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An exploration of the systemic risks emerging from the interaction between energy, finance and the economy

Louis Delannoy

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THÈSE

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Une exploration des risques systémiques émergeant de l'interaction entre l'énergie, la finance et l'économie

An exploration of the systemic risks emerging from the interaction between energy, finance and the economy

Présentée par :

Louis DELANNOY

Direction de thèse :

Emmanuel PRADOS

CHARGE DE RECHERCHE HDR, INRIA CENTRE GRENOBLE-RHONE-ALPES

Directeur de thèse

Pierre-Yves LONGARETTI

Astrophysicien, CNRS

Co-encadrant de thèse

Rapporteurs :

PAUL BROCKWAY

ASSOCIATE PROFESSOR, UNIVERSITY OF LEEDS

UGO BARDI

PROFESSEUR EMERITE, UNIVERSITA DEGLI STUDI DI FIRENZE

Thèse soutenue publiquement le **14 septembre 2023**, devant le jury composé de :

PAUL BROCKWAY

ASSOCIATE PROFESSOR, UNIVERSITY OF LEEDS

Rapporteur

UGO BARDI

PROFESSEUR EMERITE, UNIVERSITA DEGLI STUDI DI FIRENZE

Rapporteur

VICTOR COURT

ASSISTANT PROFESSOR, ENSPMR RUEIL MALMAISON

Examineur

JEAN-FRANÇOIS PONSOT

PROFESSEUR DES UNIVERSITES, UNIVERSITE GRENOBLE ALPES

Président

OLIVIER VIDAL

DIRECTEUR DE RECHERCHE, CNRS DELEGATION ALPES

Examineur

SANDRINE MATHY

DIRECTEUR DE RECHERCHE, CNRS DELEGATION ALPES

Examinatrice

Invités :

EMMANUEL PRADOS

CHARGE DE RECHERCHE HDR, INRIA CENTRE GRENOBLE-RHONE-ALPES

PIERRE-YVES LONGARETTI

CHARGE DE RECHERCHE, CNRS DELEGATION ALPES



Louis Delannoy

AN EXPLORATION OF THE SYSTEMIC RISKS
EMERGING FROM THE INTERACTION BETWEEN
ENERGY, FINANCE AND THE ECONOMY



October 20, 2023

À Mado, et à toutes celles et ceux qui se battent pour la dignité des faibles.

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RÉSUMÉ

Cette thèse s'inscrit dans le domaine naissant de la macroéconomie écologique pour explorer les risques systémiques mondiaux émergeant de l'interaction entre l'énergie, la finance et l'économie dans un contexte d'intensification des changements socio-écologiques.

L'introduction explique comment les risques systémiques sont devenus une caractéristique interne au fonctionnement des économies modernes en raison de l'interaction étroite entre les systèmes énergie-finances-économie, de l'instabilité chronique du capitalisme financier et de l'utilisation immodérée de combustibles fossiles. Après avoir conceptualisé la macroéconomie écologique, et ses apports dans le cadre actuel, on examine les modèles et les questions de recherche découlant de leurs limites, ainsi que l'approche conçue pour y répondre.

Le chapitre 2 présente trois études caractérisant les contraintes énergétiques des économies modernes. Le premier article analyse dans quelle mesure l'approvisionnement en énergie nette des produits pétroliers est affecté par l'utilisation de sources d'énergie de moindre qualité, entre 1950 et 2050. Le deuxième article traite de la même question de recherche et avec une approche similaire, mais pour le gaz fossile. Le troisième article présente un modèle dynamique de comptabilisation des infrastructures mondiales liées à la production de combustibles fossiles, des besoins en énergie et matériaux, ainsi que des émissions de CO₂ associés, pour chaque segment de la chaîne d'approvisionnement de 1950 à 2050.

