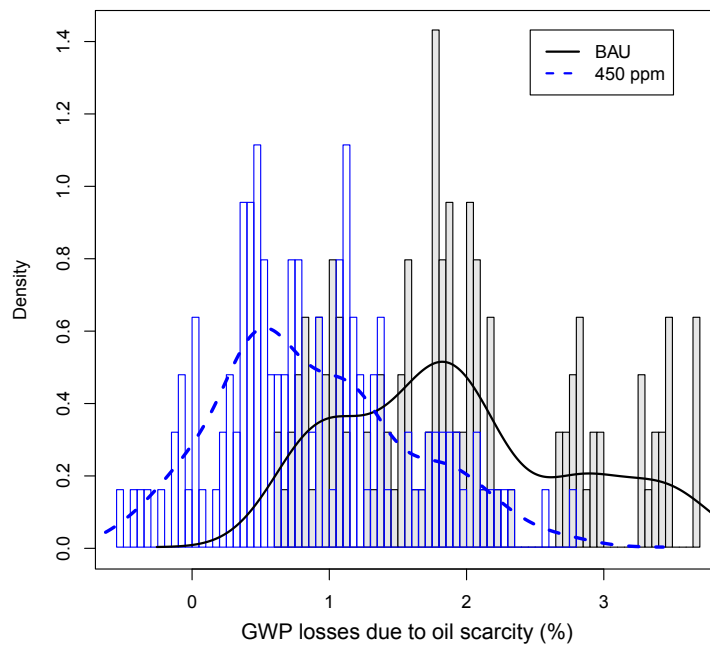


Figure 4.1: Histogram and smoothed densities of GWP losses (in %) due to constrained oil supply (discounted GWP between 2010 and 2050, with a 3% discount rate). Black filled bars and plain line for BAU scenarios; blue empty bars and dashed line for 450 ppm-stabilization scenarios. The 450 ppm histogram is shifted to the left compared with the BAU one, indicating that losses from oil scarcity are larger in absence of climate policies.

Table 4.1: Changes in the 3%-discounted GWP over the 2010-2050 period (**mean** [min ; max]) caused by fossil fuels constraints and climate policies. The reference case has abundant oil resources and no climate policies. Losses from the combination of climate policies and strong oil scarcity are smaller than the sum of both effects taken separately.

	Assumption 1: oil and gas largely available	Assumption 2: oil and gas limited	Assumption 3: oil and gas very constrained
BAU	Reference case	-1.3% [-0.6 ; -2.1]	-2.6% [-1.8 ; -3.7]
450 ppm	-1.7% [-0.4 ; -4.4]	-2.3% [-1.0 ; -4.8]	-3.3% [-2.0 ; -5.7]
Net cost of climate policies	1.7% [0.4 ; 4.4]	1.0% [0.0 ; 3.1]	0.7% [0.0 ; 2.7]

to their benefits in terms of avoided climate impacts, they bring important co-benefits in terms of resilience to oil scarcity. These co-benefits are illustrated by Fig. 7.1, which represents the histograms of GWP losses due to oil scarcity, with a distinction between scenarios without climate policies (BAU) and with climate policies (450 ppm). Two important results emerge: first, the 450 ppm histogram is shifted to the left, indicating that the mean loss due to oil scarcity is reduced by climate policies; second, the large right tail of the BAU distribution disappears in the 450 ppm distribution, meaning that climate policies eliminate a large number of scenarios with high GWP losses (larger than 3% and reaching up to 3.7%). These large mitigation co-benefits can be explained by earlier and more regular increases in final oil price. In a second-best world where anticipations are imperfect, indeed, brutal increases in energy prices cause larger welfare losses than slower increases (Nordhaus, 2007). Here, the more regular increase in energy price with climate policies prevents economic lock-ins in oil-dependent schemes and promotes the development (induced technical change) and diffusion (investment incentive) of oil-free technologies before the beginning of the depletion phase in oil production.

Climate policies, therefore, can be considered as a hedge against the potential negative impact of oil scarcity on the world economy. This hedge parallels the

climate-related hedge of early climate policies (see Yohe et al., 2004; Manne and Richels, 1992). Its net present value can be calculated as the difference between economic losses due to oil scarcity without climate policies and the same losses with climate policies; see Electronic Supplementary Material. A simple calculation suggests that this hedge has a net present value of about 11,500 US\$b, that is 19% of the 2009 Gross World Product. The overall welfare cost of climate policies is thus significantly reduced, which is a powerful incentive to adopt more stringent climate targets. Eventually, reducing the risk of future economic losses due to oil scarcity may appear as a significant side-benefit of climate policies to many decision-makers.

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5

The cost of climate change mitigation: uncertainties and metrics matter

5.1 INTRODUCTION

How much will it cost to reduce greenhouse gases emissions? Economists have been looking for an answer to this overarching question since the discipline started to look into the climate change issue. More broadly, answering this question contributes to finding the right balance between the costs of actions to slow climate change and the benefits of reducing future damages from climate change (Nordhaus, 1991, 1992, 1993).

But when addressing this issue, one stumbles over (at least) two difficulties.

A first difficulty arises from pervasive uncertainties at play. This difficulty was acknowledged since early studies, but the topic has recently received increasing interest (e.g. Scricciu et al., 2011; Haurie et al., 2012), following the recognition that some uncertainties may be irreducible. The climate change literature has widely

acknowledged that the consequences of a given greenhouse gases level in the atmosphere (and thus mitigation benefits) cannot be precisely assessed because of uncertainties on carbon cycle mechanisms, climate sensitivity and climate change damages (e.g. Heal and Millner, 2013). But on the cost side, many uncertainties also apply. Up to now, the scientific community has mainly focused on technology and policy uncertainty (Clarke et al., 2009; Edenhofer et al., 2010; McJeon et al., 2011; Lemoine and McJeon, 2013), even though Rogelj et al. (2013) encompass wider sources of uncertainties such as geophysical, technological, social and political. However, resource and economic uncertainty are generally absent from mitigation costs assessments, and the links between resource availability, social choices and economic growth — e.g. rebound effects, structural changes — are rarely considered.

Second, in response to the 'what is the cost?' question, the literature has been employing a multiplicity of metrics to evaluate mitigation costs (Edenhofer et al., 2006; Paltsev and Capros, 2013): equivalent variation, technical cost, carbon price, consumption losses, GDP losses... These metrics are not several measures of the same cost, but are conceptually different (Markandya and Halsnaes, 2001; Bernard and Vielle, 2003; Hourcade and Gherzi, 2009). For instance, the carbon price is the marginal cost of the climate constraint while GDP losses measure the full cost of the policy. The choice of the metric is sometimes constrained by the type of model that is used to evaluate mitigation costs (e.g. partial equilibrium models cannot assess GDP costs and thus focus on technical costs), and in practice, existing costs assessments often focus on a single metric, such that it is impossible to quantitatively appreciate the links and differences between the various metrics. For instance, the IPCC chose to present the evaluations of macroeconomic costs in its last report summary for policy makers (IPCC, 2007) while carbon prices are prominent in other assessments and policy debates. Paltsev and Capros (2013) compare cost concepts using the European Energy Modeling Forum (EMF28) study, and conclude that carbon prices are inadequate measures of the policy costs whereas changes in macroeconomic consumption or welfare are the most appropriate measures of policy costs.

Here, we compare the carbon price and macroeconomic losses through a vast exploration of socio-economic uncertainties. We do not take the side of a cost con-

cept, and we rather show that bringing together the issue of the cost metrics and of the uncertainties surrounding costs provides new insights for decision-making.

Rogelj et al. (2013) recently showed that energy demand was an important driver of the uncertainty surrounding carbon prices. We follow on this innovative result and open the box of future socio-economic developments influencing energy demand, considering uncertainties that are overlooked by existing studies, such as growth drivers (demography and productivity increase), behaviours and lifestyle evolutions and availability of unconventional fuels. We also consider the design of the climate mitigation instrument, and more precisely the recycling of carbon pricing revenues, as an uncertain parameter. Indeed, even though some studies consider political uncertainty (in the form of delayed action for instance in Rogelj et al., 2013), the political choices behind the implementation of a mitigation policies are rarely treated as uncertain.

We use an economy-energy-environment (E_3) model that endogenizes the evolutions in energy demand and represents the links between technical systems, behaviors and economic growth. We build a large number of scenarios to explore the uncertain parameters that determine these links.

We adopt a cost-efficiency approach, justified by the recent studies on the uncertainties on damages from climate change that cast doubt on the relevance of cost-benefit analysis in the context of climate change (Dietz, 2012; Koomey, 2013).

Given the socio-economic uncertainties considered, GDP variation is large among baseline scenarios and the macroeconomic cost of a climate policy is not a good proxy for absolute GDP in policy scenarios. In a cost-efficiency approach, absolute GDP can be a more important metric than GDP variation from a counterfactual baseline scenario.

Statistical methods are thus used to disentangle uncertainties and quantitatively explore the links between the carbon price, macroeconomic losses and absolute GDP in climate policy scenarios.

We show that socioeconomic uncertainties in one E_3 -model are large enough to generate wide range of estimates for the three variables. We also show that among a large number of scenarios, the different metrics commonly used to evaluate the performance of a climate mitigation policy are not good proxies for one another: they are not necessarily correlated nor share the same drivers. Although the con-

ceptual differences between the metrics are well known, we show here that they quantitatively matter for mitigation assessments. It is thus misleading to focus on a single cost metric. But if an answer to the 'what is the cost?' question is out of reach, we show that our approach can give insights to the reframed questions 'what drives the costs?', 'what policy design can reduce the costs?' and 'where are the trade-offs?'

5.2 METHODOLOGY

The costs of climate change mitigation are evaluated *ex ante* with numerical models called economy-energy-environment (E₃) models¹, that represent the evolutions of the economy and energy systems, and their interactions over the next decades to century. Two main types of uncertainty can be distinguished when using these models: conceptual uncertainty and parametrical uncertainty (Oreskes and Belitz, 2001). Conceptual uncertainty arises from the different mechanisms represented in models (e.g. partial vs general equilibrium effects), and the equations used to do so, whereas parametrical uncertainty comes from the wide range of possible values for input parameters of the equations.

E₃ models include hundreds of exogenous parameters that describe unknown trends (e.g., future population) or encompass poorly understood mechanisms (e.g., the evolution of consumption preferences). For instance, the equations and parameters driving future preferences, localisation and consumption choices, or wealth distribution (within and between countries) are often crude representations because modelers lack quantitative data and/or mechanisms are not perfectly known.

On the one hand, conceptual uncertainty is addressed with model comparison exercises (Edenhofer et al., 2010; Kriegler et al., 2013b,a), in which modellers standardize input parameters — when it is possible — such that the output differences result as much as possible from differences in the models structures and not from parametrical uncertainty. On the other hand, meta-analyses try to disentangle parametric and conceptual uncertainty (Fischer and Morgenstern, 2006;

¹These models are also often called Integrated Assessment models (IAMs), but this denomination introduces a confusion with more stylized models that are used to balance the costs and benefits of climate change mitigation such as Nordhaus' famous DICE model. Most E₃ models do not include a representation of damages from climate change.

Barker and Jenkins, 2007). Parametric uncertainty is surprisingly less systematically studied, with the exception of a few recent studies (Lemoine and McJeon, 2013; Rogelj et al., 2013; Gerst et al., 2013).

In this paper, we address parametrical uncertainty using one model, the Imacim-R model, and constructing a database of several hundred socio-economic scenarios.

Imacim-R is a hybrid simulation model of the world economy that represents changes in the macro-economic and technological world in a consistent general equilibrium framework (see the Appendix for a discussion of the modeling framework and its limitations, and Waisman et al., 2012, for a detailed description).

To construct a scenarios database, we identify *a priori* the parameters that can have an impact on mitigation costs and we aggregate them into six consistent parameter sets that we call “drivers.” The methodology is similar to that used in Rozenberg et al. (2013), with slightly different parameter sets. Drivers include (i) leader growth, which prescribes evolutions of labor productivity growth and population growth in the US; (ii) low-income countries’ catch-up, which gives catch-up speed towards the leader’s labor productivity level and population growth in low-income regions; (iii) consumption behaviors, which describe households’ preferences and basic needs for transportation and living surfaces, and the freight content of the economy, a proxy for localization choices; (iv) energy efficiency, which groups the parameters governing the evolution of energy input per unit of goods and services produced and its reaction to energy prices; (v) the availability of low carbon technologies, which describes potentials and learning-by-doing curves for new generation of nuclear plants, renewables, CCS and electric vehicles; (vi) the availability of unconventional fossil fuels, such as shale oil and gas and coal-to-liquids.

For each of these drivers, two or three alternatives are built with contrasted parameter values found in the literature (see the Appendix).

Combining the alternatives gives 216 baseline scenarios, or reference scenarios, i.e. scenarios with no mitigation policy. In each of these future possible worlds, we add a climate change mitigation target to build climate policy scenarios, or mitigation scenarios. The target is an exogenous constraint on global CO₂ emission trajectory leading to a 50% reduction in global emissions in 2050 with regards to

2001. A carbon tax (or equivalently a global emission trading system with permits auctioning) is endogenously calculated every year to comply with the emissions objective. The tax revenues can be recycled in two different ways. In the first option, all carbon tax revenues are given to households, in the form of a social transfer. The second option represents a revenue-neutral swap of the carbon tax for pre-existing distortionary taxes. The revenues of the carbon tax households have paid on their direct energy expenses are returned to households through cuts in income taxes, while the carbon tax paid by productive sectors are returned through a decrease of other taxes that pre-exist in the model (on production, labor and capital).² This leads to 432 mitigation scenarios — two for each baseline — that have the same climate target but different policy designs. We can thus analyze a database of 648 socio-economic scenarios.

We analyze scenarios along two of the most used mitigation costs metrics, the carbon price and the macroeconomic cost of mitigation. The carbon price is the carbon tax that is implemented to reach the mitigation target, or the price of the emission permits in an equivalent emission trading system. It is used for instance by Mastrandrea and Schneider (2004); Rogelj et al. (2013) as an evaluation of the magnitude of climate policy controls. The macroeconomic cost of mitigation is the variation of global GDP between the climate policy scenario and the corresponding baseline scenario. It is used, in particular, in IPCC assessments (IPCC, 2001, 2007). Note that macroeconomic costs are calculated with regards to a counterfactual baseline scenario that does not include climate change damages. This baseline GDP largely varies among the scenario database, given the parametrical uncertainty that is considered. Therefore, in a cost-efficiency approach it can also be relevant to analyze absolute GDP in policy scenarios and we do so in the last section of the paper.

Although there are important dynamic effects for these two costs metric and for GDP, their analysis is beyond the scope of this article and we collapse the time dimension for simplification purposes. Therefore, we analyze the average of carbon prices over the 2010-2050 horizon weighted by a discount factor, the variation of discounted global GDP per capita between policy scenarios and the corresponding baseline scenarios, and discounted global GDP per capita in policy scenarios.

²These taxes rates are calibrated with actual data for each region of the model, on 2001 data.

In all cases we use a 3% discount rate.³

5.3 RESULTS

5.3.1 A WIDE RANGE OF MITIGATION COSTS

Our first result is the wide range of mitigation costs found with a single model and a single mitigation target, when socio-economic uncertainties are accounted for. Figure 5.1 shows that the macroeconomic cost of climate policies stretches out from a slight GDP gain to 16% GDP losses, whereas the carbon price spreads between \$30 and \$320 per tCO₂. In this figure, each dot is one of the 432 policy scenarios, in the space of the two mitigation costs metrics.

The spread of mitigation costs results has the same order of magnitude as (i) recent results reported in model comparison studies, and (ii) recent results from other studies exploring parametric uncertainties in a single model. For instance, Blanford et al. (2013) analyze the costs from the EMF-27 study where a dozen E3 models explored mitigation costs after having harmonized models along a reference scenario. They report time-averaged carbon prices for a 550 CO₂-eq stabilization ranging from 5 to 50 US\$ per tCO₂, and discounted macroeconomic costs ranging from 0.4% to 8% global GDP losses compared to reference. Rogelj et al. (2013) find 2012 carbon prices ranging between 5 and 100 US\$ per tCO₂ in the case of immediate global climate policies and 50% probability of staying below 2, due to the uncertainties on mitigation technologies and energy demand that are accounted for in the MESSAGE model.

This comparison of costs ranges, and their magnitude, highlights two important conclusions. First, with the current state-of-the-art of E3 models, parametric uncertainty is as important as conceptual uncertainty to the overall uncertainty in costs evaluations. Second, as previously shown by Rogelj et al. (2013), socio-economic uncertainties are important for the evaluation of mitigation costs.

It thus appears that reference scenarios used to harmonize results in model comparison exercises significantly under-sample plausible future socio-economic sce-

³The discount rate appropriate for climate change economics is an important and debated issue. See the Appendix for a sensitivity analysis of our results to the value of the discount rate, and ... for an account of debates over the value of the discount rate.

narios. This fact is an illustration of the general observation that ensembles of model runs tend to oversample the peak and under-sample the tails of probability distributions (O'Neill, 2010; Roe, 2010).

Our results also corroborate the recent call for caution in the interpretation of mitigation costs evaluations and the warning against the risk of spurious precision they may give (Rosen and Guenther, 2013).

It is difficult to know if our wide range of results overestimates or underestimates the plausible range. On the one hand, we omitted some drivers of future mitigation costs (e.g. equity considerations) and we limited our exploration of parametrical uncertainties to a subset of input parameters. Furthermore, no black swan (e.g. breakthrough of a technology yet unknown) is included in the scenarios considered. On the other hand, it is possible that some non-modelled mechanisms would reduce the range of results if included (e.g. an omitted negative feedback loop between some elements of the system).

In any case, a precise and accurate evaluation of mitigation cost appears out of reach. Some elements of the system under study remain inherently unknowable either because they are associated with future choices, possibly influenced by policies, or because we still have an incomplete understanding of socio-economic functioning. Progress can be made on the latter, but the former is inescapable. Therefore, one should not expect the range of mitigation cost estimates to necessarily decrease as research advances. One should even consider the possibility of disconcerting learning⁴ (Hannart et al., 2013) or negative learning⁵ (Oppenheimer et al., 2008) to occur with respect to mitigation costs estimates. In this regard, it is interesting to note that the range of mitigation costs reported increased between IPCC assessments. For instance, the macroeconomic costs in 2050 of a stabilization of concentrations at 535-590 CO₂-eq range from 1% to 4% global GDP loss compared to reference in the third assessment report (IPCC, 2001), and stretch between a slight global GDP gain and 4% GDP loss compared to reference

⁴Disconcerting learning refers to a case where our uncertainty is actually prone to increase even though we learn more about the system, i.e. there is an increase in the dispersion of the probability distribution function of the result.

⁵Negative learning refers to a case where new information leads to scientific beliefs that diverge over time from the a posteriori right answer, i.e. there is an increase in the bias of the probability distribution function of the result).

in the fourth assessment report (IPCC, 2007).

We are thus in a situation of deep uncertainties on the costs of climate change mitigation, that parallels that of uncertainties on the costs of climate change damages (Yohe and Hope, 2013; Heal and Millner, 2013). If both mitigation costs and benefits from avoided damages are marked with deep uncertainties, it is illusory to expect a cost benefit analysis might indicate the optimal mitigation level to solve the climate change issue. In this regard, our analysis concurs with the first part of Pindyck (2013) diagnosis, which argues that it is irrelevant to perform a classical cost-benefit analysis with integrated assessment models to establish the optimal climate change mitigation level.

But, if our results show that it is illusory to expect a precise answer to the question 'What is the cost of climate change mitigation?', it does not mean models are of no use to contribute to the understanding of cost formation mechanisms and to inform policy decision frameworks. It is however necessary to rephrase the question under study and to foster evolutions in the ways scenarios are built and used. The analysis that follows is a step in this direction.

5.3.2 DISENTANGLING THE DRIVERS AND CORRELATIONS OF COST METRICS

We thus switch the question from 'What is the cost of climate change mitigation?' to 'What drives the cost?'. The analysis of our scenario database can give new insights on this reframed question. We look for the drivers that best explain the carbon tax and the macroeconomic cost of mitigation. Following the methodology from Gerst et al. (2013), we use a data-mining algorithm called Classification and Regression Tree (CART, see Breiman et al., 1983) to find dichotomous splits of drivers that yield the strongest possible predictions of the cost metrics.

Figure 5.1 features the first two drivers that best discriminate the two cost metrics, revealed by CART analysis⁶ (all complete trees are available in the supple-

⁶Obviously, the impact of a driver on the cost metrics depends on the numerical assumptions behind each state of the driver. The more contrasted the alternative assumptions on a parameter, the more variance the parameter set creates on cost metrics. Also, the bigger the parameter set (the more parameters in the set) the more variance it is likely to create on the results. These limitations are inherent to our methodology, but are common limitations to sensitivity analyses methods. Notwithstanding these limitations, we will see that the variance on different cost metrics are explained by different combinations of drivers, which is an important result.

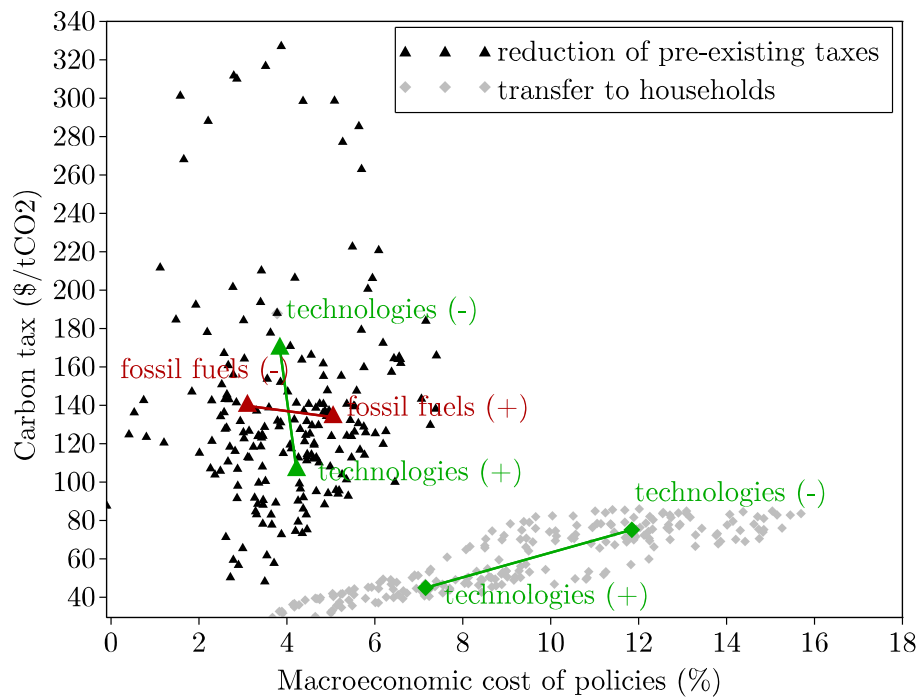


Figure 5.1: Macroeconomic cost of climate policy and carbon tax in all scenarios. Each small dot is a scenario. Larger colored dots are the average across all scenarios corresponding to the nearby caption. The first discriminating driver (tax recycling) is represented by either triangles or diamonds according to the type of recycling. The impact of the next drivers (technologies or fossil fuels) are represented by colored dots and lines. Note that a line at about 90 degrees to an axis means that the corresponding driver has no influence on the axis measure on average.

mentary material).

It shows that both the carbon price and the macroeconomic cost strongly depend on policy design, i.e. on the way the carbon tax revenue is recycled: two distinct clusters can be identified in the graph, each corresponding to a different policy design.

The figure highlights a result that was not previously discussed, to the best of our knowledge. The way the carbon tax revenues are recycled modifies the correlation between the macroeconomic cost and the carbon tax.

If tax revenues are transferred to households, the macroeconomic cost and the

tax are strongly correlated — their correlation coefficient is equal to 0.86.⁷ Conversely, when the carbon tax revenues are used to reduce pre-existing taxes, the two metrics are very weakly correlated, with a correlation coefficient of 0.030. Also, in that case there is a trade-off between lower macroeconomic costs and a higher carbon tax.

We identify here two theoretical results from the double dividend literature (Bovenberg and van der Ploeg, 1994; Goulder, 1995; Bovenberg, 1999), and show they are quantitatively significant: the recycling of carbon tax revenues through a reduction of pre-existing distortionary taxes reduces⁸ the macroeconomic cost of the climate policy, but increases the carbon tax. Indeed, the use of carbon tax revenues to reduce pre-existing taxes has a positive effect on economic activity, creating a macro rebound effect on GHG emissions. Since the carbon tax has a smaller effect on the output volume than in the transfer to households case, emissions must be reduced through more carbon intensity reduction, and the price signal therefore needs to be higher.

In addition to the absence of correlation between the carbon tax and macroeconomic cost, our results show that they have different drivers.

When tax revenues are transferred to households, both cost metrics strongly depend on the availability of low carbon technologies (Fig. 5.1, grey diamonds): if technologies are cheap and available, a relatively low carbon price induces investors to switch to low-carbon technologies and the effect on GDP is limited. Conversely, if technologies are expensive, the carbon price necessary to trigger a shift in investors' decisions is higher and so is the impact on GDP.

When the carbon tax revenues reduce pre-existing taxes, the availability of low-carbon technologies still drives the carbon price, but it has no significant influence on macroeconomic costs (the green arrow representing the impact of tech-

⁷The correlation coefficient of two variables in a data sample is their covariance divided by the product of their individual standard deviations. It is a normalized measurement of how the two are linearly related. If the correlation coefficient is close to 1, it indicates that the variables are positively linearly related and the scatter plot falls almost along a straight line with positive slope. For -1, it indicates that the variables are negatively linearly related and the scatter plot almost falls along a straight line with negative slope. And for zero, it indicates a weak linear relationship between the variables.

⁸Our results indicate a *weak double dividend*, in the sense that the tax swap reduces the macroeconomic cost of the policy but does not lead to an actual macroeconomic gain (which would be a *strong double-dividend*).

nologies is at right angle to the x-axis). The negative effect of the carbon tax on GDP is combined with a positive effect of distortionary taxes reductions (the weak double-dividend effect). If low-carbon technologies are not available, the higher carbon price creates higher revenues that are used to reduce pre-existing distortionary taxes, so that low-carbon technologies have little effect on the macroeconomic cost. Instead, macroeconomic costs are explained by the availability of unconventional fossil fuels⁹: the more expensive unconventional fossil fuels, the lower macroeconomic costs. The impact of this driver on macroeconomic costs has nothing to do with what happens in the mitigation scenarios, but comes from its impact on GDP per capita in baseline scenarios: in the absence of climate policy, abundant and relatively cheap unconventional fossil fuels lead to faster growth compared to scenarios where fossil fuels are scarce.

5.3.3 WHEN MACROECONOMIC COSTS ARE A BAD PROXY FOR GDP

In most mitigation analyses, the uncertainties considered have little impact on baseline GDP: hypotheses on low-carbon technologies, for instance, do not influence the economy in the absence of a climate constraint. The macroeconomic cost of a policy is therefore a good proxy for absolute GDP in the policy scenario.

But the analysis above showed that the assumption on unconventional fossil fuels, because it increases baseline GDP, strongly determines the macroeconomic cost of mitigation. Moreover, this assumption determines baseline emissions, hence the potential benefits from avoided impacts. This result would be relevant for a cost-benefit analysis, as there could be some links between the uncertainty on future costs and future benefits of climate change mitigation. However, the macroeconomic cost is a misleading cost concept for cost-efficiency analyses. First, the point of reference to compute the macroeconomic costs of mitigation is a counterfactual baseline with no damages from climate change. Second, the macroeconomic cost will never be observed since it results from the comparison of two future states of the system, one of which will be realized at most. It is thus an inap-

⁹Note that the assumption on unconventional fossil fuels has no significant influence on the carbon tax on average (the red arrow is almost horizontal), because substitution away from unconventional fuels is not the marginal reduction option and thus does not determine the carbon price.

appropriate metric for a cost-efficiency framework excluding damages from climate change, as ours and as it is commonly used for mitigation costs evaluations.

Let's take a step back and look at the absolute GDP per capita reached in the policy scenarios, an indicator of the policy efficiency, setting aside the fact that GDP per capita can be a poor measure of welfare (refer to Stiglitz et al., 2009; Fleurbaey, 2009; Jones and Klenow, 2010, for discussions on this topic).

Repeating the analysis from previous section for the macroeconomic cost of mitigation and the absolute GDP per capita in policy scenarios shows that (i) the two indicators are weakly correlated, and (ii) they are not determined by the same drivers (Figure 5.2).

The macroeconomic cost of mitigation is thus a poor proxy for the absolute GDP reached in a policy scenario. The two measures are weakly correlated: their correlation coefficient is equal to -0.67 if the whole set of scenarios is accounted for. If we consider only the subset of scenarios with a revenue-neutral substitution of the carbon tax for pre-existing taxes, the correlation between the two indicators is even weaker: their correlation coefficient is -0.36.

Moreover, the two indicators have different drivers. First, the assumption on fossil fuels has a significant effect on the macroeconomic cost of mitigation, whereas its effect is negligible for the absolute GDP per capita in policy scenarios (horizontal arrow in Fig. 5.2). Indeed, the carbon tax makes unconventional fossil fuels unprofitable in policy scenarios, even if there are large resources. This result corroborates the finding of Rozenberg et al. (2010) who showed that climate policies reduce the effect of fossil fuel resources on global GDP.

Second, the analysis of the discriminating drivers of the absolute GDP per capita in policy scenarios highlights two drivers that would not stand out if the focus was only on the macroeconomic cost: energy efficiency and consumption behaviours. Several mechanisms explain the impact of these drivers on GDP. First, high energy efficiency in productive sectors reduces the pressure on non-renewable resources and lowers energy prices, thus reducing production costs. This leads to lower final goods prices, which increase demand and thus long-term production. When it is coupled with energy-sober behaviors, this mechanism is amplified by even lower energy prices. Second, lower basic needs for energy services and lower energy prices allow households to consume more final goods for a given budget,

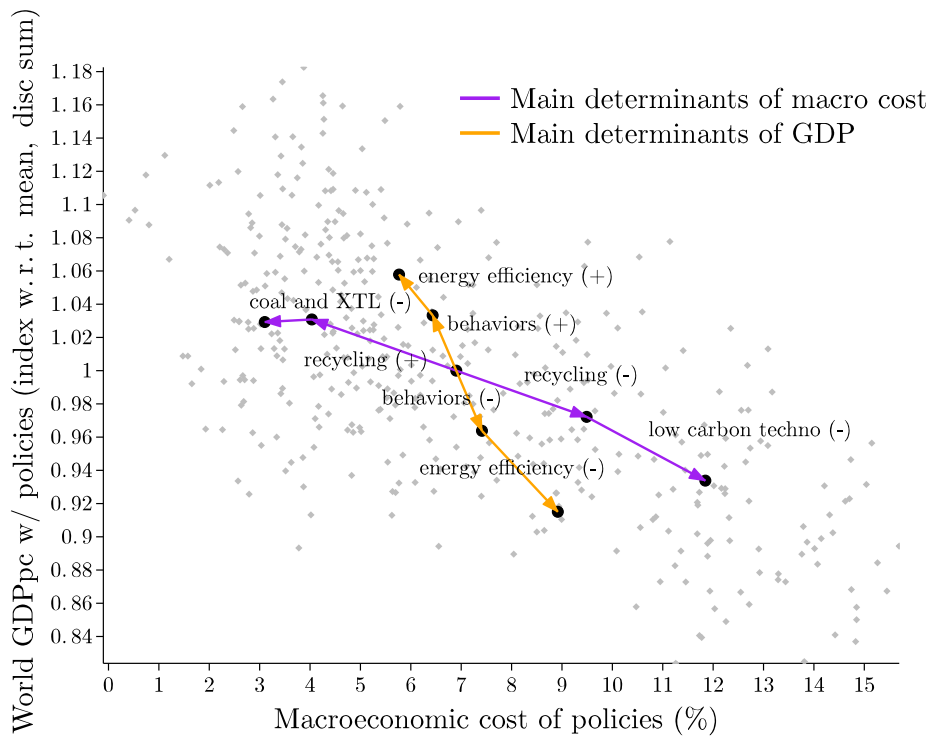


Figure 5.2: Macroeconomic cost of mitigation and global GDP per capita in climate policy scenarios, discounted with a 3% discount rate, and expressed as an index with regards to the mean across all mitigation scenarios. Each small dot is a scenario. Larger dots are the average across all scenarios corresponding to the nearby caption. The first two discriminating drivers identified by the CART algorithm are represented by colored arrows, purple for the macroeconomic cost of mitigation and orange for the global GDP per capita in climate policy scenarios. Note that a line at about 90 degrees to an axis means that the corresponding driver has no influence on the axis measure on average.

triggering structural change in the economy towards more labor-intensive sectors and amplifying the effect on GDP.

Consumption behaviors and the potential for energy efficiency have little influence on macroeconomic costs, despite their effect on GDP, because they also influence GDP per capita in baseline scenarios. Indeed, high potentials for energy efficiency and energy-sober behaviors induce faster economic growth even in the absence of a climate policy. As a result, these two drivers — especially behaviors — create little difference between baseline GDP and policy GDP even though they have a strong impact on absolute GDP per capita (Fig. 5.2, yellow arrows).

Therefore, depending on the indicator of focus, the cost-efficiency of a policy can be explained by different drivers (see the analysis of variance in the Appendix for further details on this point).

5.4 CONCLUSION

Our study of climate change mitigation costs accounting for socio-economic and technological uncertainties, building and analyzing a large number of scenarios in a cost-efficiency approach gives a number of insights.

First, socio-economic uncertainty creates a large range of estimates for future mitigation costs. Second, among a large database of scenarios, the different metrics commonly used to evaluate the performance of a climate mitigation policy are not good proxies for one another: they are not necessarily correlated nor share the same drivers. It is misleading to focus on a single cost metric. Depending on the metric of focus, the analysis points to different policy implications. Focusing on both the carbon price and the macroeconomic cost of mitigation, we highlighted the quantitative importance of the design of carbon tax revenues use. Moreover, a substitution of the carbon tax for pre-existing distortionary taxes entails a trade-off: it reduces macroeconomic costs and its range of possible values, but it increases the carbon price and its range of possible values. Focusing on the couple macroeconomic cost - absolute GDP per capita reached in the mitigation scenario, we showed the latter is strongly determined by assumptions on energy efficiency and behaviors, two drivers that do not influence significantly the macroeconomic cost. The importance of behaviors and energy efficiency for GDP per capita is a

remarkable result, given that most mitigation studies focus on technologies and policy design, and disregard the uncertainty surrounding future consumption behaviors.

One of the limitations of our study is that we did not model policies that influence consumption behaviors, increase the potential for energy efficiency or reduce the costs of low-carbon technologies. A next step would be to do so, and evaluate the costs of such policies.

As a whole, the insights gained from our analysis call for caution in costs results interpretation, presentation and communication. They show a precise answer to the 'what is the mitigation cost?' cannot be expected, due to irreducible uncertainties, and one should beware of spurious precision in the communication and use of results.

Therefore, even if progress can be made to reduce the range in evaluations, it should not be the only goal and the reduction of uncertainties in the costs evaluations should not be considered as an appropriate metric to monitor progress in climate economics.

Uncertainties cannot be a argument to discredit climate economics nor to slow down action, but it calls for methodological innovations in both building and using scenarios.

If an answer to the 'what is the cost?' question cannot be expected, it is also not needed for decision nor action. Rather, a heuristic use of models, as advocated in Peace and Weyant (2008) and in many pieces before, to give '*insights not numbers*' offers prospects to (i) gain insights on the reframed policy-relevant questions 'what drives the costs?', 'what policy design can reduce the costs?' and 'where are the trade-offs?', and (ii) progress in how to handle the abundance of uncertainties.

Climate policy decisions have to be taken under deep uncertainties on natural mechanisms, on the availability and costs of technological options, on behavioral parameters, on economic impacts from climate change etc. This constitutes an unprecedented challenge for decision-making, as well as a challenge for research to inform decision-making. This research endeavor entails (i) developing alternative decision-making frameworks able to handle this abundance of deep uncertainties (see for instance Hall et al. (2012)), (ii) quantifying the effects of uncertainties, and (iii) developing and applying new methods to use models and build scenarios.

This paper is a contribution to the second and third part of this research endeavor. It presents a first illustration of the possibilities that a large number of scenarios and statistical methods open to inform a robust decision-making framework and quantitatively evaluate trade-offs for climate mitigation policy decisions.

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6

Irreversible investment and transition to clean capital

For the past centuries, economic growth has involved the accumulation of fossil-fueled capital that releases greenhouse gases (GHG) in the atmosphere (e.g. coal power plants, gasoline-fueled cars). From a global welfare perspective, this accumulation of polluting capital is sub-optimal because it does not internalize the future economic damages caused by climate change. Stabilizing climate change requires near zero emissions in the long-run, and therefore implies stopping the accumulation of fossil-fueled capital. Future economic growth thus has to rely on clean capital.

In theory, the optimal policy to trigger such a large-scale transition from polluting to clean capital is – in the absence of any other market failure – a Pigouvian price on GHG emissions, for instance a carbon tax (Nordhaus, 1991). However, governments have been timid about the carbon price¹ and have relied instead on

¹Countries that price emissions at a national level are currently limited to the members of

instruments that redirect investment towards clean capital, such as the corporate average fuel economy (CAFE) standards in the automobile industry, efficiency standards for new buildings, or feebate programs that tax energy-inefficient equipment and subsidize energy-efficient equipment (IEA, 2014).

In this paper, we investigate how the transition to clean capital is modified when using such *investment-based* instruments instead of a carbon price. We model the accumulation of productive clean capital to replace polluting capital, as suggested by Ploeg and Withagen (1991), and we focus on the effect of the irreversibility of past investments on the transition. The transition to clean capital has been studied before, mostly through the lens of directed technical change, focusing on the interaction between pollution and knowledge spillovers externalities (e.g., Gerlagh et al., 2009; Grimaud et al., 2011; Acemoglu et al., 2012). Papers by Fischer et al. (2004), Williams (2011), Slechten (2013), and Vogt-Schilb et al. (2014), all study the optimal accumulation of clean capital but do not investigate formally implications for existing polluting capital. Here we discuss the pacing of abatement efforts over time and the impact of different policy instruments on the price of existing capital.

Our analysis builds on a Ramsey model with two types of capital: “polluting” capital, which creates a negative externality (greenhouse gases emissions), and “clean” capital, which does not. Investment is irreversible, meaning that capital can only disappear through depreciation. Firms may however underutilize existing polluting capital, so that abatement efforts can be divided out between two qualitatively different channels: (i) long-term abatement through accumulation of clean capital instead of polluting capital (e.g. people buy electric cars); (ii) immediate abatement through the underutilization (or early-retirement) of polluting capital (e.g. people drive less).

We start from a *laissez-faire* economy, in which marginal productivities of polluting and clean capital are equal. We compare two strategies (carbon price and investment-based instruments) to maintain the concentration of greenhouse gases in the atmosphere below a certain threshold, corresponding to an exogenous pol-

the European Union, Switzerland, Kazakhstan, Australia and New-Zealand. Combined with regional or sub-national initiatives, total priced emissions represent less than 10% of global emissions.

icy objective such as the UNFCCC 2C target.

We find that mitigation costs decompose as a technical cost — using clean instead of polluting capital — and a transition cost due to the irreversibility of pre-existing polluting capital. This irreversibly cost quantifies the regret that society has because of excessive past investment in polluting capital (e.g. having built a coal power plant before the climate mitigation policy has been announced). In the long run both strategies lead to the same steady state, in which most installed capital is clean and GHG concentration is maintained at a constant level. The carbon price and investment-based instruments however induce different trajectories and costs over the short run.

A carbon price maximizes inter-temporal welfare. It redirects all investment towards clean capital until polluting capital has depreciated to a level compatible with the long-term climate ceiling. The carbon price also induces a short-term decrease in the market price of existing polluting capital. This market price has three functions. It values polluting assets, it reflects the demand for new polluting capital and it signals the profitability of polluting capital to investors. If the climate constraint is stringent with regards to past polluting capital accumulation, part of this capital can be decommissioned and the rental rate of polluting capital reaches zero. These assets that loose value because of the policy are often referred to as “stranded assets” (Goulder et al., 2010; Carbon Tracker, 2013). The underutilization or early retirement of polluting capital allows high short-term abatement but has significant impact on production.

In contrast, investment-based instruments neither create stranded assets nor provide an incentive to underutilize polluting capital. Quite the contrary: by inducing a scarcity effect on polluting capital, these instruments increase the market price of existing polluting capital (i.e. generating “windfall profits” as in Goulder et al., 2010, when emission allowances are grandfathered instead of auctioned). Investment-based instruments yield a higher irreversibility cost than the carbon price as society keeps using obsolete polluting capital until the end of their lifetime instead of early-scraping it – as if refusing to recognize that past accumulation of polluting capital was a mistake. Thereby, they are less efficient (in inter-temporal welfare terms) than a carbon price.² Investment-based instruments lead

²A large literature explores their drawbacks — such as the rebound effect if lower energy

to a second-best pathway that reaches the same long-run objective as the optimal policy but delays efforts, with lower short-term impacts on output and higher efforts over the medium-run.

Our results highlight a trade-off between the optimality of a climate mitigation policy and its short-term impacts, which may influence political acceptability. If we compare the instruments in terms of welfare maximization, the carbon tax alone is always the best policy. When looking at criteria such as short-term impacts, however, investment-based instruments may appear preferable to some decision-makers and voters. In particular, the impact of the carbon price on asset prices would primarily affect the owners of polluting capital and the workers who depend on them, transforming them into strong opponents to the mitigation policy (Jenkins, In press).³

Theoretically, lump-sum cash transfers can compensate the losers and tackle the equity issues faced when implementing a carbon tax (Arrow et al., 1996). In practice, however, it may not be feasible to monitor and compensate each individual loser of climate mitigation policies (e.g., Kanbur, 2010). Another option is to announce a carbon tax in advance to allow economic actors to anticipate it and avoid stranded assets (Williams, 2011), but doing so is made difficult by the governments' limited ability to commit (Kydland and Prescott, 1977; Helm et al., 2003). Finally, one can use a cap-and-trade system where free emission allowances are distributed based on past emissions (grandfathering) or production capacity (Goulder et al., 2010). In this paper, we rethink investment-based instruments as a way to avoid stranded assets, therefore easing the political economy of climate mitigation.

By spreading the costs over time and economic agents, investment-based instruments may reduce the number of opponents to mitigation policies and make the implementation of the carbon tax easier in the long-run. They however cannot curb emissions as fast as the carbon price can. If governments are not able

intensity leads to more extensive use of equipment (Goulder and Parry, 2008; Anderson et al., 2011) — and their rationale such as Tsvetanov and Segerson (2013). Parry et al. (In press) and Allcott (2013) find however that estimated mis-perceptions of energy savings are too low to justify CAFE standards in the automobile sector.

³In this paper we focus on distributional impacts in terms of asset value for capitalists. For the impact of climate policies on income distribution for workers and households, see for instance Parry and Williams (2010) or Rose et al. (2012).

or willing to implement a carbon tax in the near future and the transition has to be triggered by investment-based instruments for political reasons, their slowness makes their implementation (and enforcement) all the more urgent.

The remainder of the paper is structured as follows. Section 6.1 presents the model and section 6.2 solves for the *laissez-faire* equilibrium. In section 6.3 we analyze the optimal growth path, that can be obtained with a carbon price, and we compare it with investment-based second-best instruments in section 6.4. In section 6.5, we study the timing issues of investment-based instruments and risks of lock-in. Section 6.6 discusses the results and concludes.

6.1 MODEL

We consider a Ramsey framework with a representative infinitely-lived household, who saves by accumulating assets⁴, receives income on assets at interest r_t and purchases goods for consumption c_t . Their wealth thus evolves as:

$$\dot{a}_t = r_t \cdot a_t - c_t \quad (6.1)$$

At time t , consuming c_t provides consumers with a utility $u(c_t)$. The utility function is increasing with consumption, and strictly concave ($u' > 0$ and $u'' < 0$).

The household maximizes intertemporal discounted utility W , given by:

$$W = \int_0^{\infty} e^{-\rho t} \cdot u(c_t) dt \quad (6.2)$$

where ρ is the rate of time preference.

Firms produce one final good y_t , using two types of available capital: polluting capital k_p (e.g., coal power plants, thermal engine vehicles) and clean capital k_c (renewable or nuclear power, electric vehicles).⁵

⁴Assets are capital and loans to other households.

⁵ k_p and k_c may also be interpreted as intangible capital; for instance, clean capital encompasses existing clean technologies (e.g. clean electricity production and electrification of the economy) as well as patents, research and development expenses and human capital necessary to develop new clean technologies.

Production is used for consumption (c_t) and investment ($i_{p,t}$ and $i_{c,t}$).

$$y_t = c_t + i_{p,t} + i_{c,t} \quad (6.3)$$

Investment $i_{p,t}$ and $i_{c,t}$ increase the stock of installed capital, which depreciates exponentially at rate δ :⁶

$$\dot{k}_{p,t} = i_{p,t} - \delta k_{p,t} \quad (6.4)$$

$$\dot{k}_{c,t} = i_{c,t} - \delta k_{c,t} \quad (6.5)$$

The dotted variables represent temporal derivatives.

Investment is irreversible (Arrow and Kurz, 1970):⁷

$$i_{p,t} \geq 0 \quad (6.6)$$

$$i_{c,t} \geq 0 \quad (6.7)$$

This means that for instance, a coal plant cannot be turned into a wind turbine, and only disappears through depreciation. However, firms may use only a portion q_t of installed capital k_t to produce the flow of output y_t given by:

$$y_t = F(A_t, q_{p,t}, q_{c,t}) \quad (6.8)$$

$$q_{p,t} \leq k_{p,t} \quad (6.9)$$

$$q_{c,t} \leq k_{c,t} \quad (6.10)$$

F is a classical production function, with decreasing marginal productivities, to which we add the assumption that capital can be underutilized. A_t is exogenous technical progress, and increases at an exponential rate over time.

In the remaining of this paper, q_t will be called utilized capital and k_t installed capital. Although it is never optimal in the *laissez-faire* equilibrium, the underutilization of installed polluting capital can be optimal when a carbon price is imple-

⁶We used the same depreciation rate for polluting and clean capital to keep notations simple, but this assumption plays no particular role in the analysis.

⁷Following the wording by Arlesou (1999) and Wei (2003) capital is putty-clay.

mented.⁸ For instance, coal plants can be operated part-time and low-efficiency cars can be driven less if their utilization is conflicting with the climate objective.

Polluting capital used a time t emits greenhouse gases ($G \times q_{p,t}$) which accumulate in the atmosphere in a stock m_t .⁹ GHG atmospheric concentration increases with emissions, and decreases at a dissipation rate ε :¹⁰

$$\dot{m}_t = G \cdot q_{p,t} - \varepsilon m_t \quad (6.11)$$

Note that since emissions are a function of polluting capital and capital has a decreasing marginal productivity, the carbon intensity of output increases with the polluting capital stock.

6.2 LAISSEZ-FAIRE EQUILIBRIUM

In the *laissez-faire* equilibrium, intertemporal utility maximization leads to a classical arbitrage equation which gives the basic condition for choosing consumption over time (E.1):

$$\frac{\dot{c}}{c} = \frac{-u'(c)}{c \cdot u''(c)} \cdot (r_t - \rho) \quad (6.12)$$

As the elasticity of substitution is positive ($\frac{-u'(c)}{c u''(c)} > 0$), consumption grows if the rate of return to saving r_t is higher than the rate of time preference ρ .

Firms rent the services of polluting and clean capital from households at respective rental rates $R_{p,t}$ and $R_{c,t}$. The flow of profit is given by:

$$\Pi_t = F(A_t, q_{p,t}, q_{c,t}) - R_{c,t} \cdot k_{c,t} - R_{p,t} \cdot k_{p,t} \quad (6.13)$$

A competitive firm takes $R_{c,t}$ and $R_{p,t}$ as given and maximizes its profit by using all installed capital, equalizing at each time t the marginal productivity of polluting

⁸In this paper, underutilization of clean capital is never optimal: $\forall t, q_{c,t} = k_{c,t}$.

⁹In the remaining of the paper, “carbon” will refer to GHG.

¹⁰The dissipation rate allows maintaining a small stock of polluting capital in the steady state. The linear relation between polluting capital and pollution emission is not a necessary assumption but simplifies the notations.

and clean capital to their respective rental rates:

$$\partial_{q_p} F(q_{p,t}, q_{c,t}) = R_{p,t}$$

$$\partial_{q_c} F(q_{p,t}, q_{c,t}) = R_{c,t}$$

The classical equilibrium in capital markets in a Ramsey model applies:

Proposition 1. *In the laissez-faire equilibrium, households are indifferent between investing in polluting or clean capital or lending to other households, so that the marginal productivities of clean and polluting capital net of depreciation are both equal to the interest rate :*

$$R_{p,t} = R_{c,t} = r_t + \delta \quad (6.14)$$

In the next section, we find that the carbon price forces the marginal productivity of polluting capital to be higher than that of clean capital. Also, because investment is irreversible, the relative price of polluting capital decreases during the transition. We then discuss implications for the political economy of climate mitigation policies.

6.3 DISCOUNTED WELFARE MAXIMIZATION: CARBON PRICE

In this section, we adopt a cost-effectiveness approach (Ambrosi et al., 2003) and analyze policies that allow maintaining atmospheric concentration m_t below a given ceiling \bar{m} :

$$m_t \leq \bar{m} \quad (6.15)$$

This threshold can be interpreted as a tipping point beyond which the environment (and output) can be highly damaged, or as an exogenous policy objective such as the UNFCCC “2C target” (Allen et al., 2009; Matthews et al., 2009).

We solve for the welfare maximization program, in which institutions internalize the GHG ceiling constraint. A social planner maximizes intertemporal utility given the constraints set by the economy budget, the capital motion law, investment irreversibility and the GHG ceiling. The same strategy can be decentralized

by imposing the shadow price of emissions on producers and consumers through an optimal carbon tax or a universal cap-and-trade system (E.3).

The social planner program is:

$$\begin{aligned} & \max_{c,i,k} \int_0^{\infty} e^{-\rho t} \cdot u(c_t) dt & (6.16) \\ \text{subject to } & F(q_p, k_c) - c_t - i_{p,t} - i_{c,t} = 0 & (\lambda_t) \\ & \dot{k}_{p,t} = i_{p,t} - \delta k_{p,t} & (v_t) \\ & \dot{k}_{c,t} = i_{c,t} - \delta k_{c,t} & (\chi_t) \\ & \dot{m}_t = G q_{p,t} - \varepsilon m_t & (\mu_t) \\ & m_t \leq \bar{m} & (\varphi_t) \\ & i_{p,t} \geq 0 & (\psi_t) \\ & q_{p,t} \leq k_{p,t} & (\beta_t) \end{aligned}$$

We indicated in parentheses the co-state variables and Lagrangian multipliers (chosen such that they are positive): λ_t is the value of income, v_t and χ_t are the prices of polluting and clean capital, and μ_t is the price of carbon, expressed in terms of utility at time t . The present value Hamiltonian associated to the maximization of social welfare can be found in E.2.

The main first-order conditions of our problem are (E.2.1):

$$u'(c_t) = \lambda_t = v_t + \psi_t = \chi_t \quad (6.17)$$

$$\partial_{k_c} F = \frac{1}{\lambda} ((\delta + \rho)\chi_t - \dot{\chi}_t) \quad (6.18)$$

$$\beta_t = \frac{1}{\lambda} ((\delta + \rho)v_t - \dot{v}_t) \quad (6.19)$$

$$\partial_{q_p} F = \beta_t + \tau_t \cdot G \quad (6.20)$$

Where τ is the price of carbon expressed in dollars per ton:

$$\tau_t = \frac{\mu_t}{\lambda_t} \quad (6.21)$$

Before the ceiling on atmospheric GHG is reached, a classical result (e.g., Goulder and Mathai, 2000, footnote 11) is that the carbon price exponentially grows at the

endogenous interest rate r_t plus the dissipation rate of GHG (E.2.3):

$$\forall t, m_t < \bar{m} \implies \dot{\tau}_t = \tau_t (r_t + \varepsilon) \quad (6.22)$$

The steady state is reached when $m_t = \bar{m}$. In the steady state, atmospheric emissions are stable, implying that polluting capital is constant at $k_{p,t} = \bar{m} \varepsilon / G$ ($\dot{m}_t = 0$, eq. 6.11) and the rest of the economy keeps growing on a balanced growth path, thanks to exogenous technical change A_t .

In equations 6.18 and 6.19 we recognize the rental rates of clean and polluting capital $R_{c,t}$ and $R_{p,t}$, as defined by Jorgenson (1967):

$$R_{c,t} := \frac{1}{\lambda} [(\delta + \rho)\chi_t - \dot{\chi}_t] \quad (6.23)$$

$$R_{p,t} := \frac{1}{\lambda} [(\delta + \rho)v_t - \dot{v}_t] \quad (6.24)$$

where χ_t and v_t are respectively the clean and polluting capital shadow prices.

The following proposition can be deduced from the first-order conditions:

Proposition 2. *Along the optimal path, the marginal productivity of clean capital equals the rental rate of clean capital:*

$$\partial_{k_c} F = R_{c,t} \quad (6.25)$$

The marginal productivity of polluting capital is equal to the rental rate of polluting capital plus the marginal cost of carbon emissions:

$$\partial_{q_p} F = R_{p,t} + \tau_t G \quad (6.26)$$

Proof. Equation 6.25 derives from eq. 6.18 and 6.23. Equation 6.26 is obtained by substituting β_t in eq. 6.20, using eq. 6.24. \square

In the *laissez-faire* equilibrium, the marginal productivity of polluting capital was also equal to its rental price. This is no longer the case when the pollution externality is internalized, as firms have to pay the carbon tax when they use polluting capital. Also, the rental rate of polluting capital $R_{p,t}$ is no longer equal to that of clean capital, as it is now affected by an irreversibility cost:

Proposition 3. *Along the optimal path, the interest rate r_t that arbitrates between consumption and investment is given by:*

$$r_t = R_{c,t} - \delta \quad (6.27)$$

The rental rate of polluting capital can be lower than that of clean capital:

$$R_{p,t} = R_{c,t} - p_t \quad (6.28)$$

Where the irreversibility cost p_t is the monetary impact of the irreversibility constraint on the rental rate of polluting capital:

$$p_t = \frac{1}{\lambda_t} ((\rho + \delta)\psi_t - \dot{\psi}_t) \in [0, R_{c,t}] \quad (6.29)$$

Proof. See E.2.2 for eq. 6.27. Equation eq. 6.28 is obtained by replacing v_t by $\chi_t - \psi_t$ (eq. 6.17) in eq. 6.24. Since $R_{p,t} = \beta_t \geq 0$ (eq. 6.19), $p_t = R_{c,t} - R_{p,t} \leq R_{c,t}$. \square

Because investment is irreversible, when the policy is implemented the stock of polluting capital cannot be instantaneously adjusted to its optimal level. Polluting capital therefore becomes overabundant and its rental rate decreases.

The irreversibly cost p_t quantifies the regret that society has because of excessive past investment in polluting capital (e.g. having built a coal power plant before the climate mitigation policy has been announced). It allows decomposing the shadow price of emissions τ_t as a “technical” abatement cost (e.g. renewable power plants are more expensive than coal power plants) plus an irreversibility cost:¹¹

$$\underbrace{\tau_t}_{\text{economic cost}} = \underbrace{\frac{\partial_{q_p} F - \partial_{k_c} F}{G}}_{\text{technical cost}} + \underbrace{\frac{p}{G}}_{\text{irreversibility cost}} \quad (6.30)$$

with $p \in [0, \partial_{k_c} F]$

The next proposition shows that an irreversibility cost necessarily appears when the carbon tax is implemented (in t_o).¹² Once polluting capital has adjusted through

¹¹Combining equations 6.25, 6.26 and 6.28.

¹²Contrary to (Arrow and Kurz, 1970), who find that the irreversibility constraint is binding if

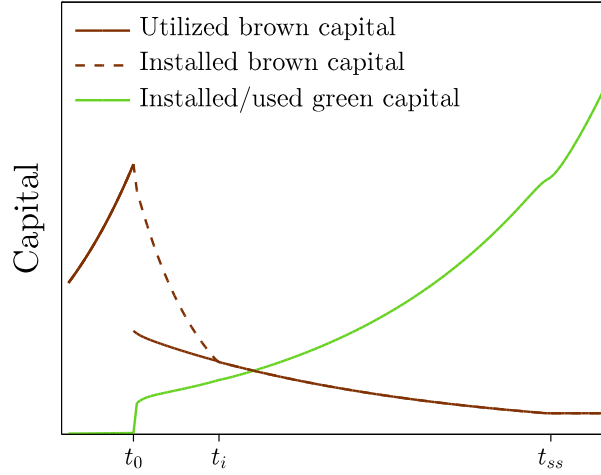


Figure 6.1: Polluting and clean installed capital, and utilized polluting capital in the first-best optimum. Before t_0 , the economy is on the *laissez-faire* equilibrium. At t_0 the carbon price is implemented and polluting capital depreciates until t_i ($\forall t \in (t_0, t_i), i_b = 0$). During this period, polluting capital may be underutilized ($q_{p,t} < k_{p,t}$). Polluting investment then starts again, and the steady state is reached at t_{ss} .

natural depreciation, the irreversibility cost is null.

Proposition 4. *Two phases can be distinguished during the optimal transition to clean capital:*

- *First, a phase when the market price of polluting capital is lower than that of clean capital and no investment is made in polluting capital:*

$$0 < p_t \leq R_{c,t}$$

$$R_{p,t} < R_{c,t}$$

$$i_{p,t} = 0$$

- *Then, a phase when the market price of polluting and clean capital are equal and*

the initial capital is higher than the steady-state level, here the irreversibility constraint is binding for any level of initial polluting capital because of the new constraint on emissions.

polluting investment is strictly positive:

$$\begin{aligned} p_t &= 0 \\ R_{p,t} &= R_{c,t} \\ i_{p,t} &> 0 \end{aligned}$$

Note that during this phase net investment is negative (when accounting for depreciation) until it is equal to zero in the steady-state state.

Proof. E.2.4. □

During the first phase, the irreversibility constraint prevents the economy from transforming polluting capital into either clean capital or consumption and the market price of polluting capital falls below the marginal utility of consumption (eq. 6.17).