S'appuyant sur les méthodes précédemment développées, le chapitre 3 présente deux études ayant trait à la modélisation des contraintes énergétiques dans les modèles macroéconomiques. Le premier article introduit un nouveau modèle macroéconomique écologique stock-flux cohérent nommé TEMPLE, conçu pour évaluer les conséquences économiques d'un scénario de transition énergétique mondiale compatible avec l'objectif de 1,5°C de l'accord de Paris. Nos résultats indiquent que réaliser cette transition génèrera des dynamiques similaires à celle d'une économie de guerre, avec une inflation et des taux d'investissements ou d'emploi élevés. Une autre conclusion importante est qu'un ralentissement du taux de croissance de l'économie réduit l'inflation et facilite donc la transition. La deuxième étude est un article d'opinion fédérant une fraction importante de la communauté d'analyse énergétique nette. À travers l'explicitation du consensus émergent, l'article identifie les domaines d'investigation pour la communauté, discute des conséquences de l'énergie nette dans le contexte de la transition énergétique, et souligne les problèmes liés au fait de ne pas en tenir compte. Il présente en ce sens une évaluation critique de la manière dont l'énergie industrielle du secteur de la production énergétique est prise en compte et dont les interactions entre l'énergie et l'économie sont modélisées dans les modèles d'évaluation intégrée (IAM). Enfin, il suggère des pistes pratiques pour y remédier, en soulignant la nécessité d'intégrer une perspective de macroéconomie écologique et d'encourager les efforts de collaboration entre nos différentes communautés de recherche.

La conclusion résume le travail effectué au cours de la thèse et appelle à un changement de paradigme pour la modélisation économique ainsi qu'à l'appréciation du champ de la post-croissance. Elle s'adresse également et de manière plus large aux différentes communautés de la science de la durabilité, en soutenant une institutionnalisation de l'approche systémique, à tous les niveaux.

Mots clés : risques systémiques, macroéconomie écologique, transition bas-carbone, pétrolier, EROI, post-croissance, modèles stock-flux cohérents, modèles d'évaluation intégrée.

SUMMARY

This thesis builds upon the incipient field of ecological macroeconomics to explore the global systemic risks emerging from the interaction between energy, finance and the economy in a context of intensifying socio-ecological changes.

The introduction details how systemic risks have become a feature of modern economies due to the tight interaction between energy-finance-economy systems, the economic instability of financialized capitalism and the immoderate use of fossil fuels. It also critically reviews ecological macroeconomics modeling frameworks before presenting research questions that arise from their limitations, and the approach designed to address those questions.

Chapter 2 presents three studies advancing the understanding of energy constraints of modern economies. The first article analyzes the extent to which the net-energy supply of oil products is affected by the use of lower quality energy resources, from 1950 to 2050. The second article treats the same research question with a similar approach but for gas. The third article presents a dynamic model of the global fossil fuels production infrastructures and materials requirements for each segment of the supply chain, as well as the embedded energy and CO₂ emissions from 1950 to 2050. These three articles highlight the systemic risks associated with the energy depletion of fossil fuels, and more specifically the growing energy and materials requirements of oil and gas extraction, for wider systems.

Relying on the methods previously developed, Chapter 3 presents two studies dealing with the modeling of energy constraints in macroeconomic models. The first paper introduces a new ecological, stock-flow consistent macroeconomic model, named TEMPLE, designed to assess the economic consequences of a global energy transition scenario compatible with the 1.5°C target of the Paris Agreement. Our results indicate that achieving this transition will generate dynamics similar to those of a wartime economy, with high inflation, investment and employment rates. Another important finding is that a slowdown in the economy's growth rate reduces inflation and therefore facilitates the transition. The second study is a comment piece federating an important fraction of the net energy analysis community. By making the emerging consensus explicit, the article identifies areas of investigation for the community, discusses the consequences of net energy in the context of the energy transition, and highlights the problems associated with ignoring it. In this sense, it presents a critical assessment of the way in which industrial energy in the energy production sector is taken into account, and how the interactions between energy and the economy are modeled in integrated assessment models (IAM). Finally, it suggests practical ways forward, highlighting the need to integrate an ecological macroeconomics perspective and encourage collaborative efforts between our different research communities.

The conclusion summarizes the work carried out during the thesis, calling for a change of paradigm for modeling practices and an appreciation of the post-growth research field if ecological macroeconomics is to take account of the systemic risks of the energy–finance–economy nexus. It also speaks more broadly to different communities on sustainability issues, supporting a systemic approach requiring institutional shift at all levels.

Key words: systemic risks, ecological macroeconomics, low-carbon transition, EROI, peak oil, post-growth, stock-flow consistent models, integrated assessment models.

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¹Zoé Steep is a collective name for the work done under the aegis of the STEEP Research team in INRIA Grenoble. It is the collective voice of this team and its allies that is presented to the public. The editorial coordination was done by Louis Delannoy (STEEP INRIA Grenoble), Vincent Jost (CNRS G-SCOP and STEEP INRIA Grenoble), Mathieu Mangeot (STEEP INRIA Grenoble) and Sophie Wahnich (CNRS PACTE and STEEP INRIA Grenoble) with the active support of Mathilde Jochaux du Plessix (STEEP INRIA Grenoble).