The maximum value of the irreversibility cost p_t is $\partial_{k_c} F$, the marginal productivity of clean capital, as the maximum regret cost is the cost of not having invested in clean instead of polluting capital before t_0 . Indeed, if $p_t = \partial_{k_c} F$, the rental rate of polluting capital falls down to zero (eq. 6.28), reflecting that polluting capital is overabundant:¹³

Proposition 5. *During the first phase (when polluting investment is null) if the carbon price is higher than the marginal productivity of installed polluting capital, polluting capital is underutilized until its marginal productivity equals the carbon price:*

$$\tau_t G > \partial_{k_p} F(k_p, k_c) \implies \begin{cases} p_t = R_{c,t} \\ R_{p,t} = 0 \\ q_{p,t} < k_{p,t} \\ \partial_{q_p} F(q_p, k_c) = \tau_t G \end{cases} \quad (6.31)$$

Proof. Eq. 6.26 implies that the rental rate of polluting capital $R_{p,t}$ is the difference between the marginal productivity of polluting capital and the carbon price. As the

¹³The strictly positive marginal productivity of utilized polluting capital is transferred to households through the tax revenue $\tau_t G$.

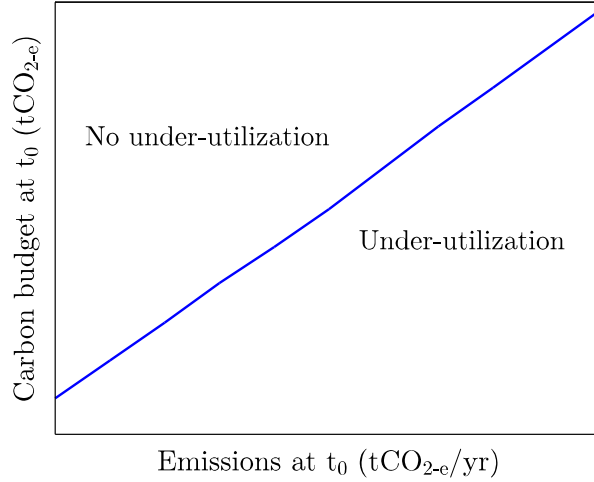


Figure 6.2: Depending on initial emissions (i.e. initial brown capital $k_{b,o}$) and on the concentration ceiling (\bar{m}), brown capital is underutilized or not in the first-best optimum.

rental rate of polluting capital $R_{p,t}$ is equal to the positive multiplier associated to the capacity constraint β_t (eq. 6.19 and 6.24), when the carbon price is higher than the marginal productivity of installed polluting capital the rental rate of polluting capital is null and capital is underutilized. \square

The underutilization of brown capital depends on the ceiling \bar{m} , on the initial stock of brown capital k_{b,t_0} and on other parameters of the model such as the functional forms of F and u , on the depreciation rate δ and the preference for the present ρ . As illustrated in Fig. 6.2, for a given set of functions and parameters the underutilization of brown capital happens if initial brown capital is high (right end of the x-axis) and/or if the ceiling is stringent (lower part of the y-axis).

In this section, we have found that under irreversible investment, society has to live with past mistakes for a while, once it realizes it has been on a non-optimal growth path. A way to limit the associated irreversibility cost is to give up part of installed polluting capital in order to reduce emissions faster (thereby creating stranded assets). In the next section, we find that investment-based policies reduce emissions without affecting existing polluting capital, and therefore increase the social cost of GHG abatement.

6.4 INVESTMENT-BASED INSTRUMENTS

Current climate mitigation policies rarely include carbon prices and rely instead on investment-based instruments such as energy efficiency standards or fiscal incentives for green investment (as feebates, which impose additional fees on polluting capital and rebates for clean capital). These instruments redirect investment towards clean capital but have no effect on the use of existing capital.

In this section, we investigate the optimal transition to a clean-capital economy using investment-based instruments. We find that (i) they are less efficient than the first-best carbon tax in terms of inter-temporal welfare maximization, (ii) they allow reaching the same steady state, and (iii) they induce a full utilization of polluting capital in the short run, thereby reducing short-term income losses.

A way to trigger the transition to a clean economy is to differentiate investment costs with feebate programs, i.e. fiscal incentives that include subsidies on clean investment ($\theta_{c,t} > 0$) and taxes on polluting investment ($\theta_{p,t} > 0$). With such a feebate program, π_t , the flow of firms' net receipt at time t is equal to:

$$\pi_t = F(q_{p,t}, q_{c,t}) - (\lambda_t - \theta_{c,t}) i_{c,t} - (\lambda_t + \theta_{p,t}) i_{p,t} \quad (6.32)$$

Where λ_t is the price of investments. The optimal values of $\theta_{c,t}$ and $\theta_{p,t}$ can be obtained with a maximization of social welfare given the ceiling constraint. The same steady state as in the social optimum is reached (at a date $t_{ss,2}$ which is different than $t_{ss,1}$ in general). On the steady-state the optimal value of $\theta_{c,t} + \theta_{p,t}$ is equal to the first-best carbon tax multiplied by the marginal emissions of polluting capital:¹⁴

$$\forall t \geq t_{ss,2}, \theta_{c,t} + \theta_{p,t} = \tau_{t,1} \cdot G \quad (6.33)$$

Investment-based instruments induce a different short-term transition than with a carbon tax. Over the short-run, investment in polluting capital stops. However, as firms do not pay carbon emissions directly, it is never optimal to underutilize

¹⁴Note that the same outcome can be reached using taxes on polluting investment alone or subsidies to clean investment alone, since what matters is the sum of the tax plus the subsidy. A tax and a subsidy lead to different transfers in the society, which can play a key role on the acceptability of a particular environmental policy (e.g Sterner and Höglund Isaksson, 2006; Fischer, 2008)

polluting capital (E.4). As a consequence, short-term output may be higher than in the first-best strategy:¹⁵

Proposition 6. *With a feebate program, short-term output is equal or higher than in the first-best solution with a carbon price.*

Proof. The first-best carbon price may induce underutilization of polluting capital in the short-run ($q_{p,1,t} < k_{p,t}$). In the second-best solution capital is not underused ($q_{p,2,t} = k_{p,t}$). As both strategies start with a phase during which polluting investment is null, installed capital is identical with both policies in an interval (t_0, \tilde{t}) . During this interval, utilized polluting capital, hence output, is higher in the second-best strategy. \square

Similarly to the carbon price, investment-based instruments differentiate the marginal productivities of capital (E.4):

$$\partial_{q_p} F = \partial_{k_c} F - \underbrace{\frac{1}{\lambda_t} ((\rho + \delta)\psi_t - \dot{\psi}_t)}_{p_t} + \underbrace{\frac{1}{\lambda_t} ((\delta + \rho)(\theta_{c,t} + \theta_{p,t}) - (\dot{\theta}_{c,t} + \dot{\theta}_{p,t}))}_{\tau_{t,2} G} \quad (6.34)$$

where p_t is the irreversibility cost. In this second-best setting the shadow price of carbon $\tau_{t,2}$ is still equal to a technical abatement cost plus the irreversibility cost:

$$\underbrace{\tau_{t,2}}_{\text{economic cost}} = \underbrace{\frac{\partial_{q_p} F - \partial_{k_c} F}{G}}_{\text{technical cost}} + \underbrace{\frac{p}{G}}_{\text{irreversibility cost}} \quad (6.35)$$

The irreversibility cost p is no longer bounded by the marginal productivity of clean capital but by the shadow price of carbon $\tau_{t,2}$ (E.4). Indeed, preventing underutilization is like refusing to recognize that past accumulation of polluting capital was a mistake. When society keeps using obsolete polluting capital instead of early-scraping it, the irreversibility cost can be as high as the cost of the carbon emissions that installed brown capital produces.

¹⁵Analytically the effect on consumption is ambiguous because it involves the offsetting impacts from a substitution effect and an income effect: short-term output is higher, but investments in clean capital may also increase since the saving rate is endogenous.

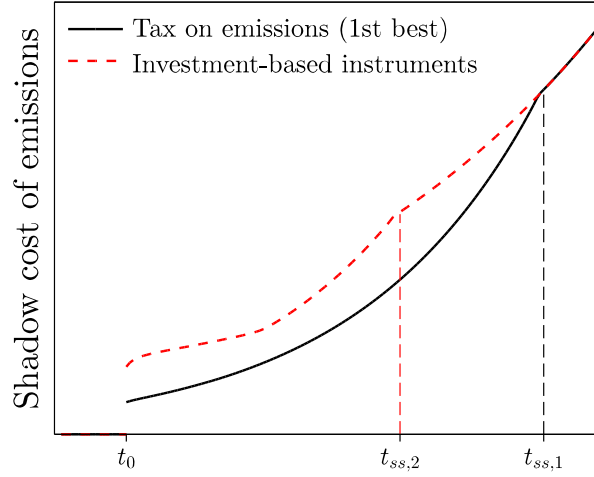


Figure 6.3: The shadow price of emissions (or carbon price) is higher with investment-based instruments than with a carbon price.

The short-term utilization of obsolete polluting capital leads to a different shadow price of carbon than in the first-best case with a carbon tax:

$$\forall t \in I_{u,1}, \tau_{t,2} - \tau_{t,1} = \frac{1}{G} \left[\partial_{q_p} F(q_{p,2} = k_p) - \partial_{q_p} F(q_{p,1} < k_p) + a_t \right] \quad (6.36)$$

Where $I_{u,1}$ is the interval during which capital is underutilized on the first-best pathway and $a_t = p_t - \partial_{k_c} F$ is the extra cost associated to the utilization of obsolete polluting capital on the second-best pathway. This extra-cost can be interpreted as a temporary subsidy on the utilization of polluting capital in the welfare-maximization framework (E.5).

Figure 6.3 compares the shadow prices of carbon with the first and second-best policies. Investment-based policies generate a higher emissions shadow price than the carbon tax alone, however the dynamics of capital accumulation mean that the social cost of abatement cannot be translated into consumption losses in a trivial way (see also Vogt-Schilb et al., 2014). Even if investment-based instruments set a higher emissions shadow cost at each time t (Fig. 6.3), output is higher over the short-run (Prop. 6, Fig. 6.4).

Investment-based policies only differ temporarily from the first-best pathway, in a way that smooths the transition costs: they decrease efforts in the short-run

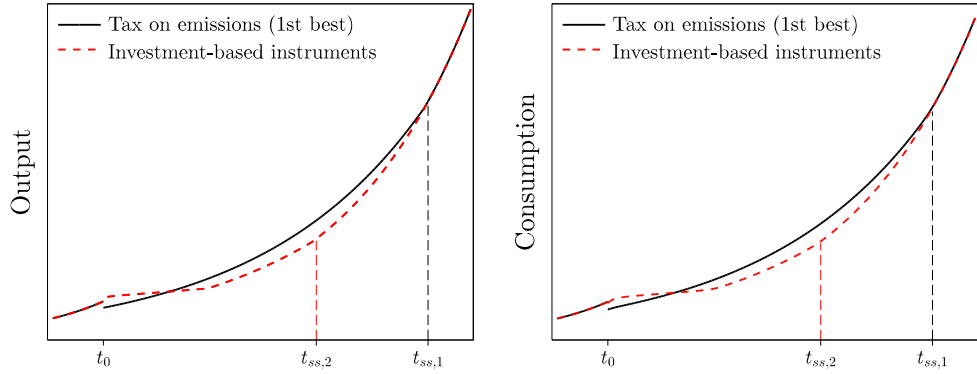


Figure 6.4: On the left, output y in the two cases. In the short-run output is lower in the first-best case because of the adjustment of polluting capital utilization. On the right, consumption c is higher in the second-best case because of a higher output y . t_{ss} is the date at which the steady state is reached, it is reached sooner in the second-best case ($t_{ss,2} < t_{ss,1}$).

(Prop. 6), leave them unchanged in the long-run (eq. 6.33), and (therefore) increase efforts in the medium-run (Fig. 6.4). Moreover, feebate programs induce a different intra-generational distribution of abatement efforts from the carbon tax, since they avoid stranded assets. By preventing new investment in polluting capital, they even increase the value of existing polluting assets:

Proposition 7. *With a feebate program, the market price of polluting capital is initially higher than the price of clean capital, and than the marginal utility of consumption.*

Proof. First-order conditions for firms' receipt maximization give:

$$v_t = \chi_t + \theta_{c,t} + \theta_{p,t} - \psi_t \quad (6.37)$$

where v_t is the price of polluting capital and χ_t is the price of clean capital. The policy creates a scarcity effect on polluting capital, that increases its price while the irreversibility constraint reduces its price in the short-run. E.4 shows that $\theta_{c,t} + \theta_{p,t} - \psi_t \geq 0$. \square

Investment-based instruments are not limited to feebates and may include performance standards for new capital.¹⁶ Such performance standards include for in-

¹⁶Investment costs can also be differentiated using financial markets, as proposed by Rozenberg et al. (2013).

stance existing energy-efficiency standards for new vehicles, buildings, and appliances.

Proposition 8. *In our model the optimal feebate program is equivalent to the optimal performance standard on new capital: (1) they induce the same investment and output pathways and (2) they have the same impact on the price of polluting capital.*

Proof. Appendix E.6. □

As with feebates, performance standards induce a full utilization of existing polluting capital in the short-run and redirect investments towards clean capital. They also create scarcity on existing polluting capital and therefore increase the price of polluting capital with regards to clean capital on secondary markets.¹⁷

6.5 TIMING OF ACTION AND CARBON-INTENSIVE LOCK-IN

The utilization of investment-based instruments is limited by their slowness in reducing emissions. Indeed, since they maintain a full utilization of polluting capital in the short-run, investment-based policies result in higher short-term emissions than the carbon tax (Prop. 6 and Fig. 6.5) and might not be sufficient for stringent climate objectives as regards to past capital accumulation.

Figure 6.6 proposes a visualization of this issue. Starting from low polluting capital stocks (thus low emissions), a carbon tax does not lead to underutilization of polluting capital and reaching the climate target is possible and optimal without a downward step in income. In this case, the carbon price consistent with the climate target leads to the exact same pathway as investment-based policies. This is a situation of “flexibility” in which a country can choose a polluting or a clean development path at low cost, using either a carbon price or investment-based instruments.

But as long as climate policies are absent (or very lax), the economy accumulates polluting capital, making GHG emissions grow and reducing the residual carbon budget for a given climate target (the arrow “conventional growth”).

At one point, the threshold when the marginal productivity of polluting capital is lower than the optimal carbon price is crossed (see eq. 6.31), meaning that

¹⁷In this model the capital lifetime is endogenous and therefore people cannot extend the lifetime of their polluting capital.

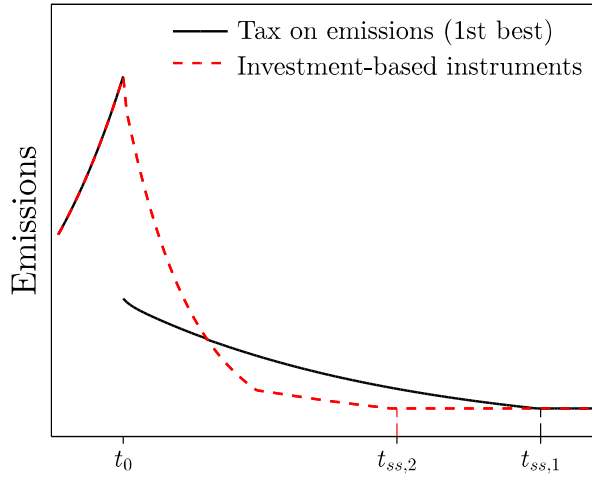


Figure 6.5: GHG emissions in the two cases. The carbon price induces spare polluting capital and thus reduces carbon emissions faster in the short-run.

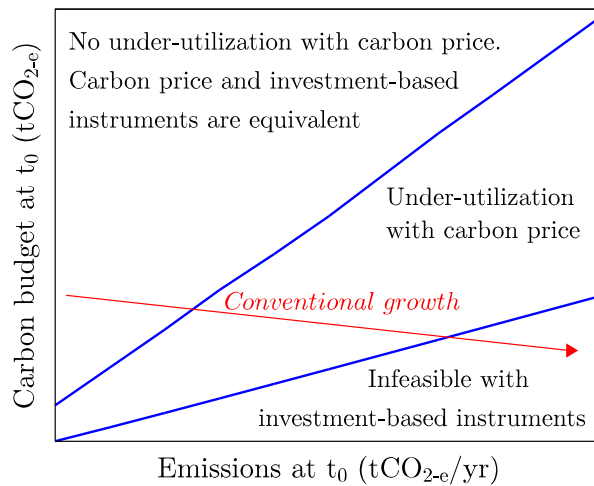


Figure 6.6: Depending on initial emissions (i.e. initial polluting capital k_{b,t_0}) and on the carbon budget ($\bar{m} - m_{t_0}$), the carbon tax and investment-based instruments can lead to different or similar outcomes (for a given set of parameters, and in particular ρ and δ). If the carbon budget is too stringent, such that waiting for polluting capital depreciation is not sufficient, the investment-based instruments cannot be used. If the carbon budget is not stringent, there is no underutilization of polluting capital in the first-best optimum with the carbon tax and investment-based instruments are equivalent. While the economy is on the laissez-faire growth path (red arrow), polluting capital accumulates and the carbon budget is reduced for a given climate objective.

polluting capital should be underutilized and output reduced. From there, a carbon price becomes more difficult to implement because of political-economy constraints. But the alternative option of using investment-based instruments is available, leading to higher inter-temporal costs but no immediate drop in income. There is a window of opportunity, during which alternative investment-based instruments may induce a smooth and acceptable transition to a low-carbon economy.

If this occasion is missed (right hand side, Fig. 6.6), it becomes impossible to reach the climate target without underutilization of polluting capital and investment-based options are not available any more (if the climate objective is not revised). In this last area, not only the economic cost of reaching the climate target is higher, but the political economy also creates a carbon lock-in: the only option to reach the climate target requires early-scraping and thus has a significant short-term cost, making it more difficult to implement successfully a climate policy consistent with the target.

The zone in which polluting capital must be underutilized to remain below the ceiling depends on the capital depreciation rate δ , the GHG dissipation rate ε , initial GHG concentration m_o and initial polluting capital k_o . The lower blue line in Fig. 6.6 is expressed analytically in E.7 and can be approximated by:

$$\bar{m} < m_o + \frac{G k_o}{\delta}$$

According to Davis et al. (2010), the level of existing polluting infrastructure in 2010 is still low enough to achieve the 2C target without under-utilizing polluting capital, suggesting that the global economy is not in this last region yet. They find that if existing energy infrastructure was used for its normal life span and no new polluting devices were built, future warming would be less than 0.7C. Yet, reaching the 2C target might imply to stop investing in polluting capital very soon, which depends on our ability to overcome infrastructural inertia and develop clean energy and transport services (Davis et al., 2010; Guivarch and Hallegatte, 2011). Note that Davis et al. (2010) do not discuss whether the least-cost policy would lead to under-utilization, that is whether we are in the top or the middle triangle in Fig. 6.6.

6.6 DISCUSSION

Choosing the best instrument in terms of welfare results in choosing the lowest social cost of abatement but not the highest consumption at each time t . There is a trade-off between efficiency (maximum intertemporal welfare), intergenerational equity (distribution of efforts over time) and implementation obstacles (political economy). The carbon tax is the best tool to maximize discounted welfare, but public policy is especially difficult in contexts where costs are immediate, concentrated and visible, while benefits are invisible (avoided damages) and diffuse over time and over citizens (Olson, 1977). Policy-makers may use other criteria than social welfare maximization to choose the policy to implement (Beltratti et al., 1994; Chichilnisky et al., 1995).

One possible reason why investment-based instruments are preferred by policy-makers is that they give the owners of existing polluting capital some time to adapt to the new economic conditions – without carrying a loss for past decisions – and prevent capital underutilization. Indeed, underutilization of capital may appear as a waste of resources, results in an output drop and creates unemployment. Also, the owners of obsolete polluting capital and the workers whose jobs depend on this capital can be strong opponents to climate policies. Governments may thus be captured by the owners of polluting capital (Laffont and Tirole, 1991) who claim compensations because they invested under pre-existing rules and will own stranded assets. Finally, governments may also be captured by individuals who have different time preferences from the social planner's. Indeed, time preference heterogeneity makes it unappealing for some people to pay now for remote future benefits. This is even more so because future generations are likely to be richer and the ones benefiting from reduced climate change damages. Since investment-based strategies postpone mitigation efforts to the medium-run, they would be preferred by people with high discount rates.

Investment-based instruments therefore ease the political economy of the transition to clean capital. While the outcome of such instruments is lower in terms of discounted intertemporal welfare, they have the potential to tackle both the effectiveness (they trigger a transition to clean capital) and the equity (they compensate losers) functions of a climate mitigation policy, as well as inter-generational

distributional issues.

Our analysis is incomplete and further analyses of the distributional impacts of mitigation instruments could model capital retrofit (an intermediary solution between investing in new clean capital and early-scraping existing polluting capital) or learning-by-doing and knowledge spillovers (which would improve the productivity of clean capital). We also omitted to consider cases with myopic agents or limited ability to commit. Nevertheless, our results suggest that investment-based instruments respond to a political acceptability issue as regards to climate mitigation policies.

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7

Funding low-carbon investments in the absence of a carbon tax

7.1 INTRODUCTION

Climate change is now widely recognized as a threat to the environment, economic growth, and social welfare. In response, many countries have set individual long term objectives or commitments in terms of future greenhouse gas (GHG) emissions. The European Union committed itself to reduce emissions by 20% in 2020, relative to 1990 levels.¹ France and the UK have a long term objective of dividing by four their emissions by 2050. Collectively, the countries of the world have decided to aim for limiting global warming at 2C above pre-industrial global temperature. To do so, world emissions need to be divided by two by 2050 (O'Neill

¹This target might become more stringent since the EU “Roadmap for moving to a low-carbon economy in 2050” has moved to an objective of at least 25% reduction in GHG emissions by 2020.

et al., 2010). These targets are very ambitious and require immediate and energetic political action. Reaching these targets will require significant investments, in particular in energy, building, transport and end-use equipments. The World Development Report 2010 (World Bank, 2010) estimates that incremental costs of mitigation in developing countries could reach \$140-\$175 billion a year by 2030. Added to current needs, these costs lead to total financing needs of about \$264-\$563 billion over the same period. These numbers however pale in comparison to current global Gross Fixed Capital Formation (GFCF) which amounts to about US\$11 trillion per year, suggesting that the challenge is less to increase global investments than to shift them toward low-carbon projects.² Doing so would be highly facilitated by attributing a price to carbon emissions. The High-level Advisory Group on Climate Change Financing (AGF (Advisory Group on Climate Change Financing), 2010) indeed emphasized the importance of a carbon price in the range of US\$20-US\$25 per ton of CO₂ equivalent in 2020 to succeed in leveraging US\$100 billion per year dedicated to climate finance.

Beyond its impacts on low-carbon investment,³ attributing a price to carbon emissions can help coordinating the ambitious transition toward a low-carbon economy. This price can also influence household behaviors, change optimal production processes, and help local authorities coordinate their action. Since climate change is an environmental externality, it can theoretically be solved in an optimal way by internalizing the externality with a carbon price (Nordhaus, 1994; Rezai et al., 2012). Moreover, because climate change is not the only externality in the economic system (Hallegatte et al., 2012), additional measures are needed to deal with other market failures, such as a R&D subsidy to cope with knowledge spillover.

It appears attractive to create this carbon price through the introduction of a carbon tax. Its advantages include universal applicability, simplicity, efficacy, and low set-up costs due to existing administrative institutions. But the carbon tax suffers from a lack of political acceptability, as illustrated by the failure of its in-

²The proportional increase in investment needs is different depending on the considered sector; it is for instance likely to be relatively larger in the energy sector.

³By introducing a price for carbon, the profitability of “regular” capital falls, because it now has to pay for its carbon emissions. Low carbon capital becomes more profitable and is able to obtain investment funds from the market more easily.

roduction in France in 2010. Two main difficulties have to be overcome. The first difficulty relates to intragenerational equity, since a carbon tax may have negative redistributive effects between contemporary businesses and households. Indeed, correcting the externality can be done in such a way that it maximizes the social welfare (aggregated over all individuals and discounted over time), but it may decrease the welfare of some individuals (in other terms, it is not Pareto improving).⁴ Zero-cost lump-sum inter-individual transfers are required to make a welfare-maximizing solution Pareto-improving (e.g. Harberger, 1978). In spite of technical difficulties (Kanbur, 2010), past experience in fossil fuel subsidy removal has shown that these distributional effects can be compensated through ad hoc measures or pre-existing safety nets (Hope and Singh, 1995).

The second difficulty arises from intergenerational distributive impacts and is more complicated to tackle. Indeed, the perceived necessity to pay now for an expensive transition in exchange for remote future benefits is one of the obstacles to the implementation of ambitious climate policies. In a period of economic crisis, this trade-off may appear particularly unappealing to voters and decision-makers.

As a consequence of this political unacceptability — that can be understood as a government failure — a carbon tax⁵ appears unrealistic in the current context and other tools may have to be used to address the climate change issue, at least in the short-term. In particular, several initiatives have been developed to shift global (public and private) investments toward low-carbon projects in the absence of a carbon price. Even though this is a second-best option, it represents a significant progress compared to a business-as-usual scenario.

Private initiatives are essential in seeking out and implementing least-cost options for climate mitigation. They however require public policies to establish the incentive frameworks necessary to catalyze high levels of private investments. Today low-carbon projects suffer from a lack of funding because of market failures affecting innovation and dissemination of new technologies, high risk perceptions due to uncertainties about future climate policies and carbon prices, and excess

⁴In fact, correcting one externality always increases welfare only if there is only one externality. In presence of multiple externalities, correcting one of them can reduce welfare (Lipsev and Lancaster, 1956).

⁵A carbon market with full auctioning of allowances, and covering all economic sectors, is also an unrealistic option in the short-run.

upfront costs that make them unable to offer returns that are commensurate with their (perceived) risk. The challenge is to convince investors to change the technical content of their projects by providing them with cheaper capital, e.g. by using limited public resources as leverage for private capital. A paper by World Bank et al. (2011) lists innovative instruments that have been proposed to do so: subsidies on fossil fuel use can be redirected to public climate finance; market-based instruments for international aviation and maritime bunker fuels can be used as an innovative source of climate finance; carbon offset markets can play an important role; and there are significant opportunities for Multilateral Development Banks to mobilize resources through new pooled financing arrangements (see for instance the Climate Investments Funds (CIFs) and Global Environment Fund (GEF)).

This chapter proposes another approach to provide cheaper capital to low-carbon projects, through the use of differentiated interest rates. The interest of this solution is that it can be designed in a way that avoids intergenerational distributive impacts and is thus more politically acceptable than other options. Since GHG emissions and climate change are an uncorrected negative externality, climate change mitigation can be Pareto-improving — with all generations benefiting from action — provided that intergenerational transfers are implemented (Sinn, 2007; Rezai et al., 2012). Our proposal is based on the idea that such transfers are possible through manipulation of the interest rate. Even though it comes at the expense of aggregate efficiency (efficiency being measured using social welfare), this option is however easier to implement because it is Pareto-improving⁶ compared with a business-as-usual scenario.

In practice, the carbon externality can be corrected by mitigation expenditures and investments, at the cost of a reduced total economic output over the short-run. The intergenerational distributional impacts of mitigation actions can then be prevented, and the welfare cost for current generations canceled, if total investments are reduced such that immediate consumption is not affected.⁷ On the one hand, such an action would impact negatively future generations, by providing them with less capital. On the other hand, it would benefit them through lower

⁶This solution is Pareto-improving only if intragenerational distributional effects can be compensated through ad hoc measures or pre-existing safety nets.

⁷Even though production Y is affected by ΔY , consumption C is maintained by reducing investment I by ΔY

climate change impacts, while protecting the consumption of current generation.⁸

To do so, it is possible to manipulate interest rates so that capital becomes more expensive for carbon-emitting investments and consumption is encouraged. In addition, low-carbon investments could benefit from lower interest rates (i.e., lower capital cost), to provide an incentive to reduce GHG emissions.⁹ From a welfare maximization perspective, this solution is suboptimal because the carbon externality is internalized only in the cost of capital, and not in all relevant decisions. Also, the impact on discounted social welfare of these intergenerational transfers is ambiguous (e.g., this impact depends on the discount rate and on the form of the utility function). This option is nevertheless potentially able to bring the economy closer to its social-welfare frontier, reducing the welfare consequences of the carbon externality.¹⁰

This chapter proposes an institutional framework in which low-carbon projects have access to cheaper loans. This framework can be set up in a single country, at the European level, or even at the international level.¹¹

7.2 CARBON CERTIFICATES AS A TOOL TO FINANCE LOW-CARBON PROJECTS

Box 1: The need for MRV standards. Measuring the contribution of a project to GHG emission reduction is extremely difficult, as suggested by the Clean Development Mechanism (CDM) experience (Schneider, 2009). Accurate project-based accounting of avoided emissions on a case by case basis is hardly feasible or very costly to perform. Avoided emissions are indeed nec-

⁸The welfare derived from consumption would be preserved, even though the structure of consumption would be modified by changes in relative prices.

⁹The increase in low-carbon investments (and their extra-costs relative to regular projects) would be compensated by a decrease in regular investments.

¹⁰Note that this chapter does not touch upon the choice of mitigation targets, but deals only with ways of reaching a pre-determined target. These two questions are related, for instance through the discount rate that influences the weight of future climate change impacts on current decisions.

¹¹Application at the international level combined with a reform of the international monetary system is discussed in Hourcade et al. (2012).

essarily calculated from a controversial baseline, and indirect effects of investments cannot be fully integrated in projects' appraisal (Shalizi and Lecocq, 2009). Using avoided carbon emission as bank reserves requires a very high standard of measurement and verification that has not been met with CDMs. A more robust alternative approach is to define a taxonomy of low-carbon projects and conventionally attribute a number of carbon certificates to each type of projects, regardless of whether the project is "additional" or not. For instance, a photovoltaic electric plan would be allocated a number of certificates as a function of its production capacity and the average carbon content of electricity production in the country. In the same way, an urban public transportation investment (e.g. a new metro line) would receive certificates as a function of the expected number of passengers, its electricity consumption, and the average carbon content of electricity production in the country. Using such a typology of projects will make it unnecessary to carry out a detailed analysis of each project. It allows simplifying procedures, reduces transaction costs and project uncertainty, and mitigates fraud risks. The entire scheme is however dependent on a well-defined typology and on appropriate rules and procedures. In particular, the procedures need to be able to adjust for new information and technical change (e.g., be able to accommodate a new way of producing renewable energy).

The first step would be to set a carbon value. However it would not be applied directly to all prices in the economy through a carbon tax: it would be used to value new assets that we call carbon certificates. These carbon certificates would have a fixed face value and would be considered as legal reserve assets that can be used by commercial banks to respect legal-reserve regulatory constraints.¹² They would be created and allocated by an independent monitoring unit to low-carbon project investors at the beginning of their project, the number of certificates depending on

¹²In countries where legal reserves are not binding, which is the case of most advanced economies, this mechanism would not be very efficient. Instead, one can think more generally about the implementation of stronger macroprudential policies by central bank authorities aimed at controlling more effectively the allocation of credit by private banks. It will be the focus of further work.

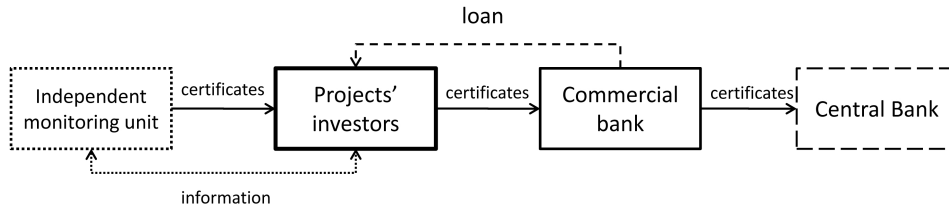


Figure 7.1: An investor receiving carbon certificates can exchange them for a concessional loan. Banks can use the certificates as legal reserve assets.

the project contribution to carbon emissions mitigation. This poses a problem of metric to monitor, control and verify projects, which we address briefly in Box 1. The independent monitoring unit would also fix a lifetime to the certificates, as a function of the project category.

As depicted in 7.1, an investor who has been allocated carbon certificates can give them to a bank in exchange for a concessional loan. The bank would provide such a loan because it can then use the certificates as a reserve asset to reduce its capital costs and respect legal-reserve regulatory constraints. In countries where legal reserves are not a constraint, one can think about turning carbon certificates into capital for the bank (Hourcade et al., 2012).

Legal reserve requirements are an instrument in the hands of central banks to control money supply, in addition to their open-market operations that target a given short-term interest rate (Bank of England, 2011; European Central Bank, 2011; Federal Reserve Bank of San Francisco, 2004): it sets the minimum reserves each commercial bank must hold at the central bank as a counterpart to customer deposits and notes. Let r equal the required reserves-deposits ratio, e the excess reserves-deposits ratio and c the currency-deposits ratio. The amount of money M_1 (currency plus checkable deposits) is then proportional to MB (Monetary Base) through the money multiplier m (Mishkin, 2010):

$$M_1 = m \cdot MB \text{ with } m = \frac{1 + c}{r + e + c} \quad (7.1)$$

If reserves MB are exogenously increased by carbon certificates, and if the central bank maintains its target short-term interest rate (\bar{i}) then banks will expand deposits M_1 through additional loans, unless bank customers withdraw currency (i.e., an increase in c), or banks decide to keep these reserves as excess reserves (i.e., an

increase in e). If c , e , r and \bar{i} remain unchanged, then an increase in MB by $x\%$ translates into an increase in M_1 by $x\%$. Attributing carbon certificates to low-carbon projects would thus increase MB , and in turn increase M_1 (if $\Delta MB = C$ where C are carbon certificates in the central bank, then $(M_1 + \Delta M_1) = m (MB + \Delta MB)$ and $\Delta M_1 = m C$). Since legal reserves influence demand for MB (even if r remains unchanged), they are one propagation channel for monetary policy that targets a given short-term interest rate (i.e. the price of MB). We claim that using legal reserves would be an efficient tool to finance mitigation. For a commercial bank, receiving carbon certificates from a project investor allows increasing legal reserves and the amount of loans, thereby increasing revenues (Box 2 gives an example of the potential gains for both the investor and the commercial bank). This system thus provides a strong incentive for commercial bank to fund low-carbon projects with lower-rate loans. Accordingly, the lower the reserve ratio r , the more additional loans can be made for each carbon certificate. When r is very low, or in the most extreme case when $r = 0$ like in the UK, banks are not constrained by reserve requirements, however loans are limited by the Basel III ratios (for instance, the capital ratio sets the maximum risk-weighted assets a bank can hold as a counterpart of its capital). In this case, for the certificates to be efficient it would be necessary to turn them into capital for the bank, so that the certificates help the bank meet its macroprudential requirements.

Box 2: Example of a transaction with carbon certificates. Suppose a low-carbon project is entitled to \$100 in certificates (e.g. $\$20/tCO_2 \cdot 5tCO_2$) and needs an investment of \$4000. The investor gives the \$100 certificates to a commercial bank, which can gradually put them in its central bank account along with the project completion. If the reserve ratio (r) is 10%, then the commercial bank can issue \$1000 “for free,” and only needs to take \$1000 from other loans (thus reducing its opportunity cost). Let i be the interest rate. A “surplus,” equal to $i \times 1000$, has to be shared between the bank and the investor: a part of the \$1000 will be lent for free to the investor, thus reducing the loan real interest rate i_r , and the rest will be lent by the bank to other projects at the interest rate i . If $i_r = 3000/4000 \times i$ (i.e the bank lends \$1000 for free to the

investor) then all the surplus goes to the investor; on the contrary if $i_r = i$ the whole surplus goes to the bank. The loan real interest rate will then be defined as $0.75 i < i_r < i$.

Carbon certificates are not redeemable, i.e. they cannot be sold to the central bank and their face value only comes from their status as legal reserve. However, since carbon certificates allow banks to increase their revenues, a use value can be attributed to them. If a project was to be financed by savings or equity only, the investor would be allowed to sell certificates to a commercial bank, or to another low-carbon investor who needs to borrow from a commercial bank. This mechanism would provide a financial support to low-carbon projects, even when no loan is needed. Note that there is no reason why the certificates use value should be equal to their face value (i.e. the legal carbon price, which determines the value of carbon certificates as legal reserves assets). The selling price of certificates among investors would reflect the value they attach to an access to concessional loans, or the value of additional reserves for commercial banks. The distribution of carbon certificates will create money to finance low-carbon investment. The quantity of additional money is given by the legal carbon value and the number of available projects. To control this money creation, a limit on the number of certificates could be introduced, or the number of certificates conventionally attributed to various projects could be adjusted. Accordingly, this framework can only be instituted in a country where the Central Bank is able to implement efficient monetary policies. Also, confidence in monetary policy must be high enough to eliminate expectations of run-away inflation. Of course, this mechanism is no magic and does not make low-carbon investments possible for free. There is indeed an additional cost of these projects, relative to the projects that would be implemented in the absence of GHG constraints, and this additional cost can be felt through accelerated inflation due to increased money creation. Whether or not the Central Bank reacts to prevent or counter this additional inflation will determine who pays for the mitigation policy. Note that this scheme would not modify monetary policies or central banking procedures (or ask them to take into account environmental issues), so it is unlikely to meet an opposition from Central Bankers. If the Cen-

tral Bank increases its inflation target and leaves the nominal short-term interest rate constant, an “inflation tax” will finance low-carbon projects at the expense of lenders and depositors. The scenario of an increased inflation target has been suggested by Blanchard et al. (2010), who question the low inflation policy which has been adopted by central banks for over a decade, and suggest that a four percent inflation rate might not be more costly than a two percent rate. Moreover, in Europe, this additional inflation could be seen as a way out of the 2011 debt crisis, and generate more activity in the current situation of underemployment and underutilization of production capacities.¹³ If increased inflation is seen as unacceptable or undesirable, several additional policies can be implemented by the Central Bank:

1. In order to reduce M_1 (see Eq. 7.1), legal reserve ratios r can be increased. In that case, banks have to decrease the amount of loans they provide, except for low-carbon projects that deliver carbon certificates. This solution increases borrowing rates for regular projects. Regular-project investors consequently pay for low-carbon projects through more expensive loans.
2. But since most central banks follow an inflation-targeting strategy (Bernanke and Mishkin, 1997), the introduction of carbon certificates would induce them to anticipate an increase in inflation¹⁴ and to increase nominal interest rates (increased \bar{i}). In that case, the cost of capital is higher for all projects, except for low-carbon projects that are granted concessional loans in exchange for carbon certificates. Hence, as in (1), regular investors pay for the low-carbon projects.

In these last two cases, this scheme amounts to creating differentiated interest rates, low-carbon projects benefiting from lower capital costs than regular projects. In reality, the additional cost of low-carbon projects is likely to be financed by a combination of increased economic activity, accelerated inflation, and higher capital cost for regular projects.

¹³However, accelerated inflation will have a negative effect on the exchange rate. This effect can in turn decrease the attractiveness for investors, with consequences on employment and growth, and carbon leakage. These international aspects require further research to assess their significance.

¹⁴Note that if inflation increase is a surprise, the central banks would react afterwards but increase interest rates anyway, in order to lower inflation to its target.

Because during the last decades central banks in advanced economies have preferred to use as their main monetary policy instrument the reference interest rate, that is the price of reserves, instead of the quantity of reserves, one can imagine a policy that would directly differentiate the price of capital for low-carbon projects. However, such policy would create many difficulties and should be the subject of further research.

7.3 CONCLUSION

Eventually, this framework would have a redistributive impact among generations. Since it increases interest rates for carbon-emitting projects, it uses future generations' wealth to pay for a hedge against a potentially dangerous climate change. In other words, reducing conventional investment in favor of consumption and mitigation is a way of shifting the costs of reducing emissions from the current generation to future generations, who will benefit from reduced climate change impacts. An intragenerational distribution effect, which depends on whether inflation is increased or interest rates for regular projects are raised, might also be observed. But the immediate, first order effect would be much milder than those of a carbon tax, that affects all economic actors rather than investors only. Of course, the creation of carbon certificates is not as efficient as a carbon tax since it does not address directly consumption behaviors: it only internalizes part of the carbon externality through differentiated capital costs. In other words, the aggregate welfare cost of reaching the same target is higher than with a carbon tax. Also, it would focus efforts toward capital-intensive solutions, which have no reason to be the most efficient and are impaired by rebound effects. Given the amount of capital needed to shift investments towards clean technologies in energy, building, transport and end-use equipment, it has however the merit of developing these technologies and facilitating these investments, even in absence of a carbon tax. The objective of mitigating climate change interplays with the current financial and economic crisis. Carbon externalities (which are a transfer from future to current generations, e.g. Chichilnisky et al., 1995) should be a component of the broader reflection on the sustainability of public and private debts and the related pressure on current consumption levels. Also, any action on interest rates should be included in the

design of short term monetary policies — especially in the current European and American context —, and Keynesian mechanisms need to be taken into account to assess the consequence of such a policy. In a context of economic crisis, the certificates could increase money creation (therefore increasing low-carbon investments) and, if central banks do not act to compensate for this additional money creation through “sterilization” actions, this policy could also act as a “green stimulus” policy (Zenghelis, 2011). In times of economic growth, the central bank can increase its rate to avoid undesired inflation. Choices concerning low-carbon investments can thus be separated from choices concerning monetary policy: creating carbon certificates does not constrain monetary policy, but shifts investments toward low-carbon projects. Finally, it might be time to move away from what economists have presented as the “optimal” policy, that is a uniform carbon tax, which appears politically compromised over the short term, at least in many countries. The scheme proposed here is a second-best solution that does not act on all possible levers. But it seems easier to implement than a carbon tax, because its direct distributional impact on households and businesses appears milder. What justifies the introduction of this second-best option is more a policy failure than a market failure, namely the lack of political acceptability of a carbon tax. The introduction of carbon certificates as legal reserve instruments and the creation of differentiated interest rates for low-carbon projects may appear as an interesting first step in the trajectory toward a low-carbon economy.

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Conclusion

Climate policy decisions have to be made under deep uncertainties on the climate system, the availability and costs of technological options, behavioral parameters, economic impacts from climate change and many other factors. This constitutes a challenge for decision-making, as well as a challenge for research to inform decision-making. Overcoming these challenges entails developing decision-making frameworks able to handle this abundance of deep uncertainties.

The first part of the thesis contributes to a research endeavor that tries and improve the use of integrated models for support to decision-makers. It illustrates the possibilities that a large number of scenarios and statistical methods open to quantitatively evaluate synergies or trade-offs in climate mitigation policy decisions, and better connect scenario storylines with the reality of the models.

An important finding is that it is misleading to assess mitigation costs as the variation of GDP or consumption with regards to a counterfactual baseline, ie with regards to a scenario without additional mitigation efforts beyond those in place today and without any impacts from climate change. Projecting a difference is indeed hazardous when the reference is so uncertain and unobservable. To illustrate this point, we have built a database of scenarios to show that minimizing the difference with regards to a baseline is not equivalent to maximizing GDP in mitigation scenarios. In a context where countries have already agreed on the objective to limit climate change to 2C above pre-industrial levels, the relevant issue is rather the second one, i.e that of maximizing GDP or consumption in the mitigation scenario.

The choice of the indicator has an influence on what appears as a good policy. This thesis shows that if one wants to reduce GDP losses with regards to a baseline,

the priority is to recycle the tax revenues through a reduction of other taxes and to reduce the cost of low-carbon technologies. On the other hand, for increasing GDP per capita in mitigation scenarios the priority is to invest in energy efficiency and focus on behaviors.

Accordingly, these results depend on the model that has been used and on the experimental design. To make these results more robust, one would need to use many models, instead of one as in this thesis. Given the increasing number of inter-model comparison exercises, the methodologies applied to one model in this thesis could be extended to several models. Such an exercise is cumbersome as it requires a careful definition of the models structure and an harmonization of input hypotheses. It could however highlight the modeling choices most determinant for several indicators of future mitigation costs and could enrich the cost assessments published by the IPCC. Existing databases such as the IAMC AR5 database¹⁵ are good starting points, even though formatting them to apply data-mining techniques to the results is a difficult task. Current research clearly points towards that direction (Nelson et al., 2013; Kriegler et al., 2014b; Riahi et al., 2014; Kriegler et al., 2014a) and the new SSP framework, which defines five new socio-economic storylines for future research on adaptation and mitigation, could be very useful to support such endeavor. Indeed, the new framework will allow harmonizing scenario hypotheses across many different models and disciplines, and could be formatted in a way that allows for systematic uncertainty exploration.

The second part of the thesis tackles the feasibility of climate mitigation. To start closing the gap between the 2C target and current climate action, and move forward toward a low-carbon economy, we have to recognize the political economy obstacles to the implementation of more stringent climate policies, and work around them. The bulk of future greenhouse gas abatement will come from a replacement of fossil-fueled capital by low-carbon capital. Such a redirection of investments can be triggered by a carbon tax, but also by subsidies on clean capital, or performance standards. The thesis argues that triggering the transition to a low-carbon economy through these “investment-based” instruments is easier than through a carbon tax. Since those instruments only affect new capital, their direct

¹⁵<https://secure.iiasa.ac.at/web-apps/ene/AR5DB/dsd?Action=htmlpage&page=about>

short-term impact on households and businesses are milder, making them more politically-acceptable. The net present cost of these policies is however higher than that of a carbon price, and they cannot curb emissions as fast as the carbon price can. If governments are not able or willing to implement a carbon tax in the near future and the transition has to be triggered by investment-based instruments for political reasons, their slowness makes their implementation (and enforcement) all the more urgent.

Further research is needed to better assess the inter and intra generational trade-offs of different instruments and the optimal timing of action. First, models could explicitly publish the value of polluting capital that requires being early-scrapped in the optimal transition to climate stabilization targets. Rogelj et al. (2013) do so for coal power plants and the two degrees target and this work could be extended to several sectors and climate scenarios. Since there are some trade-offs between the immediate cost of a policy and its intertemporal cost, quantifying the (immediate) losses due to early-retired capital and comparing it to the extra intertemporal cost of policies focused on new capital is policy-relevant.

In the same line, using all existing capital until the end of its lifetime would require the new capital to emit even less carbon than in the optimal strategy. It would be interesting to quantify this effect through the assessment of the resulting constraint on the carbon intensity of the new capital. Results might show that some targets become unrealistic without early retirement of a significant fraction of existing capital (since using it until the end of its lifetime would require unreasonable decrease in the carbon intensity of new investment).

To go further on the acceptability of mitigation instruments, political-economy models could complete the analysis, to quantify the trade-off between efficiency and feasibility. The design of efficient “investment-based” instruments requires in particular a better understanding of investment decisions and risk perception in the private sector, and an analysis of the incentives and ability-to-commit of public decision-makers. This represents a significant research effort bringing together different research communities, but it may provide valuable insights to the identification of efficient but also implementable climate policies.

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The IMACLIM-R model and the dialogue between economists and engineers

A.1 GENERAL DESCRIPTION

IMACLIM-R is a hybrid recursive general equilibrium model of the world economy divided into 12 regions and 12 sectors (see table A.1).

- (a) It is a hybrid model in the classical sense: its structure is designed to combine Bottom-Up information in a Top-Down consistent macroeconomic framework. Energy is explicitly represented in both money metric values and physical quantities so as to capture the specific role of energy sectors and their interaction with the rest of the economy. The existence of explicit physical variables (e.g. the efficiency of cars) allows indeed a rigorous incorporation of sector based information — coming from bottom-up models and experts' judgement¹ — about how final demand and technical systems are transformed by economic incentives. This dual vision of the economy is a precondition to guaranteeing that the projected economy is supported by a realistic technical background and, conversely, that any projected technical system corresponds to realistic economic flows and relative prices.

¹Expert opinion includes *inter alia* data from Bottom-Up models such as POLES (LEPII-EPE, 2006), from the IEA (Fulton and Eads, 2004; IEA, 2008) and from private business experts on technological potentials.

Regions	Sectors
USA	Coal
Canada	Oil
Europe	Gas
OECD Pacific(JP,AU,NZ,KR)	Liquid fuels
Former Soviet Union	Electricity
China	Air Transports
India	Water Transports
Brazil	Other transports
Middle-East Countries	Construction
Africa	Agriculture
Rest of Asia	Energy-intensive industry
Rest of Latin America	Composite (services and light industry)

Table A.1: Regional and sectoral disaggregation of the IMACLIM-R model

- (b) It is hybrid in the sense of Solow (2000)², i.e. it tries and bridges the gap between long-run and short-run macroeconomics, as efforts were devoted not only to model long-term mechanisms but also focus on transition and suboptimal pathways through possible underutilization of production factors. We seek, indeed, to capture the transition costs with a modeling architecture that allows for endogenous disequilibrium generated by the inertia in adapting to new economic conditions. This inertia arises from imperfect foresight and non flexible characteristics of equipment vintages available at each period (putty-clay technologies). In the short run, the main available flexibility lies in the rate of utilization of capacities, which may induce excess or shortage of production factors, unemployment and unequal profitability of capital across sectors.

Technically, the model can be labeled as “recursive dynamic”, since it generates an energy-economy trajectory by solving successive yearly static equilibria of the economy, interlinked by dynamic modules.

- (a) Within the static equilibrium, in each region, the demand for each good derives from households’ consumption, government consumption, investment and intermediate uses from the production sectors. This demand can be provided either by domestic production or imports, and all goods and services are

²Solow (2000): “I can easily imagine that there is a “true” macrodynamics, valid at every time scale. But it is fearfully complicated[...]. At the five-to-ten-year time scale, we have to piece things together as best we can, and look for a hybrid model that will do the job.”

traded on world markets. Domestic and international markets for all goods — except factors such as capital and labor — are fully cleared by a unique set of relative prices that depend on the behaviours of representative agents on the demand and supply sides. The calculation of this equilibrium determines the following variables: relative prices, wages, labor, quantities of goods and services, value flows.

Within each yearly static equilibrium, producers are assumed to operate under short-run constraints of (i) a fixed maximal production capacity $Cap_{k,i}$ (for a good i in region k), defined as the maximum level of physical output achievable with the equipment built and accumulated previously, and (ii) fixed input-output coefficients representing that, with the current set of embodied techniques, producing one unit of a good i in region k requires fixed physical amounts $IC_{j,i,k}$ of intermediate goods j and $l_{k,i}$ of labor. In this context, the only margin of freedom of producers is to adjust the utilization rate $\frac{Q_{k,i}}{Cap_{k,i}}$ according to the relative market prices of inputs and output, taking into account increasing costs when the production capacities utilization rate approaches one. This represents a different paradigm from usual production specifications, since the “capital” factor is not always fully operated.

- (b) Between two static equilibria, the dynamic modules shape the accumulation of capital and its technical content; they are driven by economic signals (such as prices and sectoral profitability) that emerge from former static equilibriums. They include the modelling of (i) the evolution of capital and energy equipment stock described in both vintage and physical units (such as number of cars, housing square meter, transportation infrastructure), (ii) the technological choices of economic agents described as discrete choices in explicit technology portfolios for key sectors such as electricity, transportation and alternative liquid fuels, or captured through reduced form of technology-rich bottom-up models, and (iii) endogenous technical change for energy technologies (with learning curves).

The dynamic modules therefore represent flexible technical choices, but they modify only at the margin the input-output coefficients and labor productivity embodied in existing equipment vintages that result from past technical choices. This general putty-clay assumption is critical to represent the inertia in technical systems, and allows to distinguish short-term rigidities and long-term flexibilities (Johansen, 1959).

Our model growth engine is composed of exogenous demographic trends (UN World Population Prospects, medium scenario, United Nations, 2005) and exogenous trends of labor productivity, as in Solow’s neoclassical model of economic growth (Solow, 1956). To build these trends we draw on stylized facts from the literature, in particular the convergence assumption (Barro and Sala-i Martin, 1992) and two empirical analyses on economic convergence, one investigating the past trends by Maddison (1995), and the other one looking at future trends, by Martins et al. (2005). We retained a “leader,” the US, whose labor productivity growth trend lies between 2% today and 1.65% in the long run. The other regions labor productivity trends catch up with the leader’s, i.e. their labor productivity growth is higher when their absolute labor productivity is farther from the leader’s level.

The two sets of assumptions on demography and technical change, although exogenous, only prescribe potential growth. Effective growth results endogenously from the interaction of these driving forces with short-term constraints: (i) available capital flows for investments and (ii) rigidities, such as fixed technologies, immobility of the installed capital across sectors or rigidities in real wages, which may lead to partial utilization of production factors (labor and capital).

A.2 DYNAMIC EQUATIONS THAT WILL BE USED TO BUILD SCENARIOS

This appendix is not an exhaustive list of all equations in IMACLIM-R dynamic modules, but it presents the equations concerned by the parameters in Section B.4.1, and some modelling choices. For more details, the reader should refer to Sassi et al. (2010).

A.2.1 NATURAL GROWTH DRIVERS

The natural growth rate of the economy defines the growth rate that the economy would follow if it produced a composite good at full employment, like in standard neoclassical models developed after Solow (1956).

Equation A.1 represents labor productivity growth through the decrease of unitary labor input l in each region j and at each time step t .

$$\dot{l}_{t,j} = e^{-\frac{t}{\tau_1}} \cdot l_{t_0,j} + \left(1 - e^{-\frac{t}{\tau_1}}\right) \cdot \left[\frac{t}{\tau_2} \left(l_{t,j} - l_{t,leader} + \dot{l}_{t,leader}\right)\right] \quad (\text{A.1})$$

A.2.2 THE “OIL AND GAS MARKETS” PARAMETER SET

FIRST SUBSET : OIL

In this parameter set we built three Assumptions describing different levels of oil scarcity.

The modeling structure of oil supply in IMACLIM-R is based on 3 general principles. First, a physical description of oil resources with an explicit differentiation by region and nature (conventional vs. non-conventional) is used into the dynamic set-model describing the evolution of oil producing capacities (see Equation A.2). Oil resource availability is based on data from USGS (2000); Greene et al. (2006); Rogner (1997) and was corrected according to estimations from Total³ about oil resources and future field production profile. Secondly, an explicit differentiation is made between fourteen (seven conventional and seven non conventional) categories of resources in each region according to the cost of exploration and exploitation. As oil must be discovered before it is produced, the temporal availability for production of a given category of oil resource depends on the characteristics of the discovery process, which is subject to two main effects: the information effect (the more an oil slick is exploited, the more information about the localization of remaining resources is obtained) and the depletion effect (the more a slick is exploited, the less oil remains in the soil). Following Rehrl and Friedrich (2006), inertias in the deployment of oil producing capacities resulting from the combination of these technical constraints on the discovery process are captured through independent bell shaped curves that shape the time-evolution of oil producing capacities for each category of oil in each region.

We distinguish the regional oil resources into different categories according to their production costs (*i.e.* including exploration and exploitation costs) and the nature of the resource (conventional or non-conventional). To do so, we associate with each resource category a bell-shaped time profile of its production:

$$\frac{Q_{\infty} b e^{-b(t-t_0)}}{(1 + e^{-b(t-t_0)})^2} \quad (\text{A.2})$$

where t is the current date, t_0 is the starting date of oil production for this category, Q_{∞} is the amount of ultimate resources and b a parameter that captures the intensity of constraints slowing down the production growth.

As to the dynamics of production capacities, IMACLIM-R makes a distinction between 2 types of oil producers according to their investment behaviors. All non Middle-East countries are supposed to be motivated by short-term return on investments, which implies that they will bring a category of oil reserve into produc-

³French oil company

tion as soon as it becomes profitable (that is when the selling price on world market exceeds the total cost of exploration and exploitation). From then on, the deployment of production capacities is thus limited by geological constraints and strictly follows the corresponding bell shaped curve. These producers who do not adopt any strategic behavior are referred to as “fatal producers” (Rehrl and Friedrich, 2006). For Middle-East producers, the situation is different as the amount of their oil resource gives them a market power and allows them to adopt a strategy to fulfill a precise objective (either a price or a market share target). For a given year, the Middle-East production capacity is still bounded by a bell-shaped curve but its actual production can be below this limit if the chosen strategy requires a production restriction. This “swing producer” (Rehrl and Friedrich, 2006) behavior is consistent with past OPEC production, which has no longer fit the discovery trend since the 70’s oil shocks (Laherrere, 2001).

Inside this oil supply module, we decided to explore the uncertainty on three major parameters components: the amount of ultimately recoverable resources, the investment behavior of OPEC oil producers to postpone the beginning of depletion at the oil field scale, and the level of inertia that will shape the development of non conventional production.

- In each region of the model, ultimately recoverable resources can have two values: the first value is such that the world total amount of ultimately recoverable resources is 3.1 Tb (conventional and unconventional oil); the second value is 15% higher.
- Then, to take into account in our analysis that, for a given oil field, the oil production shape will highly depend on the sequence of investments made to postpone the beginning of the depletion phase, there are two possible shares of the OPEC’s amount of ultimately recoverable resources that can be extracted before depletion begins. The Middle-East oil production depletion can begin either when one half or three quarters of the resources have been extracted. The former leads to a bell-shaped production curve while the latter leads to a plateau-shaped curve.
- Furthermore, the shape of the curve modeling unconventional oil production capacity can differ, because of inertias in their diffusion. In our analysis, the deployment of unconventional oil can be easy, with the same curves modeling conventional and unconventional production capacities. Conversely, this deployment can be difficult, with a slower diffusion of unconventional oils because of specific additional inertias. In that case, unconventional oil production capacities are modeled with outstretched bell-shaped curves. Therefore, the third parameter of the ‘oil and gas markets’ subset is

the spread of the bell-shaped curve modeling unconventional production capacities.

Assumptions on the amount of recoverable resources and on investments made to postpone the beginning of the depletion phase are combined to build three possibilities (instead of two) for conventional oil: when the amount of recoverable resources is low the production follows either a bell-shaped curve or a “plateau-shaped” curve (depending on the investments in the oil sector), while when the amount of recoverable resources is high the production always follows a “plateau-shaped” curve. In order to simplify the results section, we will call Assumption 1, Assumption 2 and Assumption 3 the three assumptions for this subset. Assumption 1 corresponds to the case with a high amount of recoverable resources ; Assumption 2 to the case with a low amount of recoverable resources and a plateau-shaped curve (sustained investments) ; and Assumption 3 to the case with a low amount of resources and a bell-shaped curve (delayed investments). The parameter modeling unconventional oil production capacities depends on the amount of recoverable resources: in Assumption 2 and 3 the deployment of unconventional oils is slower than for conventional oils, while in Assumption 1 there is no difference.

SECOND SUBSET: GAS

In the model, gas world production capacities answer to demand growth until ultimately recoverable resources enter a depletion process. Gas prices variations are indexed on that of oil prices via an indexation coefficient (0.68, see Equation A.4) calibrated on the World Energy Model IEA (2007). When oil prices increase by 1%, gas prices increase by 0.68%. In Assumption 1 for the “oil and gas markets” parameter set, this indexation disappears when oil prices reach 80\$/bl: beyond this threshold, the evolution of gas prices only depends on production costs and possibly on the depletion effect, which leads to a sharp price increase (due to an augmentation of the producer mark-up rate). In Assumptions 2 and 3, gas prices remain indexed on oil prices whatever their evolution, but an additional price increase occurs when gas production enters its depletion phase.