CHAPTER 1 | INTRODUCTION

Power is domination, control, and therefore a very selective form of truth which is a lie.

Wole Soyinka

1.1. GLOBAL SYSTEMIC RISKS IN THE ANTHROPOCENE

The world is in crisis. The increasing interconnectedness of social-ecological systems, coupled with the intensification of environmental pressures¹ and degradation of natural resources, has multiplied the frequency and severity of shocks to the economy. The global financial crisis and the rapid spread of the COVID-19 epidemic, two events that have severely impacted our social, energy, and economic systems, are prime examples. These shocks add to the crises already underway, and interact to form a transverse and polymorphic crisis, depriving the term of its original meaning since it no longer prefigures an outcome but designates an upheaval with no temporality of its own, no master plan, no governance and no blueprint response. Some see it as a permanent crisis (Chesney, 2020), others as a never-ending crisis (Revault d'Allonnes, 2016) or prefer to detach themselves from the word “crisis” (Paglia, 2015), considered to be overused.

Characterizing the source of the polycrisis is the first step in building a more sustainable, just and resilient society. And as Mankind has not ceased to draw from the access to inexpensive energy resources the roots of his ability to dominate its environment² (Smil, 2017; Court, 2022), it seems appropriate to recognize the period of energy modernity in the industrial age as a historical marker of a new geological era: the Anthropocene (Steffen et al., 2011; Malm and Hornborg, 2014; Lewis and Maslin, 2015; Bonneuil and Fressoz, 2016; Love and Isenhour, 2016; Syvitski et al., 2020; Spangenberg, 2022). Recurrent systemic instability phenomena and other shocks are thus conceived and defined as the systemic risks in the Anthropocene, and have three common characteristics (Keys et al., 2019). First, global systemic risks emerge from processes that

¹For instance, it is estimated that several hundred plant and animal species have become extinct on the planet over the past 250 years due to habitat loss, pests invasion, pollution, climate change, overfishing, and overhunting (Dirzo et al., 2014). Current rates of extinction are not only much higher than historically observed, but are increasing to the point where a sixth mass extinction is considered to be taking place, a precursor to inevitable ecosystem collapse if the course of the recent history is not modified (Spalding and Hull, 2021).

²This dualistic conception of ‘culture’ versus ‘nature’ (Descola, 2005), inherited from the West, explains in part why environmental pollution linked to the use of energy have been largely neglected (Jarrige and Le Roux, 2017).

are largely driven by human activities, as is climate disruption. Second, they are amplified by the growing interaction between socio-ecological systems, inherited from globalization policies put in place after the Second World War. Third, they exhibit complex non-linear behaviors, capable of translating from one geographical scale to another—one example among others are climatic tipping points, i.e. critical thresholds at which the global system reorganizes itself, often abruptly and/or irreversibly (Wang et al., 2023a).

Other definitions of systemic risks are used, notably through the use of concepts derived from global networks, complex adaptive systems, disasters or chaos theory—see for example Pescaroli and Alexander (2018) or Reyers et al. (2018)—but are criticized for undermining smaller scale consequences of the Anthropocene (Biermann et al., 2016) or for their omission of issues of power, equity, ethics and justice (Keys et al., 2019). They are also under the spotlight for not fully acknowledging the changing nature of hazard and disaster risks, including the redefinition of what constitutes extremes (Cutter, 2020) or for concealing the systemic nature of the risks (Goldin and Mariathasan, 2014). One useful practical addition to the definition of global systemic risks in the Anthropocene is, however, the differentiation between two broad types of risk depending on the processes involved: short-term (months or years) systemic contagion risks and long-term (decades) trend risks (Longaretti, 2020). The former, which are more intermittent and random, refer to the propagation of shocks which, amplified by feedback mechanisms, spread until they trigger failures or cascading intersectoral catastrophes in different sectors. The second, long-term trend risks, emerge from the double relationship between complexity and energy, and from the transgression of the biophysical limits of the current world system.