Gas price in each region at year t is equal to :

$$p_{gas}(t) = p_{gas}^{ref} \cdot \tau_{gas}(t) \quad (A.3)$$

where:

p_{gas}^{ref} is the gas price in this region at year 1

While gas depletion has not started, $\tau_{gas}(t)$ in each region is:

$$\tau_{gas}(t) = 0.68 \times \left(\frac{1}{3} \times wp_{oil}(t) + \frac{2}{3} \times wp_{oil}(t-1) \right) \times \frac{1}{wp_{oil}^{ref}} \quad (A.4)$$

where:

$wp_{oil}(t)$ is the world oil price at year t ;

wp_{oil}^{ref} is the world oil price at year 1

Moreover, if depletion has started in this region, $\tau_{gas}(t)$ is increased by 5% each year, regardless of oil prices.

A.2.3 “THE OPEC STRATEGY” PARAMETER SET

As presented in section A.2.2 the IMACLIM-R modeling structure makes a distinction between “fatal producers” (Rehrl and Friedrich, 2006) and the OPEC, who has market power. As a result, the OPEC strategy is a critical parameter whose evolution needs to be explored. The Middle-East countries can use their market power in two polar ways (and any combination in between). The first is to secure high price levels over the short-run by limiting the expansion of production capacities; but this strategy has the drawback of inciting the oil importing countries to accelerate their efforts to develop oil-free technologies and to adopt energy-sober consumption patterns. The second one is a “market flooding” strategy to maintain rather low prices over the short-term in order to favor oil consumption and discourage oil importing countries from sustaining oil-saving efforts. The trade-off is between low revenues in the next decades and higher rents in the long run, the lower price elasticity of the oil demand being due to the lack of large scale cheap substitutes to oil. The trade-off between these two assumptions does not depend only on the flows of export revenues, it also depends upon geopolitical considerations and long term objectives of the Middle-East governments, including the way they prepare the “post-oil” era. The conduct of these strategies will depend upon the internal cohesion among OPEC members and of Middle-East countries. In fact, when the OPEC’s coordination is secure, they can agree to cut back production so that oil prices are high; conversely, when they are divided, they tend to produce more individually, resulting in lower oil prices. In Assumption 1 the low short-term price aimed at by the OPEC is 40\$/bl while in Assumption 2 it is 80\$/bl.

A.2.4 THE “COAL MARKET” PARAMETER SET

Coal is treated in a different way than oil and gas because of the larger amount of available resources which prevents coal production from entering into a depletion process before the end of the 21st century. We describe price formation on the world coal market with a reduced functional form which relates price variation to production changes. This choice allows us to capture the cyclic behaviour of this commodity market. In Assumption 1, coal price growth sensitivity with respect to coal production growth is quite low, so that the coal production growth can be absorbed without prices variations. On the contrary coal price growth is very sensitive to coal production growth in Assumption 2.

Coal price each year is equal to:

$$p_{coal}(t) = p_{coal}^{ref} \cdot \tau_{coal}(t) \quad (A.5)$$

where:

p_{coal}^{ref} is the coal price in this region at year 1.

$\tau_{coal}(t)$ is defined as:

$$\tau_{coal}(t) = \tau_{coal}(t-1) \cdot (1 + \alpha_{1or2} \cdot g_{coal}(t)) \quad (A.6a)$$

$$\text{with } g_{coal}(t) = \frac{Q_{coal}^{world}(t) - Q_{coal}^{world}(t-1)}{Q_{coal}^{world}(t-1)} - g_{lim} \quad (A.6b)$$

where:

$Q_{coal}^{world}(t)$ is the world coal production at year t

g_{lim} is the production growth rate that would not lead to price fluctuation

We distinguish upwards and downwards movements of production growth, in order to introduce asymmetry in price response: we use α_1 when production growth is lower than g_{lim} and α_2 when production growth is greater than g_{lim} .

A.2.5 THE “POWER GENERATION DECARBONIZATION” PARAMETER SET AND NEW TECHNOLOGIES LEARNING CURVE

The electricity supply module in IMACLIM-R represents the evolution of power-generating capacities over time, depending on the amount of available investment and changes in fuel and production factors prices. The expectations are adaptive: the model anticipates ten years forward the potential future electricity demand, extrapolating from demand past trends, and computes an optimal mix of electricity-productive capacities to face future needs at the lowest cost, given anticipations of future fuel prices. Moreover, the modeling structure accounts for

the physical constraints that – in absence of competitive technology for electricity storage – hamper the extensive deployment of renewable capacities within the electrical grid (e.g., the fact that production is intermittent, especially for solar and wind energy). Given that electricity decarbonization can have a strong impact on the oil sector through electric vehicles development, the uncertainty analysis is focused on carbon-free technologies such as renewable energy generators (simply called renewables), carbon capture and sequestration (CCS) and nuclear plants. The social acceptability and the future technological availability of these technologies spark off debates: future deployment, when technically possible, can be constrained by bottleneck phenomena (like the lack of technical skills) or political barriers (solidly grounded or not). Our approach implies that we do not pretend to settle these debates; rather, we test for each technology the resulting effective availability dates and the maximum penetration rates as critical parameters that can take higher or lower values (see Figure A.1). There are two Assumptions in this parameter set: in Assumption 1, renewable energies, CCS and nuclear energy can penetrate the markets early and at a large scale, while their costs drop quickly thanks to learning-by-doing effects; in Assumption 2, they face strong constraints on their deployment.

We use the learning rate described as follows by McDonald and Schrattenholzer (2001): “In its most common formulation, unit costs decrease by a constant percentage, called the learning rate, for each doubling of experience”. For each technology, the investment cost at year t is given by:

$$C_{inv}(t) = C_{inv}^{ref} \cdot (1 - \gamma)^\omega \text{ with } \omega = \frac{\log(I_{cum}(t)/I_{cum}^{ref})}{\log(2)} \quad (\text{A.7})$$

where:

C_{inv}^{ref} is the investment cost for the technology in the reference year;

$I_{cum}(t)$ is the cumulated investment in the technology at year t ;

I_{cum}^{ref} is the cumulated investment in the technology in the reference year;

γ is the technology learning rate.

Our modelling choice can be rewritten following Gillingham et al. (2008) formulation:

$$C(K) = aK^{-\beta}$$

where C is the unit cost of a technology, K is the cumulative installed capacity, a is the cost of the first unit (a normalization parameter), and β is the learning elasticity. This implies that a doubling of experience will reduce specific costs by a factor of

$2^{-\beta}$. In our equation this factor is $(1 - \gamma)$. From $2^{-\beta} = (1 - \gamma)$, we get Eq. (A.7):

$$\beta = -\frac{\log(1 - \gamma)}{\log(2)}$$

$$C(K) = C(K_0) \cdot e^{-\beta \log(K/K_0)} = C(K_0) \cdot (1 - \gamma)^{\frac{\log(K/K_0)}{\log(2)}}$$

New technologies penetrate the markets according to their profitability, but are constrained by a maximum market share, represented in Figure A.1 for CCS.

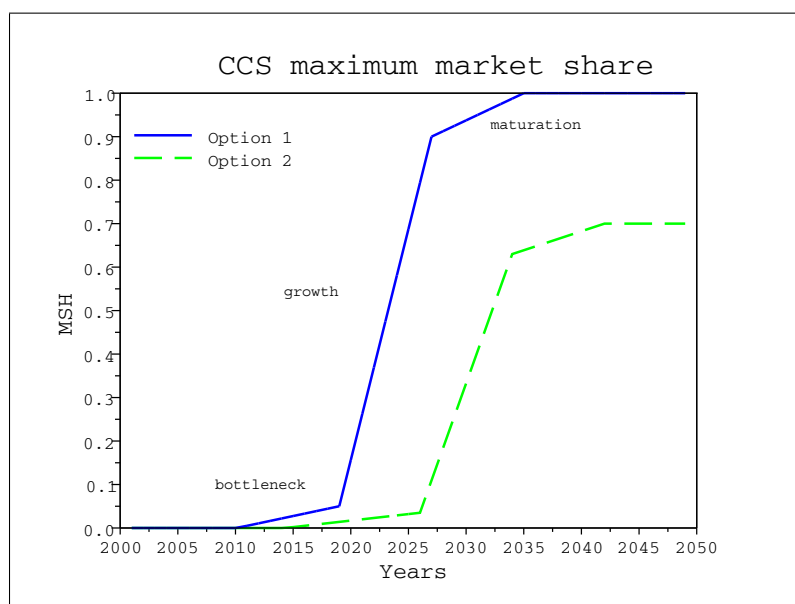


Figure A.1: Maximum market share for new technologies penetration, with the different phases

A.2.6 THE “ENERGY END-USE TECHNOLOGIES” PARAMETER SET

Final demand for oil refined products arises from production sectors and household consumption. The evolution of this demand is of course related to the general level of activity but its ability to adjust to oil prices movements is highly impacted by inertias (i) on the renewal of equipments and (ii) on technical progress in the three major oil-consuming sectors (industry, residential and transport). In these sectors, inertias on equipments are captured by a description of capital vintages, each of them being characterized by an energy intensity and a final energy mix.

At each point in time, energy prices affect the selection of new equipments (that include technology-explicit portfolio for automobile transportation) but do not

influence the existing production capacities.

Since IMACLIM-R relies on an endogenous technical change framework, the costs of equipments and production techniques are related to their cumulative production through the usual learning curves (see Equation A.7). Thus, endogenous technical change parameters are driven by the cumulated effect of economic choices over the projected period. Because of the embodiment of technical change in equipments, endogenous technical change captured in IMACLIM-R has to be interpreted as encompassing both R&D and learning-by-doing.

For the transport sector (private cars and freight), technical change interacts with the overall demand for mobility through the interplay between the following parameters: (i) the total user's costs of the vehicle (ii) the availability of road infrastructures and alternative assumptions (railways, soft modes) (iii) the saturation of the time budget the consumer can allocate to transportation (the so-called Zahavi law) (Zahavi and Talvitie, 1980). Other parameters control constraints on the electrical vehicle deployment (see Figure A.1). This modeling choice allows us to capture (i) the possibility that progress on the efficiency of vehicles generates a rebound effect on mobility demand (Greening et al., 2000) and (ii) that additional transport demand can be induced by new transportation infrastructures (Goodwin, 1996).

Freight energy consumption at year t , for each country:

$$CI_{freight}^{fuel}(t) = \mu_f(t) \cdot CI_{freight}^{fuel}(0) \cdot \left(\frac{pIC_{freight}^{fuel}(t)}{pIC_{freight}^{fuel}(0)} \right)^\varepsilon \quad (A.9)$$

where:

$\mu_f(t)$ is a multiplier coefficient at year t ;

$CI_{freight}^{fuel}(0)$ is the freight energy consumption for each country in the reference year, in each country;

$pIC_{freight}^{fuel}$ is the price for fuel consumption in the freight sector, in each country (it takes into account all taxes, including the carbon tax);

ε is the fuel consumption elasticity to fuel prices, in each country.

In the residential sector parameters rule the energy consumption of buildings (see Equation A.10), as well as the decrease of oil consumption in case of high oil prices.

Housing energy expenditure:

$$H_{Exp} = \sum_e (\mu_h(t) \cdot \alpha_{m2}^e \cdot b_{stock} \cdot pFD_e) \quad (A.10)$$

where:

H_{Exp} is the total energy expenditure in housing, for each country;

$\alpha_{m_2}^e$ is the energy consumption of buildings e per m^2 , in each country (exogenous trend calibrated on POLES: see LEPH-EPE (2006))

$\mu_h(t)$ is a multiplier coefficient at year t ;

b_{stock} is the building stock in each country;

pFD_e is the price for final demand for energy e in each country (it takes into account all taxes, including the carbon tax).

Accordingly, in Assumption 1 for energy end-use technologies, the deployment of new technologies in the transportation and residential sectors is made easier than in Assumption 2, in which inertias prevents them from penetrating the markets effectively.

A.2.7 THE “ALTERNATIVE LIQUID FUEL SUPPLY” PARAMETER SET

In our numerical exercises with the IMACLIM-R modeling framework, biofuels (first and second generation) and Coal-To-Liquid fuels represent the main alternatives to refined oil over the 21st century. The penetration of biofuels in energy supply is modeled according to worldwide supply curves published by the IEA (2006). These supply curves define the maximum amount of biofuels that can penetrate the liquid fuel market, at a given date and for a given oil refined products price (including taxes). Figure A.2 shows these biodiesel supply curves for each level of oil refined products price. The same type of curves are used for ethanol.

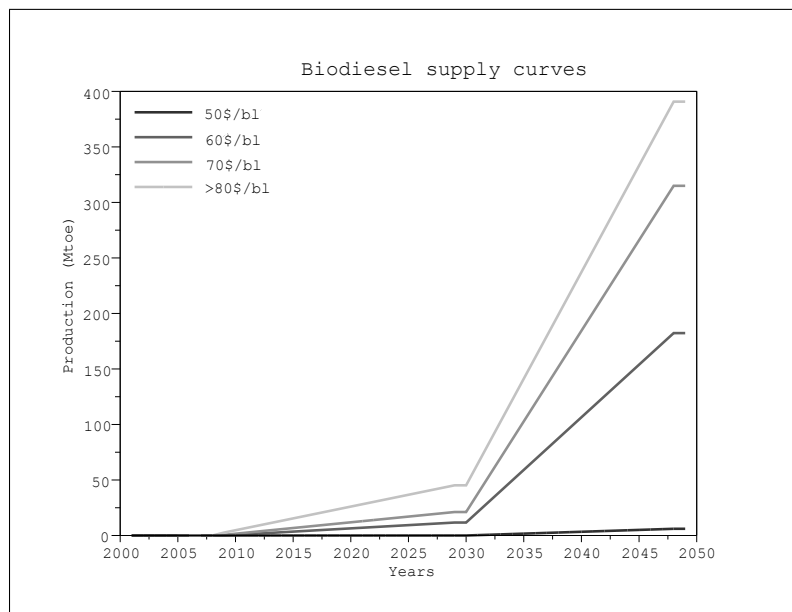


Figure A.2: Biodiesels supply curves in Mtoe. Each curve corresponds to a given price per barrel of Gasoline equivalent (including taxes).

They evolve over time to mimic technical improvements in production processes and account for limits to production due to constraints on land availability and conflicts with other uses of biomass (including food)⁴. In addition to that, an exogenous maximum constraint – which encompasses other kinds of inertias that could affect the deployment of these technologies – is imposed to the annual biofuel production growth. These constraints and their feedback on the cost of biofuels are one major reason why synfuels may become a potentially competitive alternative to oil.

In the simulations with IMACLIM-R, the main share of synfuels is taken by Coal-To-Liquid (rather than Gas-To-Liquid) because of the abundance of coal resources. The decision to initiate CTL production is captured through a threshold value for oil price p_{CTL} above which CTL producers take the risk of launching large scale production. If we note $D^{LF}(t)$ the estimated demand of liquid fuels and $RO(t)$ the supply of refined oil and biofuels, the desired CTL production (\widetilde{CTL}) is given by:

$$\widetilde{CTL}(t) = f(t) \cdot \text{Max} [D^{LF}(t) - RO(t), 0] \quad (\text{A.11})$$

CTL producers are willing to fill a growing fraction of the gap between total fuel demand and the supply of refined oil and biofuels. This fraction depends on investors' beliefs on profitability of CTL investments. We capture this effect through $f(t)$, defined as an increasing function of the cumulated oil prices from 2001 ($p_{oil}^{cum}(t) = \sum_{i=2001}^t \text{Min} [p_{oil}(i), p_{oil}^{max}]$ with $p_{oil}^{max} = 110\$/bl$): the higher the cumulated price, the higher the confidence in CTL profitability and the level of desired CTL production (see Figure A.3).

Eventually, constraints on the delays of maturation of production investments and the time necessary to adapt distribution networks are captured by a limitation on CTL production growth, through the following equation:

$$CTL(t) = \text{Max} [CTL(t-1) + \Delta CTL^{IEA}(t), \widetilde{CTL}(t)] \quad (\text{A.12})$$

Where ΔCTL^{IEA} represents the largest possible increase in CTL production and is calculated as a linear interpolation between three values from IEA scenarios, in 2030, 2035 and 2050, according to IEA values (IEA, 2008).

A.2.8 THE “DEVELOPMENT PATTERNS” PARAMETER SET

In addition to the uncertainty surrounding technological changes, the IMACLIM-R model allows to include contrasted views on development patterns. These dynamics are not determined by pure economic decisions; they involve political bargaining, households' preferences and are far from the classical “carbonomics.” Yet,

⁴For the treatment of this constraint see Hourcade et al. (2010)

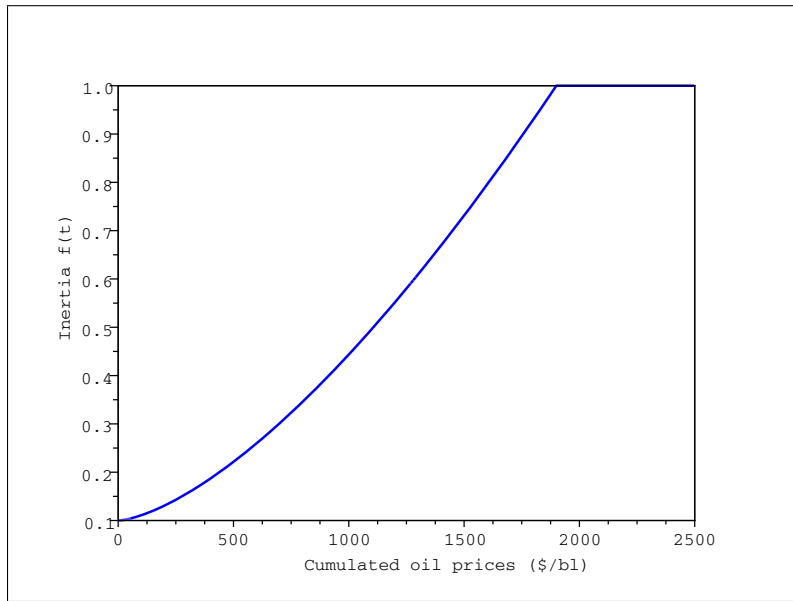


Figure A.3: Investors' beliefs on profitability of CTL investments ($f(t)$)

these patterns are key in determining and describing economic growth, and more particularly its energy content, as they affect the need for energy services in sectors such as transport or dwellings. The articulation between consumption styles, technological and localization patterns is a critical parameter for the energy future with and without climate policies for any region in the world. However, the major uncertainty is about how this articulation will be made by developing countries in the next decades. Even though the economic context will matter in the shaping of development patterns, it will do so together with infrastructure decisions that involve political bargaining, as well with the evolution of households preferences in various cultural contexts. Our parameters set describes either a 'mimetic' development pattern, in which developing countries want to catch up with the western lifestyle (vast houses in spread and mobility-intense cities, high calorie intake per capita) and asymptotically the US development pattern, or a less carbon-intensive development pattern. To do so, we take into account infrastructure policies (which encourage or not urban sprawl), agents preferences for automobile transport and vast individual dwellings (through income elasticities), as well as a more limited role of the "just in time" and distributed industrial processes. The reader must keep in mind that endogenous outputs will be influenced by those parameters, but remain coherent with the economic context, thanks to the resolution of the economic equilibrium.

For each country, evolution of the number of cars per capita (with λ extracted from data from the IEA model MOMO (Fulton and Eads, 2004) in the reference

case):

$$cars_{pc}(t) = cars_{pc}(t-1) + \lambda \cdot \Delta GDP_{pc} \quad (A.13)$$

where:

GDP_{pc} is the country real GDP per capita

The parameters are μ_s^{ini} (income elasticity of buildings stock growth) and A (asymptote to surface per capita in developing countries).

$$\mu_s(t) = Min \left[\mu_s^{ini}, \left(1 - \frac{b_{stock}(t-1)}{L_t(t-1)} \cdot \frac{1}{A} \right) \cdot \mu_s^{ini} \right] \quad (A.14a)$$

$$s_{pc}(t) = Min \left[A, \frac{b_{stock}(t-1)}{L_t(t-1)} \cdot \left(1 + \mu_s(t) \cdot Max \left[0, \left(\frac{R(t)}{L_t(t-1)} \cdot \frac{L_t(t-2)}{R(t-1)} \right) - 1 \right] \right) \right] \quad (A.14b)$$

$$b_{stock}(t) = s_{pc}(t) \cdot L_t(t) \quad (A.14c)$$

where:

μ_s^{ini} is the income elasticity of buildings stock growth for each country at year 1;

$\mu_s(t)$ is the income elasticity of buildings stock growth for each country at year t ;

b_{stock} is the building stock in each country;

L_t is the total population in each country;

s_{pc} is the surface per capita in each country;

b_{stock} is the building stock in each country;

R is the households net income in each country;

A is the asymptote to surface per capita in developing countries

The parameter η describes the saturation level of household industrial goods consumption, expressed as a multiplier factor of the calibration year consumption volume.

$$Dpc_{indus}^{max} = \frac{D_{indus}^{ref}}{L_t^{ref}} \cdot \eta \quad (A.15a)$$

if $Dpc_{indus}(t) > Dpc_{indus}^{max}$ then

$$s_{indus}^{income}(t+1) = s_{indus}^{income}(t) \cdot Dpc_{indus}^{max} \cdot \frac{L_t(t)}{Dpc_{indus}(t)} \quad (A.15b)$$

where:

D_{indus}^{ref} is the final demand for industrial goods, in each country, at year 1;

Dpc_{indus} is the final demand per capita for industrial goods, in each country;

L_t^{ref} is the total population, in each country, at year 1;

$L_t(t)$ is the total population, in each country, at year t ;

s_{indus}^{income} is the share of desired industrial goods w.r.t households' income in each country.

A.2.9 THE "IMPLEMENTATION OF CLIMATE POLICIES" PARAMETER SET

The assumptions as regards to climate policies are the following: the model represents (i) a "Business As Usual" (BAU) world with no constraint on emissions, or (ii) a "stabilization" world in which a carbon tax reduces emissions such that CO₂ concentration is stabilized at, for instance, 450 ppm in the long run. To do so, the model calculates an endogenous carbon tax in order to comply with an exogenous trajectory of emissions, consistent with concentration level of 450 ppm in 2050.

This concentration level corresponds approximately to 550 ppm if all gases are included. It is close to the concentration targets investigated in the Working Group III of the IPCC (IPCC, 2007).

The carbon tax yields a government income which can be recycled in multiple ways. For instance, it can be entirely given back to households, or recycled based on a lump sum principle in which each sector receives back what they have paid, except for the power generation sector whose payoff is given to the consumer. As a consequence, the number of BAU scenarios is doubled everytime we model a different type of recycling.

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B

Building scenario databases for chapters 2 to 4

B.1 SCENARIOS: NEITHER “BEST GUESS” NOR ARBITRARY “STORYLINES”

IMACLIM-R is able to produce long-term scenarios of the world economy evolution. But these scenarios are highly uncertain as they depend on unknown exogenous trends (e.g., future population) and parameter values that are debated or encompass poorly understood mechanisms (e.g., penetration of new technology through investment). To get a better understanding of this uncertainty, we computed a large number of scenarios from the combination of hypotheses on selected exogenous parameters. These hypotheses are derived from experts judgment and represent possible values for the parameters.

Decisions for large scale technological projects like the EV (Electric Vehicle), the nuclear power or the bioenergy have to be made in a context of radical uncertainty. The approach selected in this thesis tries and avoids both the traps of the “best guess” or “most likely” scenarios, which come to an illusory reduction of uncertainty and the symmetric trap of defining somewhat arbitrary “storylines” amongst the many possible ones. It aims in some way at giving a structure to uncertainty in order to disentangle the role of:

- (a) exogenous uncertainty about critical parameters;
- (b) regulatory uncertainty (such as the existence of climate policies);

- (c) endogenous uncertainty created by the interplays between the parameters in the modeling structure.

The detailed representation of the dynamics that drives the energy system and the material content of the economic growth in the IMACLIM-R model allows us to describe in a consistent manner:

- (a) the interplay between consumption styles (C), technological choices (T) and localization patterns (L) (Hourcade, 1993) that drive the mobility needs and global energy demand;
- (b) critical technical uncertainty (e.g. carbon capture and sequestration (CCS) availability, ultimately recoverable fossil resources availability and accessibility).

At each level, uncertainty on different topics is translated into a wide set of uncertain parameters. For CCS for example, these parameters include the date of availability in each region, capital costs, technology learning rate, maximum socially and technically achievable market shares. These parameters take part in the calibration of the model and define the macro-energetic context in which the model run is performed. They must be distinguished from endogenous outputs that result from model runs. For example, the maximum possible share of CCS-equipped coal plants over the whole electric sector is a parameter, but the actual CCS equipment rate is an endogenous variable that is consistent with carbon prices, or electricity demand for example. To put it in another way, a scenario defined with optimistic parameters about the ultimate performance of a technology may result in a non penetration of this technology if the economic conditions of this penetration are not met.

One difficulty arises from the multiplicity of parameters; we identified hundreds of parameters on which a sensitivity analysis can be useful, and each parameter can take an infinite number of values. To avoid combinatorial explosion, the parameter domain has been simplified. First, the selected parameters are aggregated into a few consistent parameter sets. For instance, all parameters describing the future availability of oil and gas are aggregated into an “oil and gas markets” parameter set. Then, two or three sets of values (referred to as “Assumptions”) are associated to each parameter set. For instance, the “oil and gas market” parameter set has three possible Assumptions of increasing scarcity for both oil and gas; each of these Assumptions consists of values for the parameters that compose this set.

B.2 SELECTING RELEVANT DRIVERS FOR FUTURE CHALLENGES TO ADAPTATION AND MITIGATION FOR CHAPTER 2 AND BUILDING THE DATABASE

B.2.1 IDENTIFYING THE A PRIORI DRIVERS OF CHALLENGES TO ADAPTATION AND MITIGATION

Hallegatte et al. (2011) propose three dimensions to explore climate change vulnerability and adaptation challenges, and it appears that these dimensions are also relevant for mitigation challenges. To map the space of possible futures and cover plausible challenges to mitigation, however, it is necessary to add a fourth one. The four resulting dimensions— globalization, equity, environmental stress, and carbon supply – are presented in this section.

GLOBALIZATION: A “CONVERGING” WORLD VS. A “FRAGMENTED” WORLD

In a converging world, the economic structure of developing countries converges rapidly toward the structure of industrialized countries. For instance, the share of agriculture in their economies decreases in terms of gross domestic product (GDP) and exports. Also, available technologies are similar in industrialized and developing countries; and urbanization rates converge around rich-country standards. Developing countries undergo a demographic transition so that population age structure converges and global population growth rates decrease. In a more fragmented world, conversely, developing-country economies catch up more slowly, and for an extended period of time they remain based on agriculture, raw-material extraction, and tourism. These countries remain largely rural. In such a world, developing countries depend more on rich countries for high-technology goods and can balance their imports only thanks to low-value-added goods and services. Population remains young in developing countries, with high fertility and mortality rates, and global population growth rates are higher than in a homogenous world.

This dimension is mainly about changes in economic structures and not trade and openness, even though a converging world has more international trade than a more fragmented one. Indeed, in a homogenous world, industrial and commercial policies seek export-led growth, whereas a fragmented world induces a more inward-oriented growth. In such a world, globalization of financial markets is limited, whereas in a homogenous world, capital markets are integrated.

This dimension is important for IAV (Impacts, Adaptation, and Vulnerability) analysis for two main reasons. First, agriculture in developing countries is likely one of the sectors most negatively affected by climate change (Lobell et al., 2008). In a more homogenous world, these countries would be less vulnerable because

agriculture becomes less important in their economy. They would also be at reduced risk of food insecurity because of better access to world food markets, thanks to alternative non agricultural exports (Chen and Kates, 1994). Second, the future of urbanization matters because urban and rural areas have different main vulnerabilities (e.g., floods in urban areas vs. droughts in rural areas). Population matters because it has important impacts on food security, flood risks, or housing.

This dimension is relevant for MP (Mitigation Policies) analysis because the economic structure of developing countries will determine their energy consumption and production. In a fragmented world, developing countries remain mainly rural and based on agriculture, so their future patterns of energy consumption are similar to those today, i.e., much lower than in developed countries. In a converging world, developing countries' energy consumption will depend on the other dimensions, for instance, the type of technologies available and the magnitude of urban sprawl. Globalization is also important for technology transfers that can reduce mitigation costs especially in developing countries (Metz and Turkson, 2000). Population growth rates are important for MP analysis, because higher population growth rates imply higher energy consumption. Even though it is not very well understood yet, population aging is important as well it might be accompanied by a decline in the number of people per household (a process already observed in industrialized countries). As small households consume more energy per person than large households (Ironmonger et al., 1995), CO₂ emissions might increase with increased aging (MacKellar et al., 1995).

EQUITY: INCLUSIVE DEVELOPMENT VS. "GROWTH AND POVERTY" DEVELOPMENT

In an inclusive world, the poorest communities have a voice in political choices, national governance takes poverty reduction into account as an important policy goal, and policies successfully reduce the share of people in extreme poverty. Social protection is reinforced so that almost everybody gets access to basic services, such as health care, education, energy and transport, drinking water and sanitation, financial services, secured land tenure, and risk management practices.

In a more "poverty and development" oriented world, a fraction of poor-country population is excluded from these services.

This dimension is partly independent of the previous one because extreme poverty may either disappear or increase in countries, regardless of their aggregate economic growth.

This dimension can also include differences in terms of governance efficiency. In particular, in an inclusive world, environmental policies are likely to be more efficient than in a "poverty and growth" world. Conversely, a non inclusive world can include a lack of government regulation that often implies the existence of a huge informal sector (Gerxhani, 2004). Indeed, in such a world, informal mar-

ket labor is likely to be widely developed (undeclared labor, lack of social benefits, subminimum wages, poor working conditions, etc.) (Palmer, 2008).

It is important for IAV analysis to take into account this dimension because poor communities are considered the most vulnerable to climate change (Smit and Wandel, 2006). They are more exposed to environmental conditions (e.g., their access to natural resources, such as water, is not mediated by infrastructure). They also have to cope with multiple stressors (O'Brien et al., 2004) and have less capacity to adapt due to lower financial capacity, education and health, institutional capacity, or political weight, for instance (Yohe and Tol, 2002).

This dimension also has consequences for MP analysis because today, 20% of the global population lack access to electricity and 40% rely on traditional use of biomass for cooking (IEA, 2010). The burning of biomass in inefficient stoves emits black carbon, which plays a large role in global and regional warming (Luoma, 2010). In a “strong governance world,” households can more easily climb the “energy ladder” (Reddy and Balachandra, 2006; Reddy et al., 2000). An “inclusive development” world implies universal electricity access and an expansion of household access to modern fuels. This would increase global energy consumption — and global GHG emissions — more than in a “poverty and development” world, even though improved stoves and greater conversion efficiency would reduce its black carbon content (IEA, 2010).

ENVIRONMENTAL STRESS: AN “ENVIRONMENT-ORIENTED” WORLD VS. AN “ENVIRONMENTALLY-STRESSED” WORLD

In an environment-oriented world, policies, technologies, management practices, and lifestyles lead to an efficient use of natural resources and reduce environmental stresses. There is a differentiation in consumption behaviors, each region yearning — or being enforced — to follow a more energy-sober development style.

In an environmentally stressed world, water use is inefficient and energy and mobility demands are growing. Soil depletion and degradation are accelerated and reduce agricultural productivity and increase natural risks (e.g., floods). Biodiversity losses are large. In this world, the use of natural resource is already creating environmental stresses, even without climate change, and climate change impacts affect already vulnerable environments.

This dimension is partly independent of the previous ones, since economic development and poverty reduction may be accomplished— temporarily — with or without efficient use of natural resources.

Environmental stress matters for IAV analysis, because ecosystems’ ability to cope with climate change depends on the other stresses with which they have to cope (Noble, 2005) and additional resource scarcity from climate change can have different consequences depending on how they are managed. For instance, re-

duced rainfall has larger economic consequences if existing resources are already stretched by inappropriate agriculture production and if groundwater is not usable because of pollution or salinization (Arnell, 2004).

This dimension is important for MP analysis, because mobility preferences and spatial organization determine the energy content of economic growth through the populations' need for energy services. Accordingly, an "environment oriented" world has a larger capacity to mitigate climate change than an "environmentally-stressed" world.

CARBON DEPENDENCE: A "HIGH CARBON DEPENDENCE" WORLD VS. A "LOW CARBON DEPENDENCE" WORLD

To analyze mitigation, it is important to consider other drivers. In particular, the dependency to fossil fuel will play a critical role, justifying the introduction of a fourth axis in our framework.

In a "low-carbon dependence" world, the availability of fossil energy is low. World oil resources are scarce, with oil production reaching its maximum level before 2020, and gas and coal are expensive to extract. The potential for new technologies is high, and it is easy to orient technical change toward mitigation. Low-carbon technologies, such as electric cars, biofuels, CCS (Carbon Capture and Sequestration), and renewable energy sources are easy to develop, because of a low inertia in the renewal of equipments and fast technical progress.

In a "high-carbon dependence" world, fossil fuels are largely available and fossil energy prices thus remain low for a few decades. The pace and direction of technical change favors carbon-intensive technologies and carbon alternative liquid fuels (e.g., Coal-To-Liquids).

This dimension is partly independent from the previous one because it is driven by geological parameters and some technical parameters independent from the agents' choices (the pace and direction of technical change is partly exogenous and partly endogenous, since it depends on learning-by-doing mechanisms and investments in R&D).

Carbon supply matters for IAV analysis because carbon dependence will determine the potential for developing adaptation-friendly technologies (e.g., use of desalinization and air conditioning).

It is important for MP analysis because, everything else being equal, mitigation policies will be cheaper if fossil energy prices are high and low-carbon technologies are easy to develop. In a world locked into a carbon-intensive pathway because fossil energy is cheap, mitigation potential is very thin. Indeed, economy sectors are characterized by significant inertia in installed capital, infrastructure, and behaviors that cannot be changed overnight. In some sectors, productive capacities and infrastructures have lifetimes of several decades (Worrell and Biermans, 2005;

Davis et al., 2010; Guivarch and Hallegatte, 2011). For instance, most industrial installations have lifetimes spanning more than 30 years, whereas urban infrastructure, transport infrastructure, and some buildings have lifetimes lasting over a century. It is likely that urban forms imply an even larger inertia than that suggested by physical capital lifetime (Gusdorf and Hallegatte, 2007; Gusdorf et al., 2008). This inertia constrains the pace of possible decarbonisation of the sectors, and a lock-in of the transportation and residential sectors in carbon-intensive pathways can have very important consequences on mitigation costs.

B.2.2 TRANSLATING THE A PRIORI DRIVERS INTO SCENARIO PARAMETERS

NATURAL GROWTH DRIVERS

We build three alternatives for population, using demographic data on active population derived from UN scenarios (low, medium and high).

We also define three alternatives on labor productivity growth. Equation A.1 represents labor productivity growth through the decrease of unitary labor input l in each region j and at each time step t . In this equation, τ_2 can be equal to 55, 120 or 250 years depending on the assumption on convergence.

INDUCED ENERGY EFFICIENCY

In each sector, the country with the lowest energy intensity is the leader and its energy efficiency is triggered by energy prices. The other countries catch-up with the leader after a delay. We build three hypotheses (see Table B.7) using the following parameters: maximum annual improvement in the leader's energy efficiency, other countries' speed of convergence (% of the initial gap after 50 years) and asymptotic level of catch-up (% of the leader's energy efficiency).

	Option 1	Option 2
Maximum annual improvement in the leader's energy efficiency (%)	1.5	0.7
Other countries' speed of convergence (% of the initial gap after 50 years)	10	50
Asymptotic level of catch-up (% of the leader's energy efficiency)	95	60

Table B.1: Parameters options for energy efficiency

BEHAVIORS

Historically, the literature on the decoupling between energy and growth has focused on autonomous energy efficiency improvements (implicitly encompassing end-use energy efficiency and structural changes) and on the energy efficiency gap, i.e. the difference between the most energy efficient technologies available and those actually in use.

However important it may be, energy efficiency is not the only driver of energy demand. Indeed, the rate and direction of technical progress and its energy content depend, not only on the transformation of the set of available techniques, but also on the structure of households' demand. This is why IMACLIM-R endogenizes both energy efficiency strict sensu, and the structural change resulting from the interplay between consumption, technology and localization patterns. This enables us to capture the effect of non-energy determinants of energy demand, such as the prices of land and real estate, and political bargaining (set exogenously) over urban infrastructure to be represented. This endogenization of technical change is made for both stationary uses (industry and services, buildings) and non-stationary uses (freight and passenger transportation).

For behaviors, we build two assumptions using parameters which describe (a) development patterns in transport, housing and industrial goods consumption and (b) localization patterns.

DEVELOPMENT PATTERNS

Transport

Passenger mobility needs and their modal breakdown across four travel modes (ground-based public transport, air transport, private vehicles and non-motorized modes) result from the maximization of households' utility under the assumption of constant travel time (Zahavi and Talvitie, 1980) and budget constraints. This helps to represent two crucial determinants of the demand for passenger transportation, namely the induction of mobility demand by infrastructure and the conventional rebound effect consecutive to energy efficiency gains on vehicles (Greening et al., 2000).

In addition to the availability of transportation infrastructure and energy efficiency, mobility needs are dependent upon agents' localization choices (?). This is captured by differences in regional households' motorization rates, everything else being equal (income, energy prices), with dispersed spatial organizations implying a higher dependence on private transport. In each region, the motorization rates increase with disposable per capita income through variable income-elasticity η_{mot} : (a) low for very poor people whose access to motorized mobility relies on non-motorized and public modes; (b) high for households with a medium

per capita income with access to private motorized mobility (c) low again, because of saturation effects, for per capita income level comparable to that of the OECD. We make two hypotheses on this parameter for developing countries, representing the evolution of preferences (see Table B.2).

Buildings

The “Housing and Buildings” module represents the dynamics of energy consumption as a function of the energy service level per housing square meter (heating, cooling, etc.) and the total housing surface. The former is represented by coefficients encompassing the technical characteristics of the existing stock of end-use equipment and buildings and the increase in demand for energy services: heating, cooking, hot water, lighting, air conditioning, refrigeration and freezing and electrical appliances. Housing surface per capita has an income elasticity of η_H , and region-specific asymptotes for the floor area per capita, h_{max} . This limit reflects spatial constraints, cultural habits as well as assumptions about future development styles (including the lifestyles in emerging countries vis-a-vis the US, European or Japanese way of life). To account for different development patterns, we make two hypotheses on h_{max} in developing countries (see Table B.2).

Industrial goods

The industrial and services sectors are represented in an aggregated manner, each of them covering a large variety of economic sub-sectors and products. Technical change then covers not only changes and technical progress in each sub-sector but also the structural effects across sectors. In addition to autonomous energy efficiency gains, the IMACLIM-R model represent the structural drop in energy intensity due to a progressive transition from energy-intensive heavy industries to manufacturing industries, and the choice of new techniques which results in both energy efficiency gains and changes in the energy mix. The progressive switch from industry to services is controlled by saturation levels of per capita consumption of industrial goods (in physical terms, not necessarily in value terms), via an asymptote at κ_{ind} multiplied by its level in 2001. For developing countries, these saturation levels represent various types of catch-up to the consumption style in developed countries. We thus make two hypotheses on this parameter (see Table B.2).

LOCALISATION CHOICES: FREIGHT CONTENT OF ECONOMIC GROWTH

In the freight sector, total energy demand is then driven by freight mobility needs, in turn depending on the level of economic activities and their freight content. Even though the share of transportation in total costs is currently low, decoupling freight mobility demand and economic growth is an important determinant of long-term mitigation costs. In the absence of such a decoupling (constant input-

output coefficient), and once efficiency potentials in freight transportation have been exhausted, constraining sectoral carbon emissions from freight transportation would amount to constraining economic activity. We thus build two alternative evolutions of the input-output coefficient representing the transportation requirement per unit of good produced (see Table B.2).

Transport	Option 1	Option 2
Motorization rate growth with GDP per capita (η_{mot})	Values from IEA data (Fulton and Eads, 2004)	50% increase w.r.t Option 1 value
Buildings	Option 1	Option 2
Income elasticity of buildings stock growth (η_H)	0.7	1
Asymptote to surface per capita in China and India (h_{max})	40	60
Start year and fuel price for a forced decline of oil consumption in this sector	2010/1000\$/tep	2020/1300\$/tep
Industrial goods	Option 1	Option 2
Households industrial goods consumption saturation level [min-max] (κ_{ind})	[1-2]	[1.5-3]
Freight content of economic growth	Option 1	Option 2
Input-output coefficient of transportation requirement per unit of good produced	decreases along with labor productivity growth in the composite sector and along with energy efficiency in the industry sector	Constant in all sectors

Table B.2: Parameters options for behaviors

AVAILABILITY OF LOW CARBON TECHNOLOGIES

In the IMACLIM-R model technologies penetrate the markets according to their profitability, but are constrained by a maximum market share which follows a “S-shaped curve” (Grubler et al., 1999) and of which parameters are described in Table B.3.

Nuclear (new generation)	Option 1	Option 2
Start date	2001	
Bottleneck phase (years)	15	
Growth phase (years)	75	
Maturation phase (years)	25	
Maximum market share at the end of the maturation phase (%)	30	0
Renewables	Option 1	Option 2
Start date	2001	2001
Bottleneck phase (years)	2	3
Growth phase (years)	20	65
Maturation phase (years)	15	25
Maximum market share at the end of the maturation phase (%)	60	50
CCS	Option 1	Option 2
Start date	2010	2014
Bottleneck phase (years)	13	17
Growth phase (years)	8	8
Maturation phase (years)	8	8
Maximum market share at the end of the maturation phase (%)	80	30
Electric vehicles	Option 1	Option 2
Start date	2010	2010
Bottleneck phase (years)	6	6
Growth phase (years)	40	40
Maturation phase (years)	16	16
Maximum market share at the end of the maturation phase (%)	80	25

Table B.3: Parameters options for low carbon technologies

FOSSIL FUELS

For the oil sector, we build two assumptions using the following parameters: amount of ultimately recoverable resources (Q_{∞} , see eq. A.2), inertia in the deployment of non conventionals (spread of the bell-shaped curve b), maximum growth rate of Middle-East capacities and OPEC target oil price (Table B.4).

The evolution of worldwide natural gas production capacities meets demand increase until available reserves enter a depletion process. Distribution of regional production capacities in the “gas supply” module is made using an exogenous distribution key calibrated on the output of the POLES energy model (LEPII-EPE, 2006), which captures reserve availability and regional production facilities. Gas markets follow oil markets with a 0.68 elasticity of gas to oil price. This behavior is calibrated on the World Energy Model (IEA, 2007) and is valid as long as oil prices remain below a threshold $p_{oil/gas}$. At high price levels reflecting tensions due to depletion of reserves, gas prices are driven by production costs and the increased margin for the possessors of the remaining reserves. We make two hypotheses on $p_{oil/gas}$ (Table B.4).

Oil	Option 1	Option 2
Amount of ultimately recoverable resources (Q_{∞})	3.6Tb	3.1Tb
Inertia in the deployment of non conventionals (spread of the bell-shaped curve b)	No inertia ($b = 0.061$)	Inertia ($b = 0.041$)
Maximum growth rate of Middle-East capacities	1.1 Mbd/yr	0.7 Mbd/yr
OPEC target oil price	80\$/bl	120\$/bl
Gas	Option 1	Option 2
Indexation of gas price on oil price	$p_{oil/gas} = 80\$/bl$	No threshold

Table B.4: Parameters options for fossil fuels

B.3 CHAPTER 3 AND 5 DIFFERENCES WITH CHAPTER 2

B.3.1 NATURAL GROWTH DRIVERS

In line with the SSP quantifications, we build assumptions combining hypotheses on population growth, on the leader productivity growth, and on catch-up speed

for two groups of regions: high income and low income countries (see Tables B.5 and B.6).

	Option 1	Option 2	Option 3
leader productivity growth	low	middle	high
high income population growth	ssp ₃	ssp ₂	ssp ₅

Table B.5: Parameters options for leader growth and high income population growth. Data for population is available at <https://secure.iiasa.ac.at/web-apps/ene/SspDb>

	Option 1	Option 2	Option 3
low income catch-up time (τ_2 in eq. A.1, in years)	300	200	150
low income population growth	ssp ₃	ssp ₂	ssp ₅

Table B.6: Parameters options for low income catch-up speed and population growth. Data for population is available at <https://secure.iiasa.ac.at/web-apps/ene/SspDb>

B.3.2 INDUCED ENERGY EFFICIENCY

In each sector, the country with the lowest energy intensity is the leader and its energy efficiency is triggered by energy prices. The other countries catch-up with the leader after a delay. We build three hypotheses (see Table B.7) using the following parameters: maximum annual improvement in the leader's energy efficiency, other countries' speed of convergence (% of the initial gap after 50 years) and asymptotic level of catch-up (% of the leader's energy efficiency).

B.3.3 COAL MARKET AND AVAILABILITY OF COAL-TO-LIQUIDS

Unlike oil and gas markets, cumulated coal production has a weak influence on coal prices because of large world resources. Coal prices then depend on current production through an elasticity coefficient η_{coal} : tight coal markets exhibit a high value of η_{coal} (i.e the coal price strongly increases if production rises). For this sector, we make two hypotheses for η_{coal} (see Table B.8).

	Option 1	Option 2	Option 3
Maximum annual improvement in the leader's energy efficiency (%)	1.5	0.7	1.5 for OECD countries 0.7 for other countries
Other countries' speed of convergence (% of the initial gap after 50 years)	10	50	10 for OECD countries 50 for other countries
Asymptotic level of catch-up (% of the leader's energy efficiency)	95	60	95 for OECD countries 60 for other countries

Table B.7: Parameters options for energy efficiency

Coal	Option 1	Option 2
Price growth elasticity to production variations (η_{coal})	2	1.5
CTL	Option 1	Option 2
margin applied to the production cost in price equation	0.4	0.3
ratio between capital cost and coal cost in the calibration year	1.5	1
ratioOMcoalCTL	1.7	1.5
aCTL	0.05	0.3

Table B.8: Parameters options for coal and CTL

B.4 PARAMETERS CHOICES FOR CHAPTER 4

We distinguish seven parameters sets covering the major drivers of macro-energetic contexts as a combination of assumptions on natural resources, technology availabilities and international economic trends. These sets are described in details in Appendix A and are summarized here:

- 1 - Oil and gas markets (3 Assumptions): this set describes (i) the amount of ultimately recoverable resources¹; (ii) the extend of Middle-East investment to postpone depletion at the oil field scale; (iii) the inertia in non conventional production development; and (iv) the indexation of gas prices on oil prices. In Assumption 1 all parameters are combined so that the resources are abundant

¹conventional and non conventional oil

and easily extracted, while in Assumption 3 oil and gas supplies are very constrained. In Assumption 2, most parameters are the same as in Assumption 3, except that investments to postpone the depletion phase are sustained.

- 2 - Middle-East strategy (2 Assumptions): in IMACLIM-R, the Middle-East is a “swing producer” (Rehrl and Friedrich, 2006) that benefits from market power and can adjust its production to manipulate the oil price over the short-run. In Assumption 1, Middle-East producers has a target price of 40\$, versus 80\$ in Assumption 2.
- 3 - Coal markets (2 Assumptions): this set describes the coal price growth sensitivity with respect to the coal production growth.
- 4 - Alternative liquid fuels supply (2 Assumptions): this set describes the ability of biofuels and coal-to-liquid (CTL) to penetrate the energy markets.
- 5 - Carbon free options for power generation (2 Assumptions): this set describes the ability of carbon-free technologies to penetrate the electricity-generation capacities. The three technologies involved are renewable electricity generators, carbon capture and sequestration (CCS) and nuclear plants.
- 6 - Energy end-uses technologies (2 Assumptions): this set describes the more and less rapid deployment of new technologies in the transportation and residential sectors.
- 7 - Development patterns (2 Assumptions): this set describes either a “mimetic” development pattern for developing countries, who want to catch up with the western lifestyle, or a less carbon-intensive one. We take into account infrastructure policies and the agents’ preferences for automobile transport and vast individual dwelling.

All the possible combinations of the modalities in those variables lead to 3×2^6 (i.e. 192) contexts that we call baselines. In each of these baselines, we assess the effects of climate policies implementations:

- 8 - Implementation of climate policies (3 Assumptions): the model represents (i) a “Business As Usual” (BAU) world with no constraint on emissions, or (ii) two possibilities of “stabilization” worlds in which a carbon tax reduces emissions such that CO₂ concentration is stabilized at 450ppm in the long run. The two possibilities regard tax income recycling: this income is either entirely given back to households, or recycled based on a lump sum principle in which

each sector receives back what they have paid, except for the power generation sector whose payoff is given to the consumer. As a consequence, there are twice as many scenarios in the stabilization case (450ppm) as in the BAU case.

Therefore, we introduce an eighth critical parameter set covering the existence of climate policies, which leads to 576 ($3^2 \times 2^6$) scenarios. In the next section, we detail the content of each parameters set.

B.4.1 SCENARIO VARIABLES AND UNCERTAIN PARAMETERS

This section provides a detailed list of all uncertain parameters that we use in our sets. In Appendix A, we explicit the equations in which these parameters can be found, and shed some light on the underlying modeling principles.

Sets	Parameters	Assumption 1	Assumption 2	Assumption 3
Oil and gas markets	Oil	3.6 Tb no inertia ($b=0.061$) 0.8Mbd/year 2.5%	3.1 Tb inertia ($b=0.041$) 0.7Mbd/year 2.5%	3.1Tb inertia ($b=0.041$) 0.7Mbd/year 5.0%
	Gas	Indexation of gas price on oil price (see Equation A.4)		
	Amount of ultimately recoverable resources (total conventional and non conventional)** Inertia in the deployment of non conventionals (spread of the bell-shaped curve: see Equation A.2) Maximum growth rate of Middle-East capacities Remaining resources before depletion starts			

	Assumption 1	Assumption 2
OPEC behavior	40\$/bl	80\$/bl
Coal	1.5	1
	1	4
	2%	0,05%
	Price growth elasticity to production decrease (see a_1 in Equation A.6a) Price growth elasticity to production increase (see a_2 in Equation A.6a) Production growth rate which cancels out price growth rate (see g_{lim} in Equation A.6b)	

The parameters in bold are multiple parameters.

(*): different parameters according to the region.

(**): different parameters according to the region and horizontal slice in the annual monotonous load curve (between base load and peak load).

(***): different parameters according to the region and category of oil.

			Assumption 1	Assumption 2	
Power generation decarbonization	Nuclear	Maximum market shares [min - max]**	[5% - 40%]	[2.5% - 20%]	
	Renewables	Maximum market share of renewables Learning rate for renewables investment costs (see Equation A.7)	2.5% 7%	15% 3%	
	Carbon capture and storage	CCS learning rate (see Equation A.7)	13%	7%	
		CCS start date (see Figure A.1)	2010	2015	
		CCS "bottleneck phase"	7 years	10 years	
		CCS maximum market share at the end of the bottleneck phase	5%	3.5%	
		CCS growth phase	8 years	8 years	
		CCS maximum market share at the end of the growth phase	90%	63%	
		CCS maturation phase	8 years	8 years	
		CCS maximum market share at the end of the maturation phase	100%	70%	
Low carbon end-use technologies	Electric vehicles	EV start (see Figure A.1) EV "bottleneck phase" EV maximum market share at the end of the phase EV growth phase EV maximum market share at the end of the phase EV maturation phase EV maximum market share	2010 3 years 2.5% 15 years 45% 16 years 50%	No significant market penetration before 2050	
	Industry	Capital lifetime in the industry	20 years	30 years	
	Energy efficiency	Freight energy consumption (see μ_f in Equation A.9)	Trend extracted from POLES data (LEPII-EPE, 2006): starts at 1 reaches 1.1 in 2030 and stays at 1.1 until 2050	1	1
		Freight fuel consumption elasticity to fuel prices (see ϵ in Equation A.9) Buildings energy consumption per m²* (see μ_h in Equation A.10)	-0.4	-0.35	Trend which starts at 1, reaches 1.2 in 2030 and stays at 1.2 until 2050

		Assumption 1	Assumption 2
Alternative liquid fuel supply	Biofuels	Time scale of reactive anticipation for biofuels production Biofuels supply: multiplier coefficient of the supply curves (see Figure A.2 for the default value)	4 years 50% increase w.r.t Assumption 2 value
	Coal-to-liquids	Oil price threshold for CTL production start (see Equation A.11) Time scale of reactive anticipation for CTL production Maximum production growth in 2030, 2035 and in 2050 (see p_{growth}^{CTL} in Equation A.12)	6 years Value from IEA curves 200 \$/bl 8 years 0.05 Mbd - 0.10 Mbd - 0.10 Mbd
Development patterns	Transport	Motorization rate growth with GDP per capita* (see λ in Equation A.13)	Value from IEA data (Fulton and Eads, 2004)
	Buildings	Income elasticity of buildings stock growth (see μ_s^{ini} in Equation A.14) Asymptote to surface per capita in China and India (see A in Equation A.14) Start year and fuel price for a forced decline of oil consumption in this sector	1 60 2020 - 1300\$/tep
	Industrial goods	households industrial goods consumption saturation level [min-max]* (multiplier factor of the calibration year consumption volume: see η in Equation A.15)	[1-2] [1.5-3]

The parameters in bold are multiple parameters.

(*): different parameters according to the region.

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Exploring GDP trends for the SSPs with the Imaclim-R model

This chapter proposes GDP pathways for the five Shared Socio-economic Pathways (O'Neill et al., 2013). It is adapted from a note that “warned” against too contrasted GDP pathways in the interpretation of the Boulder narratives. The GDP pathways are constructed with IMACLIM-R model runs, which represents interactions between energy systems evolutions and economic growth both ways (Appendix A). In particular, the aim of the analysis is to highlight the feedbacks of energy systems on growth mechanisms.

In this short chapter, we first briefly describe the methodology used to build GDP trajectories for the SSPs. We then analyze the results to identify the important elements of energy systems feedbacks on growth. In a last section, we run alternatives for SSP₃ and SSP₅ on assumptions driving the price of coal and on assumptions on the convergence speed to better highlight the links between growth and energy consumption.

C.1 PARAMETER CHOICES FOR THE FIVE SSPs

We construct SSPs using alternative assumptions on the model parameters values in order to match the Boulder narratives (O'Neill et al., 2013):

- We use exogenous assumptions on total population and labor force growth from the IIASA SSP database. Total population trends correspond to IIASA

Table C.1: Convergence speed assumption depending on the income group and the SSP.

	Low income re- gions	Middle income regions	High income re- gions
SSP₁	fast	fast	medium
SSP₂	medium	medium	medium
SSP₃	slow	slow	slow
SSP₄	slow	medium	medium
SSP₅	fast	fast	fast

model results for each SSP. labor force is derived from age classes' population trends, using the assumption of constant participation rates.

- labor productivity growth trends are also exogenous assumptions. They result from assumptions for the leader's labor productivity growth trends and convergence assumptions for the other regions. Assumptions for the leader's labor productivity growth follow either slow (SSP₃), medium (SSP₁, SSP₂ and SSP₄) or fast (SSP₅) trends. Other regions convergence assumptions follow the catch-up equation, such as convergence speed assumption is as reported in table C.1.
- The other assumptions regroup the parameters determining the energy consumption evolutions and technology deployment. Following chapter 2, their values are chosen to be consistent with the Boulder narratives (O'Neill et al., 2011, and table C.2).

The Boulder narratives can be summarized as follows and the corresponding parameters choice are in table C.2.

SSP₁: Households' preferences are oriented towards energy-sober lifestyles. The freight content of production is reduced, representing an evolution towards local production inside each of the model regions. Maximum annual improvement of energy efficiency in the leading country is high, as well as the catch-up speed of the others. Possible market penetration of nuclear energy, renewable resources, carbon capture and storage, and electric vehicles is high. Coal and coal-to-liquids are expensive.

SSP₂: Behaviors are similar to SSP₁ and the freight content of production is reduced, but energy efficiency possibilities are low. Low-carbon technologies are

Table C.2: Other socio-economic assumptions for the SSP.

	Development patterns	Production choices	Induced energy efficiency	Coal extraction	Availability of CTL technology	Availability of low-carbon technologies
SSP1	sober	reduced freight requirement	fast potential	low	low	high
SSP2	sober	reduced freight requirement	slow potential	low	high	high
SSP3	mimetic	constant freight requirement	slow potential	high	high	low
SSP4	sober	reduced freight requirement	slow potential	low	low	high
SSP5	mimetic	constant freight requirement	slow potential	high	high	high

available, but CTL is cheaper than in SSP1.

SSP3: Households' preferences evolve towards energy-intensive lifestyles and the fret content of economic growth does not improve. Potential for energy efficiency is low and coal is very cheap, as well as CTL. Potential market penetration of low carbon technologies is low.

SSP4: Behaviors are similar to SSP1 and 2, and energy efficiency possibilities are low. Low-carbon technologies are available, and coal and coal-to-liquids are expensive.

SSP5: As in SSP3, households' preferences evolve towards energy-intensive lifestyles and the fret content of economic growth does not improve, but potentials for energy efficiency are higher. Low carbon technologies are potentially available, but coal and CTL are very cheap.

C.2 RESULTS: GDP AND EMISSIONS PATHWAYS

Figure C.1 shows GDP per capita pathways for the world and five regions (following the RCP regional aggregation). Figure C.2 gives the corresponding trends of global CO₂ emissions from fossil fuel combustion, for the five proposed SSPs.

Global GDP per capita are such that in 2100 the levels reached are in the increasing order: $SSP_3 < SSP_4 < SSP_2 < SSP_1 < SSP_5$. This seems acceptable if one has in mind that the indicator for the capacity to adapt is equal to (or correlated with) global GDP per capita.

Global CO₂ emissions levels in 2100 are in the increasing order $SSP_1 < SSP_4 < SSP_2 < SSP_3 < SSP_5$. This also seems acceptable if one has in mind that the indicator for the challenges for mitigation is equal to (or correlated with) global CO₂ emissions. A few questions arise though:

- What is the rationale to have global GDP per capita higher in SSP₅ than in SSP₁? In particular, why is GDP per capita so contrasted for OECD countries?
- None of the emission trends is above RCP 8.5. Which SSP is expected to be above: SSP₅ or SSP₃? Maybe we could reach it with assumptions making coal cheaper, but there is also the option to reach it in SSP₃ by having higher GDP per capita in that scenario. Which option makes more sense?
- Aren't GDP per capita "too contrasted" and global emissions "not contrasted enough"? In particular, would it make sense to have higher GDP per capita in SSP₃ in order to have higher emissions in this scenario?