As a result of a better understanding of the stakes and the urgency of the situation, the literature on global systemic risks has grown considerably during the past decades. Nevertheless, it remains scattered and dominated by a financial and technological approach, not well suited to account for the systemic phenomena at play. For instance, various efforts have been made to characterize the systemic risks of the financial system (Renn et al., 2017), but only recent contributions began to investigate the cross risks induced by climate change (Aglietta and Espagne, 2016; Monasterolo, 2020) or biodiversity loss (Svartzman et al., 2021). Another example are the annual Risk Reports of the World Economic Forum—an informal entity of transnational elite clubs promoting neoliberalism (Graz, 2003)—which summarize the perception of risks by political decision-makers. Those reports appear however to be somewhat biased by the hazards that occurred the year before the reports are published to create a sectoral and simplistic view of global risks³, and do not seem suitable for understanding the complex realities of the polycrisis (Evans et al., 2017; Sharma and Soederberg, 2019). Climate risks benefit from better scientific coverage, notably through the indispensable work of the Intergovernmental Panel on Climate Change (IPCC). Yet, there is a recognized need to improve the characterization of socio-economic processes, as well as how complex adaptation to climate change could modulate cross-sectoral and large-scale risks (Adler and Hadorn, 2014; O’Neill et al., 2017; Tangney, 2019). This is particularly true for integrated assessment models (IAMs), ultra-sophisticated and high-granularity mathematical models used to produce global, regionally disaggregated mitigation pathways, and whose ability to capture polycrisis is questioned due to insufficient attention paid to the systemic aspect of the global risks or the potential inconsistency of the energy-economy relationship (Desing et al., 2023; Koasidis et al., 2023). IAMs are also heavily criticized for relying on neoclassical economics⁴, a school of economic thoughts whose approach to the

³See for instance the evolution of the risks prior and after the COVID-19 pandemic (WEF, 2019, 2021).

⁴‘Neoclassical economics’ is here used equivalently for ‘mainstream’ or ‘orthodox economics’ although subtle differences distinguish the concepts (Dequech, 2007).

interaction between energy, finance and the economy, and more broadly to ecological issues in general, has been the subject of much criticism⁵.

Understanding the propagation dynamics associated with global systemic risks is made difficult by the complex and transnational relationships involved (Helbing, 2013; Folke et al., 2021) and, in the prevailing state of knowledge, it is fair to say that they remain poorly grasped. Yet, it is argued that recent global crises share a causal pattern that revolves around the finance-energy-economy nexus (Homer-Dixon et al., 2015; Hogeboom et al., 2021). Indeed, this nexus is particularly significant, linking social, economic and environmental risks. It is in the same time especially vulnerable due to the economic instability of financialized capitalism which makes a new financial crisis likely⁶ (Michie, 2022) and the energy crisis underway following Russia's invasion of Ukraine, the vagaries of OPEC+ oil production, the increasing energy costs of extraction associated with non-renewable resources depletion and the much needed energy transition towards renewable energy systems. Needless to say that the current economic context, consisting of severe economic downturns, stubborn inflation, recession risks, deterioration of the labor market—quality and quantity wise—and gloomy forecasts for many countries⁷, adds to the fear of a significant and potentially defining shock for the future. Identifying the finance-energy-economy nexus' most important feedback loops and the most fragile elements could therefore help uncover regime shifts, having the potential to trigger cascading reactions (Rocha et al., 2015), contribute to the design of resilient alternatives to existing production systems (Nystrom et al., 2019) and pave the way towards improved global governance (Galaz et al., 2017)⁸. To do so, however, it seems necessary to leave neoclassical economics and turn to a school of thought that seems better able to grasp the systemic dimension and biophysical ramifications of the polycrisis: ecological macroeconomics.

1.2. ECOLOGICAL MACROECONOMICS: AN INTRODUCTORY REVIEW

1.2.1. HISTORICAL CONCEPTUALIZATION

The very beginnings of ecological macroeconomics (EM) trace back to the origins of economics, when physiocrats saw agricultural land as the determinant of wealth (walking in the footsteps of from William Petty). Similar seeds of thought followed more quietly in the writings of Adam Smith, who insisted that a careful examination of the materiality of the evolving relationships between societies and the environment was a key element of political economic analysis (Steeds, 2021). New life was breathed into the debate as classical economists David Ricardo and Thomas Malthus engaged in a vigorous argument on whether available productive land could limit the scale of the economy⁹. The early controversy remained relatively untouched

⁵For an historic review of the critique of neoclassical economics, see Lee (2009) and Bougrine and Rochon (2022). For an introduction to the limits of the analytical frameworks, see Pottier (2016); Espagne (2018) and Asefi-Najafabady et al. (2020).