In the IMACLIM-R model, GDP growth is affected by energy consumption development patterns, the freight content of production and induced energy potential speed. If development patterns are "mimetic", the freight requirement is constant and/or the potential speed of induced energy is "slow", compared to the other alternatives (i.e. "sober" development patterns, "reduced freight requirement", "fast induced energy potential speed"), part of the production is "wasted" to pay for the energy (intermediate consumption) in two ways (i) the volume of energy is higher, but also (ii) the price paid for it is higher (because more expensive categories of energy have to be mobilized). A third mechanism is that there is less money for investments, which slows your capital accumulation, hence growth. Therefore energy systems evolutions have feedbacks on growth trends.

With this respect it is interesting to compare growth trends for Asia and Middle-East and Africa (MAF) between SSP₁ and SSP₅. Even if natural growth is higher for these regions in SSP₅ than in SSP₁ (because the leader's productivity growth trend is faster), effective growth is higher in SSP₁ than in SSP₅ for a long period of

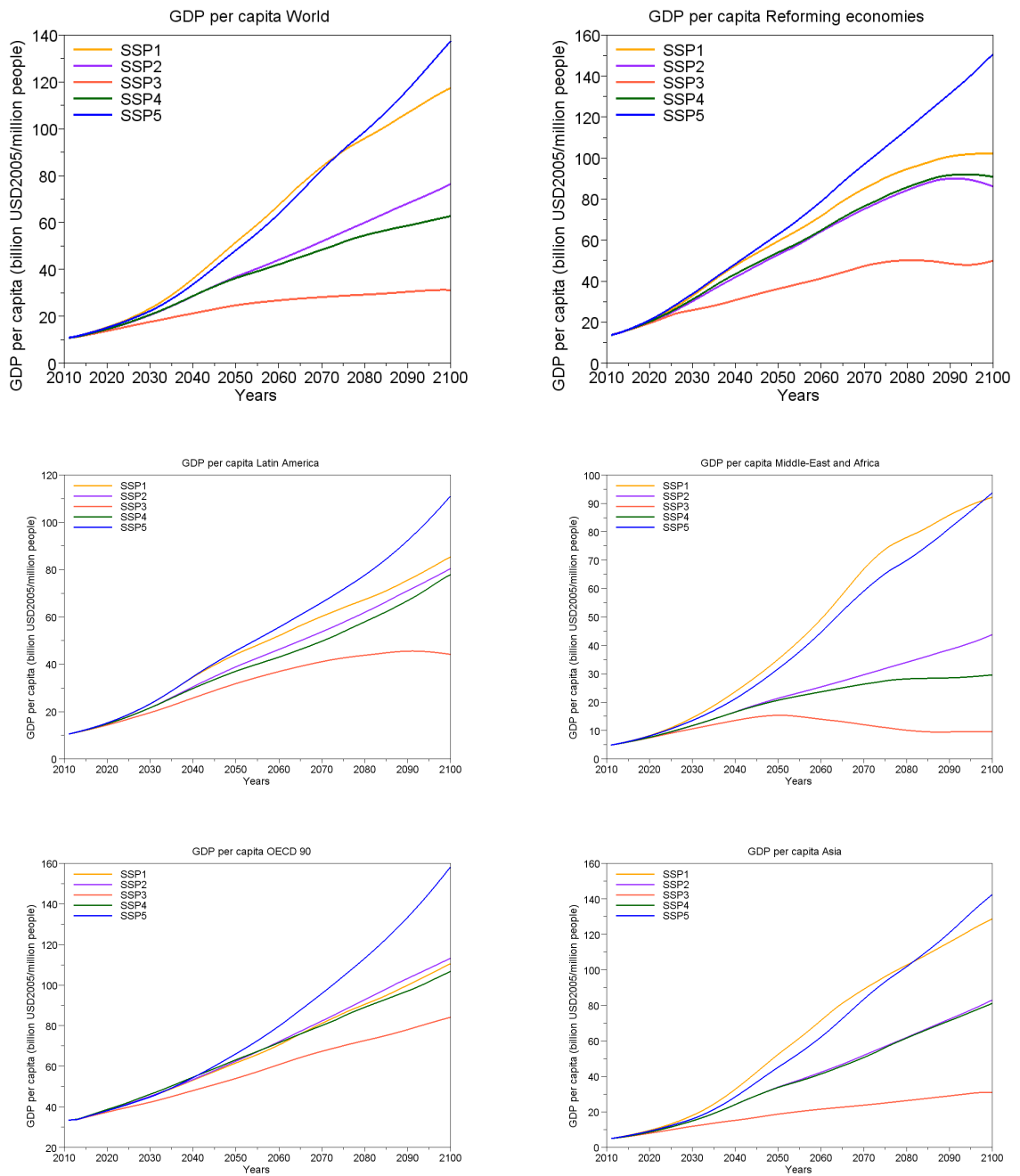


Figure C.1: GDP per capita for the world and five main world regions in the five SSPs.

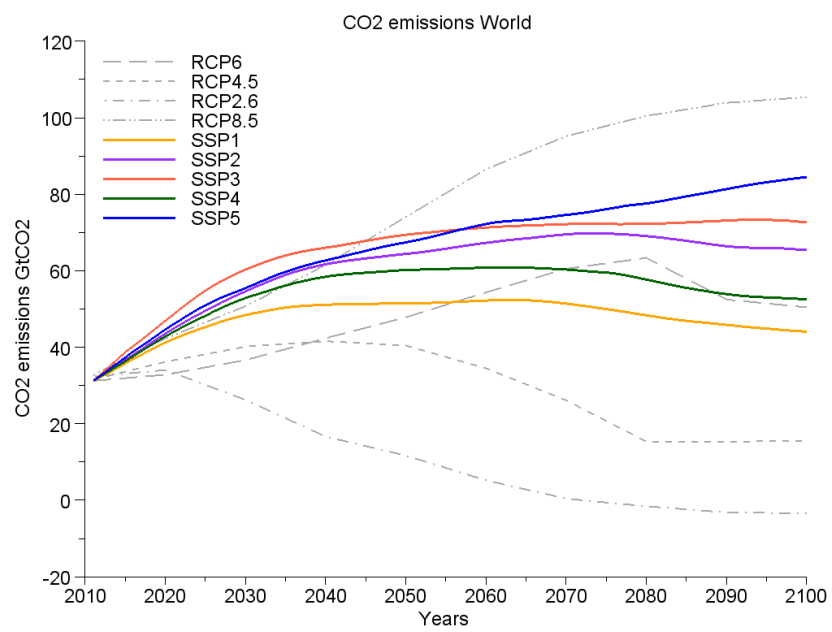


Figure C.2: Global CO2 emissions from energy consumption, compared to the RCPs.

time. During this period, energy use patterns and energy prices are more important for GDP per capita growth than convergence assumptions. At the end of the period though, effective growth becomes higher in SSP₅ than in SSP₁, because at that time the difference in potential growth between the two scenarios has a dominant effect.

Also, the comparison between SSP₃ and SSP₄ GDP per capita trends for these two regions indicates very large differences. Indeed the effects of energy intensive patterns in SSP₃ slow effective growth, which adds to the difference in natural growth (due to a slower leader's productivity growth in SSP₃ than SSP₄).

To illustrate this, figure C.3 shows potential GDP per capita (for the world) in each of the SSPs. Potential GDP per capita is calculated exogenously using, in each country, the sum of working population growth rate and labor productivity rates for GDP growth, and dividing by total population.

These potential growth trends may look surprising. Indeed, the rank of potential GDPs among the different SSPs is different from that of effective GDP. In particular, SSP₁ (and SSP₂) have the lowest GDP potentials while they have the second and third higher effective GDPs.

Below potential GDP, we represented in figure C.3 the ratio between effective and potential GDP growth in each of the SSPs. As it will be shown in chapter 3, this difference depends on the assumptions on energy efficiency potentials and consumption behaviors. Therefore, the higher the economy's energy efficiency and sobriety, the higher effective growth compared to potential growth. For this reason, in SSP₁ effective GDP is higher than potential GDP from 2040 on. Conversely, in SSP₃ which is very energy intensive, effective GDP decreases below 40% of potential GDP at the end of the century.

The objective of this exercise is to harmonize GDP trends with those of the SSP narratives and OECD quantifications, taking into account the effects of energy systems on GDP growth. Since the Boulder narratives and their quantifications state that GDP per capita is higher in SSP₅ than in SSP₁, and since SSP₅ is much more energy-intensive than SSP₁, this implies that potential GDP growth is much lower in SSP₁ than in SSP₅.

In the next section, we explore how alternative assumptions on convergence or the elasticity of coal prices impact GDP and emissions in SSP₃ and SSP₅, which are energy-intensive scenarios.

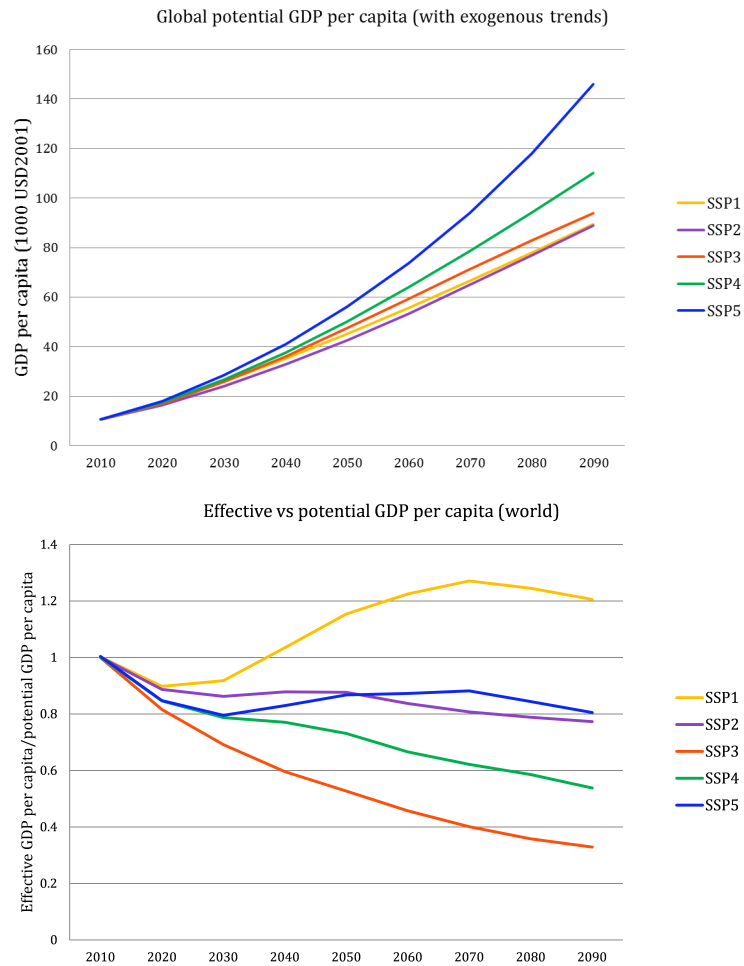


Figure C.3: On top: potential GDP per capita in each SSP, calculated from exogenous population growth rates and labor productivity growth rates. Below: ratio between effective (endogenous) GDP per capita in each SSP and potential GDP.

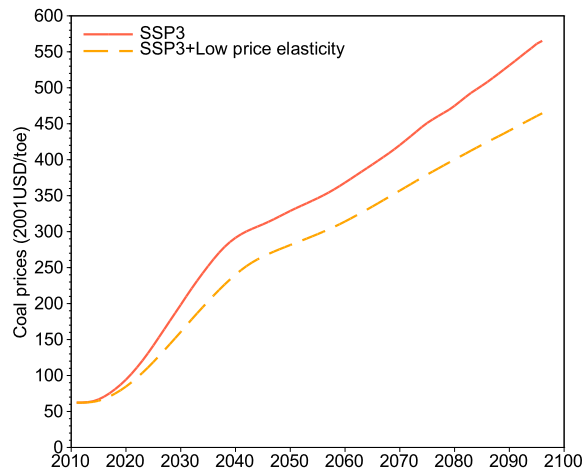


Figure C.4: Coal price in SSP3 and in variation with low elasticity of coal price.

C.3 FURTHER SIMULATIONS, VARIATIONS FOR SSP₃ AND SSP₅: CHEAPER COAL AND INCREASING CONVERGENCE FOR LOW INCOME COUNTRIES

To further explore the links between energy use and growth, we introduce the following variations for SSP₃ and SSP₅:

- The speed of convergence for low income countries is increased.¹
- The elasticities governing the coal price reaction to demand changes are changed in order to make coal even cheaper than in the “high coal extraction” alternative, that has already a high coal extraction potential (figures C.4 and C.7).

Figure C.5 and C.6 show that increasing convergence assumptions in low income countries for SSP₃ does not help increase world GDP per capita nor emissions. Indeed, low income countries are constrained by relatively high energy prices which prevent them from growing faster. Therefore, increasing convergence only widens the gap between potential growth and effective growth in SSP₃.

In scenarios with lower coal prices, conversely, GDP growth and emissions are higher than in previous SSP₃.²

¹For SSP₃, the value of τ_2 (in eq. A.1) for low income regions is taken equal to the medium convergence assumption instead of slow. For SSP₅, the convergence of labor productivity for low income regions is even higher than in the fast assumption.

²Note however that emissions remain below the RCP 8.5 level in 2100. This level could be reached with even cheaper coal, but it is not sure it would be a realistic assumption.

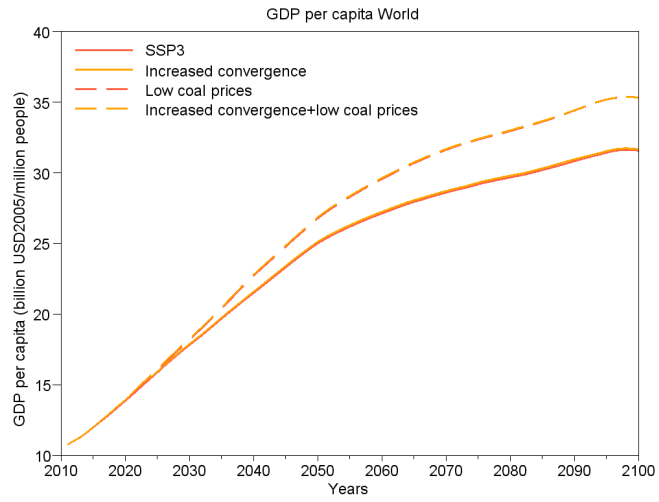


Figure C.5: World GDP per capita for different assumptions for SSP3.

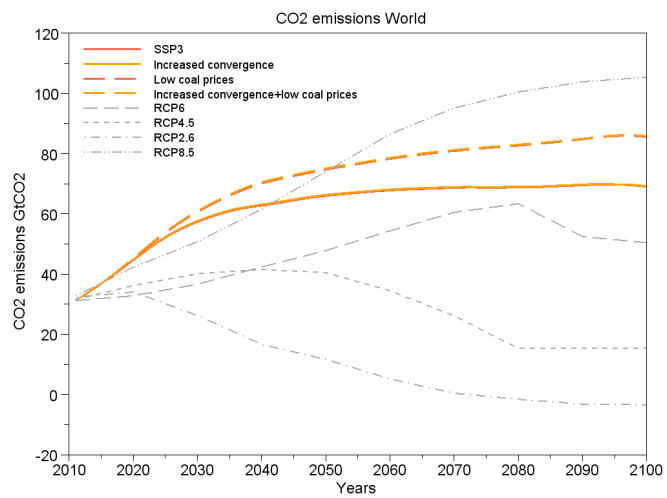


Figure C.6: World CO2 emissions for different assumptions for SSP3.

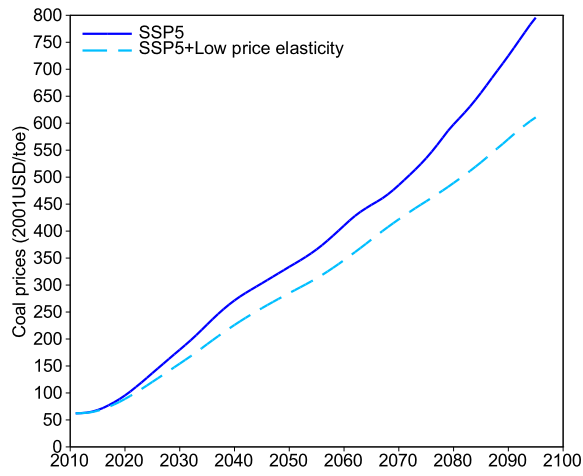


Figure C.7: Coal price in SSP5 and in variation with low elasticity of coal price.

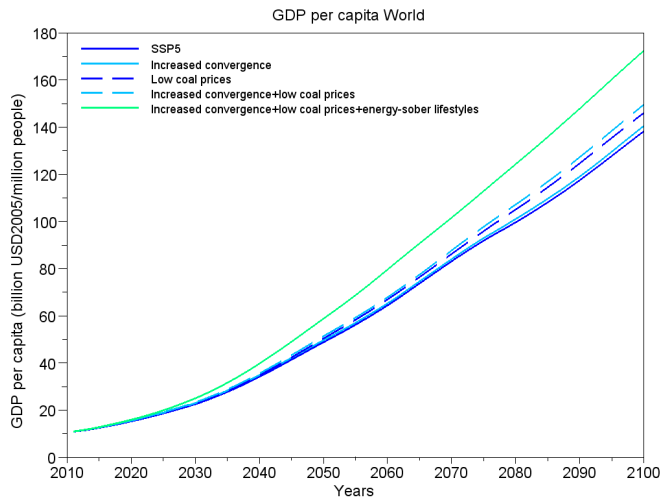


Figure C.8: World GDP per capita for different assumptions for SSP5.

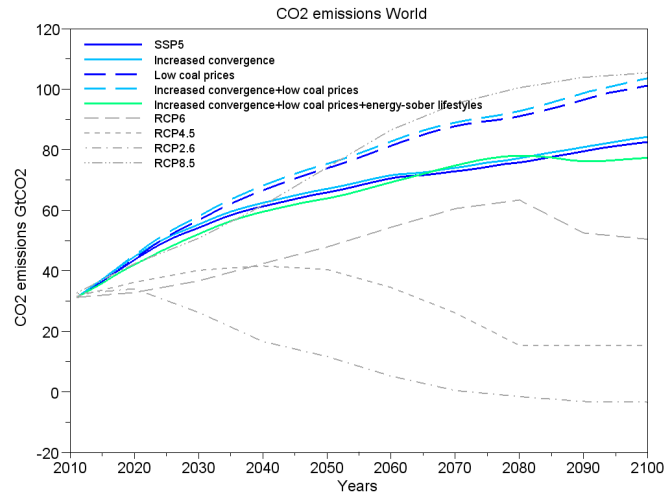


Figure C.9: World CO2 emissions for different assumptions for SSP5.

Figures C.8 and C.9 show similar results for SSP₅, even though the higher potential for energy efficiency in this scenario helps slightly increasing GDP growth when convergence increases in low income countries. Low coal prices also have the same effect as in SSP₃ by significantly increasing emissions, but they have a smaller effect on GDP per capita. As a last test, we ran a SSP₅ scenario with increased convergence for low income countries, low coal prices and energy-sober lifestyles. This last scenario (in green in Fig. C.8 and Fig. C.9) shows a significantly higher GDP per capita while emissions are similar to those of our first SSP₅. This corroborates our findings that energy-sober lifestyles increase growth because less income is used for energy consumption.

All these results on variations for SSP₃ and SSP₅ confirm that (i) energy systems evolution can have feedbacks on growth mechanisms, and (ii) in some cases, energy use patterns and energy prices are more important for GDP per capita growth than convergence assumptions.

These findings should be taken into account when building SSP quantifications, since they provide internal consistency to the scenarios. Indeed, it is important to keep in mind that in our model low energy intensity and medium growth in SSP₁ are consistent with low assumptions on growth potentials. Conversely, high growth and high energy intensity in SSP₅ are consistent with very high growth potentials and low energy prices.

In the next chapter, we will use a scenario database and data-mining techniques to disentangle the effects of different groups of parameters on growth and emissions.

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D

Appendix for chapter 5

D.1 UNCERTAINTIES AND INTEGRATED ASSESSMENT AND ECONOMY-ENERGY-ENVIRONMENT MODELS

Since early studies on the economics of climate change, uncertainty has been flagged as a critical element.

Indeed, pervasive uncertainties along the causal chain from emissions determinants to climate change damages arise (Fig. D.1). It is widely acknowledged in the climate change literature that uncertainties on carbon cycle mechanisms, climate sensitivity and climate change damages make the consequences of a given greenhouse gases level in the atmosphere (and thus mitigation benefits) uncertain (Heal and Millner, 2013). In response to this uncertainty, some authors have reframed the question into that of climate insurance (Ha Duong et al., 1997; Yohe et al., 2004; Mastrandrea and Schneider, 2004). Precisely because of the uncertainties on the physical climate system and the damages, our societies need to hedge against the risks posed by climate change. Setting aside the uncertainties on future damages, some economists adopt a cost-efficiency approach to evaluate the cost of climate change mitigation for a given climate target (e.g. 2C, 450ppm CO₂, factor 4). But in the answer to this question, many uncertainties remain.

Technological uncertainty on the costs and future availability of low-carbon technologies, resource uncertainty on unconventional fossil fuels, political uncertainty on the timing and geographical repartition of abatement efforts, and on the instruments used (norms, tax, emission trading system, use of revenues from the

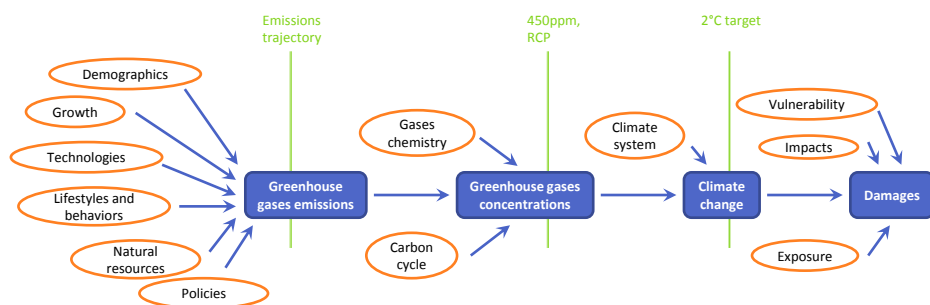


Figure D.1: Uncertainties along the causal chain from emissions determinants to climate change damages. In blue boxes: the elements of the causal chain. In orange ovals: main uncertainties. Green lines: targets at different positions in the causal chain. (Note: very simplified figure of the complex system; in particular it does not represent interactions and feedbacks between elements)

instrument if any, allocation rules for permits if any...), social uncertainty on future consumption preferences, population uncertainty and economic uncertainty on future growth and wealth distribution make the evaluation of mitigation costs a difficult exercise. Up to now, the scientific community has mainly focused on technology and policy uncertainty (Clarke et al., 2009; Edenhofer et al., 2010), even though Rogelj et al. (2013) encompass wider sources of uncertainties such as geophysical, technological, social and political. However, resource and economic uncertainty are generally absent from mitigation costs assessments, and the links between resource availability, social choices and economic growth — e.g. rebound effects, structural changes — are rarely considered.

D.2 MITIGATION COSTS METRICS

In theory, the question of the cost of climate change mitigation is part of the larger issue of finding the optimal level of climate mitigation, i.e. the one that will maximize social welfare. Answering this question requires to find the right balance, on the margin, between the welfare costs of actions to slow climate change and the welfare benefits of reducing future damages from climate change (Nordhaus, 1991, 1992, 1993). But in practice, the welfare cost is rarely reported in the studies published. Instead, the literature has been employing a multiplicity of metrics to evaluate mitigation costs (IPCC, 1995, 2001; Edenhofer et al., 2006): equivalent variation, technical cost, carbon price, consumption losses, GDP losses... These metrics are not several measures of the same cost, but are conceptually different (Markandya and Halsnaes, 2001; Bernard and Vielle, 2003; Hourcade and Gherzi, 2009). The carbon tax, for instance, is the marginal mitigation cost or, in other

words, the expense associated with eliminating one additional unit of emissions, while equivalent variation measures the additional revenues consumers would need to receive to maintain their welfare to the same level as in the baseline scenario (without climate damages).

This multiplicity of metrics co-exist because the correct evaluation of welfare costs is difficult (IPCC, 2001; Hanemann, 1991; Shogren et al., 1994), and the choice of the metric is sometimes constrained by the type of model that is used to evaluate mitigation costs (e.g. partial equilibrium models cannot assess GDP costs and thus focus on technical costs).

In practice, existing costs assessments often choose only one metric, among which the carbon price (i.e. the marginal cost) and the macroeconomic cost (i.e. the GDP cost) are the most popular. For instance, the IPCC chose to present the evaluations of macroeconomic costs in its last report summary for policy makers (IPCC, 2007) while carbon prices are prominent in other assessments and policy debates.

We analyze scenarios results along two of the most used mitigation costs metrics, the carbon price and the macroeconomic cost of mitigation. The carbon price is the carbon tax that is implemented to reach the mitigation target, or the price of the emission permits in an equivalent emission trading system. It is used for instance by Mastrandrea and Schneider (2004); Rogelj et al. (2013) as an evaluation of the magnitude of climate policy controls. The macroeconomic cost of mitigation is the variation of global GDP between the climate policy scenario and the corresponding baseline scenario. It is used, in particular, in IPCC assessments (IPCC, 2001, 2007). Note that macroeconomic costs are calculated with regards to a counterfactual baseline scenario that does not include climate change damages.

In the model GDP is calculated in real terms, i.e. using constant base-year prices, and is thus a measure of the production of goods and services in volume.

Macroeconomic costs are calculated as the difference between discounted GDP per capita in policy scenarios and the corresponding baseline scenarios, with a 3% discount rate r :

$$\text{macro_cost} = \frac{\sum_{2010 \leq t \leq 2050} (GDP_{pc}(t, \text{baseline}) / (1+r)^{(t-2010)})}{\sum_{2010 \leq t \leq 2050} (GDP_{pc}(t, \text{policy}) / (1+r)^{(t-2010)})} - 1 \quad (\text{D.1})$$

In IMACLIM-R the carbon price τ is calculated at every time step so as to comply with the given emissions constraint. Contrary to intertemporal optimization models, it does not grow at the interest rate, and is not necessarily monotonous. For this reason, using the carbon price at a given date is not a good indicator of the whole trajectory. To solve this issue, we calculate an average of the carbon price

over the whole period, weighted by the discount factor, with a 3% discount rate r :

$$\text{carbon_price} = \frac{1}{2050 - 2010} \times \sum_{t=2010}^{2050} \left(\frac{\tau(t)}{(1+r)^{(t-2010)}} \right) \quad (\text{D.2})$$

In a second step of the analysis, we will also study results in terms of absolute global GDP per capita levels reached in mitigation scenarios. GDP per capita is the ratio of real GDP over population (exogenous in the model). This third indicator will also be discounted with a 3% discount rate, and expressed as an index with regards to the mean across all mitigation scenarios, since the absolute value is not tangible in itself.

D.3 CART RESULTS

CART finds dichotomous splits of drivers that yield the strongest possible predictions of the cost measures. It gives an inverted tree with all scenarios at the top nod, and then each split presents a condition on a driver, with scenarios in agreement with the condition proceeding to the left branch, and scenarios in disagreement to the right.

CART results are presented in Figures D.2, D.3 and D.4. It gives an inverted tree with all scenarios at the top nod, and then each split presents a condition on a driver. To summarize, the main drivers are explained below:

- the carbon tax is determined by tax recycling and the availability of low-carbon technologies
- the macroeconomic cost is determined by tax recycling and either (i) the availability of low-carbon technologies if the tax is entirely redistributed to households or (ii) the availability of unconventional fossil fuels if the tax is lump-sum redistributed
- GDP per capita in climate policy scenarios is determined by behaviors and energy efficiency

D.4 ADDITIONAL GRAPHS

D.4.1 SENSITIVITY ANALYSIS

To discount rate

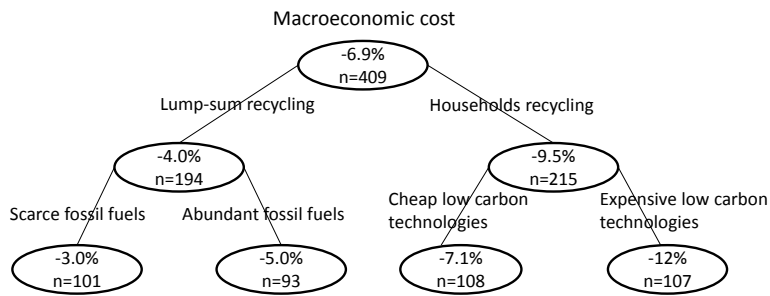


Figure D.2: CART results for macroeconomic cost.

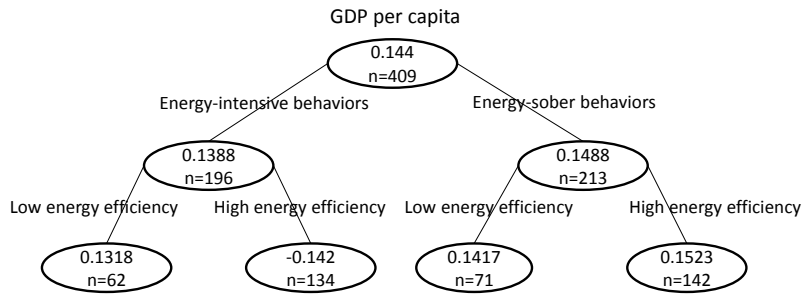


Figure D.3: CART results for GDP per capita.