⁶Or is already in its early stages of development, following the Silicon Valley Bank failure and Crédit Suisse bailout.

⁷To name a few: Europe, Latin America, Tunisia, Sri Lanka, Pakistan, Turkey, Lebanon, Egypt, Yemen, Syria, Ghana, and China, whose weak real estate activity and slow economic recovery after removal of zero-Covid policies have questioned the country's ability to export its way out of crisis (Financial Times, 2023). Even the U.S. is in a difficult situation, with the government at risk of defaulting due to the debt ceiling, which could trigger a recession and a "number of financial markets break—with worldwide panic triggering margin calls, runs and fire sales" according to Treasury Secretary Janet Yellen (Reuters, 2023).

⁸Focusing on the nexus' systemic risks does not deny or underestimate the importance and influence of other sources of concerns such as biodiversity loss, but highlights the role of shocks that may occur before the 1.5-degree threshold target is physically transgressed, as they could impede or thwart the deployment of effective ecological policies.

⁹Let us clarify that, as made clear by Kallis (2019), Malthus was not opposed to population growth. On the contrary, he saw in population growth an unalterable process which, due to the increase of food production being inferior, leads to poverty and inequality. Those were

until the end of the Industrial Revolution when John Stuart Mill explicitly posited that some of the factors involved in the production of wealth were “depending on the properties of matter, and on the amount of knowledge of those properties possessed at the particular place and time” (Mill, 1848). A few years later, William Stanley Jevons provided the first empirical and theoretical consideration of resource overexploitation, exposing the paradoxical phenomenon of energy efficiency that bears his name¹⁰ (Missemer, 2012). However, Jevons did not argue against the abuse of nature by energy-driven processes, a critique which was later developed by Karl Marx and Friedrich Engels (Clark and Foster, 2001, 2010). In an attempt to synthesize Marx and Engels works with the second law of thermodynamics, Serhiy Podolynsky provided the first labor theory of value rooted on embodied energy to be regarded as a precursor—if not an early pioneer—of ecological macroeconomics (Alier and Naredo, 1982; Ivanov et al., 2017).

Yet it was not until issues of sustainability arose in the 1970s, symbolized by the peak in conventional oil production in the United States and the *Limits to Growth* report of Meadows et al. (1972), that the first modern contributions were made by Kenneth Boulding, Nicholas Georgescu-Roegen, Herman Daly, Joan Martinez Alier, Robert Costanza and Robert Ayres, walking in the footsteps of maverick predecessors, Frederick Soddy and Karl Polanyi, and to a certain extent John Maynard Keynes (Berr, 2009). The first contemporary wave of EM experienced an intense period of intellectual profusion, contributing to a better understanding of the role of resources in macroeconomic processes and the birth of the cousin branch of degrowth (Kallis et al., 2018). Numerous and important works were however soon overshadowed by the neoclassicals who attempted to incorporate natural capital, assumed substitutable with human made capital, as a factor of production into dynamic general equilibrium models where each factor’s productive power is proportionate to its cost-share in total income (Dasgupta and Heal, 1974; Solow, 1974; Stiglitz, 1974). Such hybridization left a lasting mark on the debate by reducing scarcity considerations to price signals, relegating ecosystems complexity to a secondary level and making ecological indicators or market failures involving externalities the only topics for discussion. By the 90’s, ecological economics has been gradually deprived from its macro component to let the orthodox economics do the lion’s share of the modeling, as exemplified by the growing reach of DICE (Nordhaus, 1977, 1991). Recommended policies were not only based on assumptions that were out of touch with reality, but also contributed to accelerating the capture of ‘free-of-charge’ resources from socio-ecosystems and had poor impact on lowering the global release of pollutants¹¹.

The Global Financial Crisis and subsequent Great Recession marked a turning point and, by exposing the fundamental flaws of the dominant macroeconomic theory (supply driven, full capital utilization, rational behavior, efficient markets, neutrality of money, nullity of distributional effects, etc.), put the macro scale back on the table (Keen, 2011; King, 2012; Turner, 2015; Stiglitz, 2018). The global stakes deserved a new macroeconomics, one that would highlight both the dependence of economic systems on resources and the feedbacks of waste assimilation, as called by Antal and van den Bergh (2013) and Foxon (2013). However, ecological economics has been neglecting the macroeconomic dimension for too long and had to turn to other heterodox¹² schools of thought to catch up (Spash and Schandl, 2009). The one to

considered desirable by Malthus because, according to him, they encouraged economic activity through technological progress, the only factor capable of sustaining the unstoppable rise in population, and acted as a natural regulation.