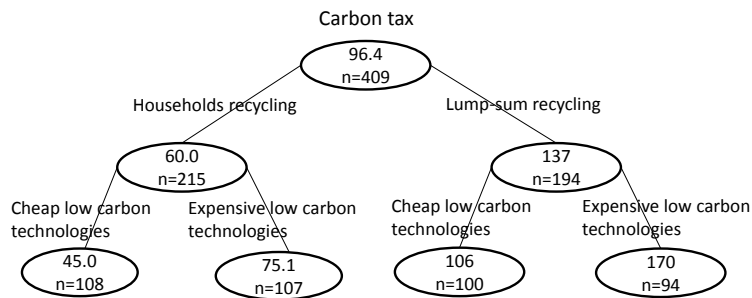


Figure D.4: CART results for the carbon tax.

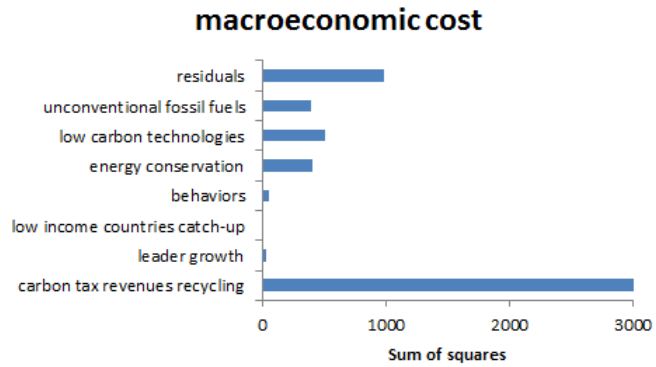


Figure D.5: ANOVA results for the macroeconomic cost.

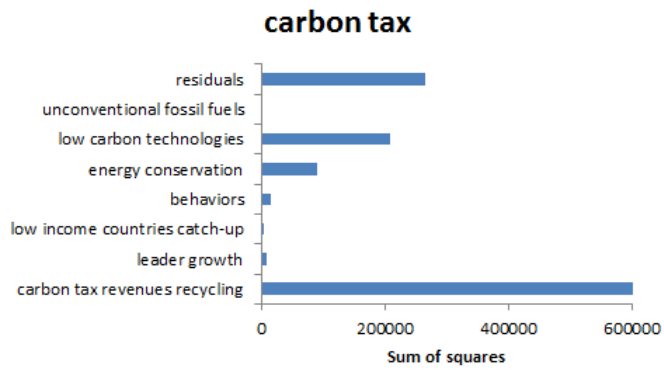


Figure D.6: ANOVA results for the carbon tax.

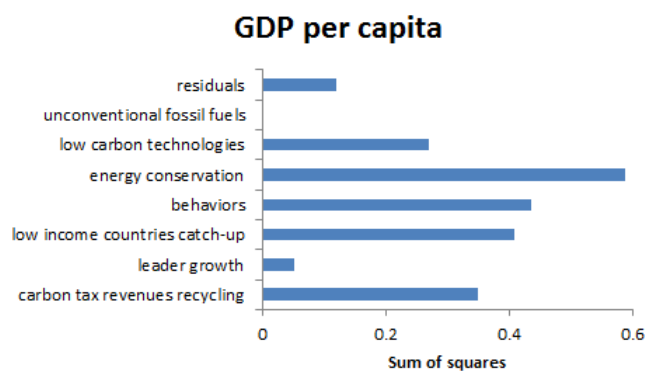


Figure D.7: ANOVA results for the GDP per capita.

D.4.2 ANALYSIS OF VARIANCE

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E

Irreversible investment and transition to clean capital: proofs

E.1 MAXIMIZATION OF THE HOUSEHOLD'S UTILITY

The household maximizes their inter temporal utility (eq. 6.2) given the motion law of wealth (eq. 6.1). The present value Hamiltonian is:

$$H_h(c_t, a_t) = e^{-\rho t} \cdot \{u(c_t) + \lambda_t[r_t \cdot a_t + y_t - c_t]\} \quad (\text{E.1})$$

where λ_t is the shadow cost of investment in assets at time t . The first order conditions for a maximum of W are:

$$\forall t, \partial_c H_h = 0 \Rightarrow \lambda_t = u'(c_t) \quad (\text{E.2})$$

$$\forall t, \partial_a H_h + \frac{\partial(e^{-\rho t} \lambda_t)}{\partial t} = 0 \Rightarrow \dot{\lambda}_t = (\rho - r_t) \lambda_t \quad (\text{E.3})$$

The dotted variables represent temporal derivatives. Differentiating eq. E.2 with respect to time and substitute for λ from eq. E.3, yields the Euler equation:

$$\frac{\dot{c}_t}{c_t} = \frac{-u'(c_t)}{c_t \cdot u''(c_t)} \cdot (r_t - \rho) \quad (\text{E.4})$$

E.2 SOCIAL OPTIMUM (SECTION 6.3)

The present value Hamiltonian associated to the maximization of social welfare (6.16) is:

$$\begin{aligned}
 H_t = e^{-\rho t} \cdot \{ & u(c_t) + \lambda_t [F(q_p, k_c) - c_t - i_{p,t} - i_{c,t}] + v_t [i_{p,t} - \delta k_{p,t}] \\
 & + \chi_t [i_{c,t} - \delta k_{c,t}] - \mu_t \cdot [G q_{p,t} - \varepsilon m_t] + \varphi_t \cdot [\bar{m} - m_t] \\
 & + \psi_t \cdot i_{p,t} + \beta_t [k_{p,t} - q_{p,t}] \} \quad (\text{E.5})
 \end{aligned}$$

All multipliers are positive.

The complementary slackness conditions are:

$$\forall t, \psi_t \geq 0 \text{ and } \psi_t \cdot i_{p,t} = 0 \quad (\text{E.6})$$

$$\forall t, \beta_t \geq 0 \text{ and } \beta_t \cdot (k_{p,t} - q_{p,t}) = 0 \quad (\text{E.7})$$

$$\forall t, \varphi_t \geq 0 \text{ and } \varphi_t \cdot (\bar{m} - m_t) = 0 \quad (\text{E.8})$$

E.2.1 FIRST ORDER CONDITIONS

First order conditions give:

$$\frac{\partial H_t}{\partial c_t} = 0 \Rightarrow u'(c_t) = \lambda_t \quad (\text{E.9})$$

$$\frac{\partial H_t}{\partial i_{p,t}} = 0 \Rightarrow \lambda_t = v_t + \psi_t$$

$$\frac{\partial H_t}{\partial i_{c,t}} = 0 \Rightarrow \lambda_t = \chi_t$$

$$\frac{\partial H_t}{\partial k_{p,t}} = -\frac{\partial(e^{-\rho t} v_t)}{\partial t} \Rightarrow -v_t \delta + \beta_t = -\dot{v}_t + \rho v_t$$

$$\frac{\partial H_t}{\partial k_{c,t}} = -\frac{\partial(e^{-\rho t} \chi_t)}{\partial t} \Rightarrow \lambda_t \partial_{k_c} F(k_{p,t}, k_{c,t}) - \chi_t \delta = -\dot{\chi}_t + \rho \chi_t$$

$$\frac{\partial H_t}{\partial q_{p,t}} = 0 \Rightarrow \lambda_t \partial_{q_p} F(q_{p,t}, k_{c,t}) - \mu_t \cdot G = \beta_t$$

$$\frac{\partial H_t}{\partial m_t} = \frac{\partial(e^{-\rho t} \mu_t)}{\partial t} \Rightarrow -\varphi_t + \varepsilon \mu_t = \dot{\mu}_t - \rho \mu_t \quad (\text{E.10})$$

E.2.2 EQUILIBRIUM ON THE CAPITAL MARKET AND INTEREST RATE: PROOF OF PROPOSITION 3

If we differentiate eq. E.9 with respect to time and substitute λ_t and $\dot{\lambda}_t$, we can write:

$$\frac{c_t \cdot u''(c_t)}{u'(c_t)} \cdot \frac{\dot{c}_t}{c_t} = (\rho + \delta - R_{c,t}) \quad (\text{E.11})$$

As in the laissez-faire equilibrium (eq. E.4), the interest rate r_t that ensures households are indifferent between consumption and investment is thus given by:

$$r_t := R_{c,t} - \delta \quad (\text{E.12})$$

E.2.3 CARBON PRICE

Eq. E.10 gives the evolution of μ_t . Using $\dot{\mu}_t = (\dot{\lambda}_t \tau_t + \lambda_t \dot{\tau}_t)$ (from eq. 6.21), eq. E.9, eq. E.11 and eq. E.12 yields:

$$\dot{\tau}_t = \tau_t[\varepsilon + r_t] - \frac{\varphi_t}{\lambda_t}$$

We call t_{ss} the date at which GHG concentration reaches the ceiling:

$$\forall t \geq t_{ss}, m_t = \bar{m}$$

During the steady state, $\dot{m}_t = 0 \implies G q_{p,t} = \varepsilon \bar{m}$ (eq. 6.11). On the long run, installed capital is not underused, polluting installed capital is thus constant at $k_{p,t} = \bar{m} \varepsilon / G$ during the steady state.

Before t_{ss} , $\varphi_t = 0$ (E.8). The carbon price thus exponentially grows at the endogenous interest rate plus the dissipation rate of GHG until the ceiling is reached:

$$\dot{\tau}_t = \tau_t[\varepsilon + r_t] \quad (\text{E.13})$$

These dynamics may be interpreted as a generalized Hotelling rule applied to clean air: along the optimal pathway, and before the ceiling is reached, the discounted abatement costs are constant over time. The appropriate discount rate is $r_t + \varepsilon$, to take into account the natural decay of GHG in the atmosphere.

E.2.4 THE IRREVERSIBILITY CONSTRAINT IS BINDING IN THE SHORT RUN : PROOF OF PROPOSITION 4

A binding GHG ceiling is imposed at t_0 . Before that, the economy was in the competitive equilibrium, such that clean and polluting capital have the same marginal

productivity and installed capital is fully used (Proposition 1):

$$\lim_{t \rightarrow t_0^-} q_{p,t} = k_{p,t} \quad (\text{E.14})$$

$$\lim_{t \rightarrow t_0^-} \partial_{q_p} F(q_{p,t}, q_{c,t}) = \partial_{k_c} F(q_{p,t}, q_{c,t}) \quad (\text{E.15})$$

We use a proof by contradiction to show that at t_0^+ (when the constraint is internalized) the irreversibility condition is necessarily binding. Suppose that the transition starts with a phase when the irreversibility constraint is not binding, i.e. $\psi_t = 0$. This would lead to (Propositions 2 and 3):

$$\lim_{t \rightarrow t_0^+} \partial_{q_p} F(q_{p,t}, q_{c,t}) = \partial_{k_c} F(q_{p,t}, q_{c,t}) + \tau_{t_0} \cdot G \quad (\text{E.16})$$

Besides, investment means that capital is a continuous function of time:

$$\lim_{t \rightarrow t_0^+} q_{p,t} = k_{p,t} \quad (\text{E.17})$$

If the GHG ceiling is binding then $\tau_{t_0} > 0$ (eq. E.13). So from eq. E.15 and eq. E.16:

$$\lim_{t \rightarrow t_0^+} \partial_{q_p} F(q_{p,t}, q_{c,t}) \neq \lim_{t \rightarrow t_0^+} \partial_{q_p} F(q_{p,t}, q_{c,t}) \quad (\text{E.18})$$

$\partial_{q_p} F$ is a continuous function of $q_{p,t}$ so eq. E.18 implies that $\lim_{t \rightarrow t_0^+} q_{p,t} \neq \lim_{t \rightarrow t_0^+} q_{p,t}$ which is incompatible with eq. E.14 and eq. E.17.

E.3 DECENTRALIZED EQUILIBRIUM WITH A TAX ON EMISSIONS

In a decentralized economy, it is possible to trigger the same outcome as in the social optimum with a lump-sum tax applied to carbon emissions. In this case, the firm's flow of profit at time t is given by:

$$\Pi_t = F(q_{p,t}, k_{c,t}) - R_{c,t} \cdot k_{c,t} - R_{p,t} \cdot k_{p,t} - \tau_t G q_{p,t} \quad (\text{E.19})$$

With $R_{p,t}$ and $R_{c,t}$ the rental prices of polluting and clean capacities respectively, and τ_t the carbon tax. The tax is redistributed through the assets equation:

$$\dot{a}_t = r_t \cdot a_t + y_t - c_t + \tau_t G q_{p,t} \quad (\text{E.20})$$

The Lagrangian corresponding to the firm's maximization program is:

$$L(t) = \Pi_t + \beta_t (k_{p,t} - q_{p,t}) + \gamma_t (k_{c,t} - q_{c,t}) \quad (\text{E.21})$$

First order conditions are:

$$\partial_{q_g} L = 0 \Rightarrow \partial_{q_c} F(q_{p,t}, q_{c,t}) = \gamma_t \quad (\text{E.22})$$

$$\partial_{q_b} L = 0 \Rightarrow \partial_{q_p} F(q_{p,t}, q_{c,t}) = \beta_t + \tau_t \cdot G \quad (\text{E.23})$$

$$\partial_{k_g} L = 0 \Rightarrow \gamma_t = R_{c,t} \quad (\text{E.24})$$

$$\partial_{k_b} L = 0 \Rightarrow \beta_t = R_{p,t} \quad (\text{E.25})$$

For all t ,

$$\gamma_t \geq 0 \text{ and } \gamma_t \cdot (k_{c,t} - q_{c,t}) = 0$$

$$\beta_t \geq 0 \text{ and } \beta_t \cdot (k_{p,t} - q_{p,t}) = 0$$

(complementary slackness conditions).

With eq. E.22 we have $\gamma_t = \partial_{q_c} F(q_{p,t}, q_{c,t}) > 0$, so $q_{c,t} = k_{c,t}$ for all t .

The combination of eq. E.22 and eq. E.24 gives

$$\partial_{k_c} F(q_{p,t}, k_{c,t}) = R_{c,t}$$

Combining eq. E.23 and eq. E.25, we find

$$\partial_{q_p} F(q_{p,t}, k_{c,t}) = R_{p,t} + \tau_t \cdot G \quad (\text{E.26})$$

In the equilibrium, the rental price of clean capacities is equal to the interest rate (plus delta): $R_{c,t} = r_t + \delta$, because clean capacities and loans are perfect substitutes as assets for households. When the irreversibility constraint is not binding (see eq. 6.6), and in particular on the balanced growth path, the rental rate of polluting capacities is equal to the interest rate as well and $R_{p,t} = R_{c,t} = r_t + \delta$.

However, when the carbon price is implemented at t_0 , the irreversibility constraint is binding (4). In this case, since the use of polluting capacities suddenly becomes too expensive, the rental rate of polluting capacities is endogenously reduced. As a consequence of a lower rate of return for owners of polluting capital, households stop investing in polluting capacities. If the carbon tax is very high, the rental rate of polluting capacities can even become nil and polluting capacities may be under-utilized.

E.4 FIRMS' MAXIMIZATION PROBLEM WITH DIFFERENTIATION OF INVESTMENT COSTS

The present value Hamiltonian associated to the firm's maximization program is:

$$H_t = e^{-\rho t} \cdot \left\{ F(q_{p,t}, q_{c,t}) - (\lambda_t - \theta_{c,t}) i_{c,t} - (\lambda_t + \theta_{p,t}) i_{p,t} \right. \\ \left. + v_t [i_{p,t} - \delta k_{p,t}] + \chi_t [i_{c,t} - \delta k_{c,t}] \right. \\ \left. + \psi_t \cdot i_{p,t} + \beta_t [k_{p,t} - q_{p,t}] \right\}$$

First order conditions give:

$$\begin{aligned} \frac{\partial H_t}{\partial i_{p,t}} = 0 &\Rightarrow \lambda_t + \theta_{p,t} = v_t + \psi_t \\ \frac{\partial H_t}{\partial i_{c,t}} = 0 &\Rightarrow \lambda_t - \theta_{c,t} = \chi_t \\ \frac{\partial H_t}{\partial k_{p,t}} = -\frac{\partial(e^{-\rho t} v_t)}{\partial t} &\Rightarrow -v_t \delta + \beta_t = -\dot{v}_t + \rho v_t \\ \frac{\partial H_t}{\partial k_{c,t}} = -\frac{\partial(e^{-\rho t} \chi_t)}{\partial t} &\Rightarrow \rho \chi_t - \dot{\chi}_t = \lambda_t \partial_{k_c} F(k_{p,t}, k_{c,t}) - \chi_t \delta \\ \frac{\partial H_t}{\partial q_{p,t}} = 0 &\Rightarrow \lambda_t \partial_{q_p} F(q_{p,t}, k_{c,t}) = \beta_t \end{aligned} \quad (E.27)$$

The complementary slackness condition $\forall t, \beta_t [k_{p,t} - q_{p,t}] = 0$ combined with equation E.27 gives that — if F satisfies the Inada conditions — capital is never underused with investment-based instruments $\forall t, k_{p,t} = q_{p,t}$.

FOCs can be reduced to:

$$v_t + \psi_t = \chi_t + \theta_{c,t} + \theta_{p,t} \quad (E.28)$$

$$\partial_{k_c} F = \frac{1}{\lambda} ((\delta + \rho) \chi_t - \dot{\chi}_t) \quad (E.29)$$

$$\partial_{q_p} F = \frac{1}{\lambda} ((\delta + \rho) v_t - \dot{v}_t) \quad (E.30)$$

We thus obtain

$$\partial_{q_p} F = \partial_{k_c} F + \underbrace{\frac{1}{\lambda_t} ((\delta + \rho)(\theta_{c,t} + \theta_{p,t}) - (\dot{\theta}_{c,t} + \dot{\theta}_{p,t}))}_{\theta_t} - \underbrace{\frac{1}{\lambda_t} ((\rho + \delta) \psi_t - \dot{\psi}_t)}_{p_t} \quad (E.31)$$

With p_t the irreversibility cost and θ_t a positive term that depends on $(\theta_{c,t} + \theta_{p,t})$.

Equation E.31 is similar to eq. E.37 with $\theta_t = \tau_{t,2} G$, where $\tau_{t,2}$ is the shadow

price of carbon. In the optimal pathway with a full-utilization of capital, θ_t is therefore equal to the shadow price of carbon (multiplied by G).

In this setting under-utilizing polluting capital is never optimal because firms do not pay carbon emissions directly. Instead, investment in polluting capital is more expensive than investment in clean capital and over the short-run, as in the social optimum the economy does not invest in new polluting capital. Once polluting capital has depreciated to a level compatible with the GHG ceiling, polluting investments become profitable and start again.

The policy creates a scarcity effect on polluting capital, that increases its price ($\theta_{c,t} + \theta_{p,t}$, eq. E.28) while the irreversibility constraint reduces its price in the short-run (ψ_t , eq. E.28).

Along the optimal transition to the new long-term steady state,

$$\begin{aligned} \partial_{k_c} F &\leq \partial_{q_p} F \\ \Leftrightarrow p_t &\leq \theta_t (= \tau_{t,2}) \\ \Leftrightarrow \psi_t &\leq \theta_{c,t} + \theta_{p,t} \end{aligned} \quad (\text{E.32})$$

so that the price of pre-existing polluting capital is higher than that of clean capital in the short-run.

In the steady state, the irreversibility cost is null ($p = 0$) and the marginal productivity of polluting capital is equal to that of clean capital plus θ_t . The same steady state as in the social optimum is reached and the optimal value of θ_t is equal to the first-best carbon tax multiplied by the marginal emissions of polluting capital:

$$\forall t \geq t_{ss}, \theta_t = \tau_t \cdot G$$

with t_{ss} the date at which the steady state is reached.

With investment-based instruments, the shadow price of emissions $\tau_{t,2}$ is still equal to a technical abatement cost plus the irreversibility cost:

$$\underbrace{\tau_{t,2}}_{\text{economic cost}} = \underbrace{\frac{\partial_{q_p} F - \partial_{k_c} F}{G}}_{\text{technical cost}} + \underbrace{\frac{p}{G}}_{\text{irreversibility cost}} \quad (\text{E.33})$$

with $p \in [0, \tau_{t,2}]$

The irreversibility cost p is now bounded by the shadow carbon price $\tau_{t,2}$ (eq. E.32). One interpretation is that preventing under-utilization is like refusing to recognize that past accumulation of polluting capital may have been a mistake. By doing so, the irreversibility cost can be as high as the cost of the GHG emissions that installed brown capital produces.

E.5 MAXIMIZATION OF SOCIAL WELFARE WITH FULL UTILIZATION
CONSTRAINT: TEMPORARY SUBSIDY ON EXISTING POLLUTING
CAPITAL

The same outcome as with feebates or standards can be reached with the same social planner program as in E.2 and a full-utilization constraint:

$$\begin{aligned} \max_{c,i,k} \int_0^{\infty} e^{-\rho t} \cdot u(c_t) dt & \quad (E.34) \\ \text{subject to } F(q_p, k_c) - c_t - i_{p,t} - i_{c,t} = 0 & \quad (\lambda_t) \\ \dot{k}_{p,t} = i_{p,t} - \delta k_{p,t} & \quad (v_t) \\ \dot{k}_{c,t} = i_{c,t} - \delta k_{c,t} & \quad (\chi_t) \\ \dot{m}_t = G q_{p,t} - \varepsilon m_t & \quad (\mu_t) \\ m_t \leq \bar{m} & \quad (\varphi_t) \\ i_{p,t} \geq 0 & \quad (\psi_t) \\ q_{p,t} \leq k_{p,t} & \quad (\beta_t) \\ q_{p,t} = k_{p,t} & \quad (a_t) \end{aligned}$$

The present value Hamiltonian associated to the maximization of social welfare is:

$$\begin{aligned} H_t = e^{-\rho t} \cdot \{ & u(c_t) + \lambda_t [F(q_p, k_c) - c_t - i_{p,t} - i_{c,t}] + v_t [i_{p,t} - \delta k_{p,t}] \\ & + \chi_t [i_{c,t} - \delta k_{c,t}] - \mu_t \cdot [G q_{p,t} - \varepsilon m_t] + \varphi_t \cdot [\bar{m} - m_t] \\ & + \psi_t \cdot i_{p,t} + \beta_t [k_{p,t} - q_{p,t}] + a_t [q_{p,t} - k_{p,t}] \} \end{aligned}$$

All multipliers are positive.

Equations 6.19 and 6.20 become:

$$\begin{aligned} \beta_t - a_t &= \frac{1}{\lambda} ((\delta + \rho)v_t - \dot{v}_t) \\ \partial_{q_p} F &= \beta_t - a_t + \tau_t \cdot G \end{aligned}$$

The rental price of polluting capital is therefore equal to $\beta_t - a_t$. The condition on the marginal productivity of polluting capital becomes:

$$\partial_{q_p} F = \beta_t - a_t + \tau_t \cdot G \quad (E.35)$$

Note that due to complementary slackness conditions, if $\beta_t > 0$ then $a_t = 0$ and if $a_t > 0$ then $\beta_t = 0$. In the first phase when polluting investment is nil, if

the carbon tax is higher than the marginal productivity of the last unit of polluting capital, the value of polluting capital is nil, $\beta_t = 0$ and the equation becomes:

$$\partial_{q_p} F = -\alpha_t + \tau_t \cdot G \quad (\text{E.36})$$

α_t is a subsidy to the utilization of polluting capital.

Similarly to the first-best pathway, the marginal productivities are differentiated as follows:

$$\begin{aligned} \partial_{q_p} F &= \partial_{k_c} F - p_t + \tau_t G \\ 0 &< p_t < \tau_t G \end{aligned} \quad (\text{E.37})$$

With the irreversibility cost $p_t > 0$ during the first phase and $p_t = 0$ when polluting capital reaches a sustainable level.

In the long run when $i_b > 0$ the equilibrium is equivalent to the social optimum. In the short run when $i_b = 0$, $\psi_t > 0$ and $R_{p,t} < R_{c,t}$, except that in this case $R_{p,t}$ becomes negative if the carbon price is higher than the marginal productivity of the last unit of polluting capital (expressed in output per emissions). Thus polluting capital is always fully-utilized.

This instrument leads to the same investments and output as the differentiation of investment costs or standards, however it is not perfectly equivalent. Indeed, the carbon tax also affects polluting capital on the secondary markets, thus the price of polluting capital decreases in the short-run. Conversely, with taxes on investments or standards on investments, polluting capital becomes scarce and so its price increase on the secondary market.

An instrument perfectly equivalent to the tax plus subsidy would be to differentiate capital costs, that is to tax both polluting investment and exchanges on the secondary market.

E.6 INVESTMENT REGULATION (PERFORMANCE STANDARDS)

Another equivalent possibility is to regulate polluting investment through efficiency standards. In particular, the most polluting investments can be forbidden. Here, we crudely impose polluting investments to be nil until polluting capital has depreciated to a level allowing to reach the carbon ceiling without under-utilizing polluting capital.

We come back to the social planner's program (beginning of section 6.3) and remove the concentration and ceiling constraints (eq. 6.11 and eq. 6.15). We can also remove the irreversibility constraint (eq. 6.6) which will not be binding in this case. Instead, we add a polluting investment constraint that forces $i_{p,t}$ to be equal

to a standard at each point in time, and we call σ_t its Lagrangian multiplier:

$$\forall t, i_{p,t} = sd_t \quad (\sigma_t) \quad (\text{E.38})$$

The standard sd_t can be optimally set to equal polluting investments found in the previous section and the next section. Basically, $sd_t = 0$ until polluting capacities have depreciated to a level compatible with the ceiling. The present value Hamiltonian associated to the maximization of social welfare is:

$$H_t = e^{-\rho t} \cdot \{ u(c_t) + \lambda_t [F(q_p, k_c) - c_t - i_{p,t} - i_{c,t}] + v_t [i_{p,t} - \delta k_{p,t}] + \chi_t [i_{c,t} - \delta k_{c,t}] + \sigma_t \cdot (sd_t - i_{p,t}) + \beta_t [k_{p,t} - q_{p,t}] \} \quad (\text{E.39})$$

λ_t is the current value shadow price of income. v_t and χ_t are the current shadow values of investments in polluting and clean capital.

First order conditions can be reduced to the following equations:

$$u'(c_t) = \lambda_t = v_t - \sigma_t = \chi_t \quad (\text{E.40})$$

$$\lambda_t \partial_{k_c} F = (\delta + \rho) \chi_t - \dot{\chi}_t \quad (\text{E.41})$$

$$\lambda_t \partial_{q_p} F = \beta_t \quad (\text{E.42})$$

$$\beta_t = (\delta + \rho) v_t - \dot{v}_t \quad (\text{E.43})$$

Here, σ_t is equivalent to $(\theta_{c,t} + \theta_{p,t} - \psi_t)$ in the previous section.

The maximization of intertemporal welfare results in the same equations as in the previous sections:

$$R_{p,t} = R_{c,t} + n_t \quad (\text{E.44})$$

$$\text{with } n_t = \frac{1}{\lambda_t} ((\rho + \delta) \sigma_t - \dot{\sigma}_t)$$

This equation is equivalent to Eq. E.31, with $n_t = \theta_t - p_t$. The variable n_t is positive, which means that the rental price of polluting capacities is higher than the interest rate. Indeed, as with the differentiation of investment costs the polluting investment standard creates a scarcity effect on polluting capital, which becomes more expensive than clean capital.

This instrument must be thought of as temporary, since once polluting capital has depreciated to a sustainable level, a carbon price can be implemented without inducing under-utilization of polluting capital, and thus becomes politically acceptable. Investment regulation can be compared with existing efficiency standards on cars or electric plants, that forbid the construction of the most polluting kinds of polluting capital.

E.7 SECOND-BEST INFEASIBILITY ZONE

This zone defines the cases when the ceiling is reached before polluting capacities have depreciated to a sustainable level. If no investment is made in polluting capacities, we have:

$$k_{p,t} = k_o e^{-\delta t}$$

Therefore, the stock of pollution follows this dynamic:

$$\dot{m} = k_o e^{-\delta t} - \varepsilon m$$

The solution to this differential equation is:

$$m_t = -\frac{G k_o}{\delta - \varepsilon} e^{-\delta t} + \left(m_o + \frac{G k_o}{\delta - \varepsilon} \right) e^{-\varepsilon t}$$

This function first increases to a maximum $m_{max} = \frac{G k_o}{\delta} e^{-\delta t}$ and then decreases. The maximum date is

$$t_{max} = -\frac{1}{\delta} \ln\left(\frac{m_{max} \varepsilon}{G k_o}\right)$$

The expression of m at the maximum date gives the limit of the infeasibility zone if $m_{max} = \bar{m}$:

$$\bar{m} = -\frac{G k_o}{\delta - \varepsilon} e^{\ln\left(\frac{\bar{m} \varepsilon}{G k_o}\right)} + \left(m_o + \frac{G k_o}{\delta - \varepsilon} \right) e^{\frac{\varepsilon}{\delta} \ln\left(\frac{\bar{m} \varepsilon}{G k_o}\right)}$$

This can be rewritten:

$$\bar{m} = \left[\left(m_o + \frac{G k_o}{\delta - \varepsilon} \right) \left(\frac{\varepsilon}{G k_o} \right)^{\frac{\bar{m}}{\delta}} \left(\frac{\delta - \varepsilon}{\delta} \right) \right]^{\frac{\delta}{\delta - \varepsilon}}$$

The “clean incentives infeasibility zone” depends on the capital depreciation rate, the GHG dissipation rate, initial GHG concentration and initial polluting capacities.