¹⁰Jevons’ paradox—also known as the rebound effect—states that technological improvements increase the efficiency with which a resource is used, the total consumption of that resource may increase rather than decrease. In particular, this paradox implies that the introduction of more energy-efficient technologies can increase total energy consumption.

¹¹Global carbon dioxide emissions have continued to rise and are 60% higher today than they were in 1990, causing temperatures to increase by 1.25°C compared to pre-industrial times and putting the world on track for exceeding the 1.5°C threshold in less than 10 years (Stoddard et al., 2021; Matthews and Wynes, 2022). Even the reduction of the ozone hole after the ratification of the Montreal Protocol, arguably the most important—and almost unique—achievement of global environmental policy, is still “unfinished business” (Solomon et al., 2020).

¹²Heterodox economics has developed considerably in the wanderings of orthodox economics to integrate various schools of thought and

which it was most natural was the Post-Keynesian, as both currents prefer to the orthodox instrumentalism a realism-driven approach in which agents are influenced, and constrained, by their environment, social relations and institutions (Gowdy, 1991; Kronenberg, 2010). It was also found that ecological economists had already adopted Keynesian principles and proposed models of consumer behavior very similar to those of the post-Keynesians (Lavoie, 2005, 2006; Harris, 2009). Post-Keynesians were also the ideal counterpart as their work has been largely neglecting climate and resource issues until then, a gap that was being acknowledged (Berr, 2015; Pollitt, 2019). Ties between the two currents accelerated and led to the publication of a joint book (Holt et al., 2009), before contributions originating from both sides flourished in various journals. Despite diverging views within each stream, the 2010's gradually saw ecological macroeconomists assert themselves and advocate for a number of Keynesian-style reforms: a stronger regulation of the financial sector, 'green' investments to counter the depreciation of nature or 'green' monetary and fiscal policies (Svartzman et al., 2019).

A special issue in 2016 in the leading journal of Ecological Economics marked the transformation of EM from childhood to adolescence, as the first critics started to make themselves louder (Rezai and Stagl, 2016). Post-Keynesian for instance pointed out the fundamental disagreement that was persisting with ecological economists, i.e. the supposed existence of a growth imperative (Cahen-Fourot and Lavoie, 2016; Jackson and Victor, 2015). Other identified the lack of system thinking (Røpke, 2016) and relative silence on the prospects for a global transition in an open economy (Guarini and Porcile, 2016) as critical missing components, precluding the sound assessment of sustainable transformations. In addition, the abandon of (neo)classical conceptions of values to integrate Marx's theory has been suggested in order to provide a valuable alternative to orthodox economics (Pirgmaier, 2021). The most virulent criticism, however, was addressed to the 'green' investments policy type, highlighting the "reductionist, normative, disembodied, ahistorical and depoliticizing vision that is strongly related to its problem-solving framework" (Magalhães, 2021). In other words, assuming that an ecological transition would be feasible on the sole condition of finding the funds to achieve it altogether "fails to discuss critical technical, institutional and ethical dimensions of a socio-ecological transition" (Svartzman et al., 2019). Notable aspects include for example local socio-environmental clashes, the adverse consequences for specific communities or sociological groups, the capture of governments by powerful vested interests, the resurgence of climate-deniers populist movements, rising international geopolitical tensions, etc¹³.

More importantly, the focus on how to increase 'green' investments has led much of the current EM research to disregard an emerging transdisciplinary and alternative literature which suggests a more complex relationship between capitalism's accumulation regimes and the socio-ecological transformations (Svartzman et al., 2019; Althouse, 2022). This strand of work—led notably by the ecology-world approach—has, for example, put into perspective the imperialist appropriation of resources of the countries of the South by the countries of the North, in a neo-colonialist perspective of the world economy (Moore, 2015; Hickel et al., 2022a). An example among others is the appropriation of materials, especially in terms of abiotic resources (fossil fuels and minerals), by France since the industrial revolution, with a behavior similar to that of a parasite (Magalhães et al., 2019). Such drain of resources thus drives the accumulation of capital to the heart of the world system while causing multiple forms of environmental

to witness the multiplication of its related literature, see among others Taylor (2004); Harvey and Garnett (2008); Lee (2009); Goldstein and Hillard (2011); Harcourt and Kriesler (2013); King (2013); Rochon and Rossi (2016); Arestis and Sawyer (2019); Blecker and Setterfield (2019); Toporowski (2020). To date, there is no formal definition of heterodox economics that is commonly agreed upon (Hodgson, 2019) although a set of almost identically shared criteria can differentiate it from orthodox economics (Lavoie, 2022).

¹³Other more technical factors could have been added to the list but are the subject of intense debate among experts, see among others the writings of Diesendorf and Elliston (2018) or Breyer et al. (2022).

degradation at the system's periphery, as well as at least as serious problems of development (poverty, exploitation of populations) and politics (corruption, etc.) (Hornborg, 2010). The driving force behind the productive and social relations of capital becomes the access to easily accessible and inexpensive resources—termed as “cheap Natures” by Patel and Moore (2017), the use of which becomes unbridled because of the disregard and misunderstanding of the consequences (Malm, 2016). The recognition of structural imbalances between the core and the periphery is therefore seen as a prerequisite for developing a global ecological theory of money capable of leading to sustainable changes in the international monetary system (Svartzman and Althouse, 2020; Alves et al., 2022).

What seems to be the greatest oversight in EM, however, is the lack of attention to the singularities of oil, which is at the same time the main source of energy for mass transportation, an input for many side products (chemicals, plastics, fertilizers, etc.), a geopolitical instrument and, above all, an intricate macrofinancial asset. Commodity like no other, the black gold has supported economic growth through adequate supply and affordable prices, and is historically associated with recessions when high oil prices meant an increase in energy expenditures as a share of GDP (Tverberg, 2012; Fizaine and Court, 2016). Indeed, the oil price needs to be high enough to make oil production viable while being low enough for consumers to access oil in a manner that allows economic growth. Yet, increasing oil supply to support economic growth will require high oil prices, that will negatively impact economic growth: this is the ‘economic growth paradox’ (Murphy and Hall, 2011a). That being said, the determinants oil prices and their effects on the economy are complex and subject to various interpretations (Kallis and Sager, 2017). One aspect that remains particularly unexplored is the rise of finance and corporate debt for oil-producing companies, suspected to disconnect the price of oil from its mechanical and energetic properties to allow financial volatility, and/or speculation and/or instability to take hold (Kallis et al., 2009; El-Gamal and Jaffe, 2010; Huber, 2013; Lapavitsas, 2013; Smith-Nonini, 2016). This raises the question of whether the evolution of oil from a catalyst for financial innovation to a tool for speculation since the rise of financialization in the 1970s has played a crucial role in accelerating the transformation of financial crises into economic downturns. (Gkanoutas-Leventis and Nesvetailova, 2015; Auzanneau, 2018).

The ability of EM to realistically represent macro-dynamics is questionable due to insufficient attention to the biophysical foundations of finance-dominated capitalism – and symmetrically from biophysical models to not sufficiently integrate finance. This is particularly troublesome as the “threat of rent extraction in a resource-constrained future” is exacerbated (Stratford, 2020). Yet, this gap has recently been recognized for instance by Victor and Jackson (2020) who, while designing a research agenda for ecological macroeconomics, found that EM have integrated biophysical and non-monetary metrics indicators (ecological footprint, energy return on investment or EROI, planetary boundaries, etc.) as well as materials throughput in a piecemeal fashion. Nieto et al. (2020b) also support this point of view, noting that “supply limits are widely included, but often related to the effects of capital and labor supply on investment and employment, respectively” whereas biophysical constraints are only dealt through natural capital depletion. More recently, Althouse and Svartzman (2022) urged EM to address contemporary challenges by adopting a political view of nature recognizing the crucial role of biophysical processes.

All of these comments are part of a larger context: the infiltration of ecological economics by mainstream ‘environmental’ economists under the guise of epistemological pluralism¹⁴ (Anderson and M’Gonigle, 2012; Nadeau, 2015; Dzeraviahia, 2018; Niu et al., 2022)—which has

¹⁴One of the reasons given by some of the more “radical” or “deep” ecological economists is the traditional view of a steady-state economy, which paves the way for the introduction of the neoclassical equilibrium theory (Pirgmaier, 2017).

been the subject of vigorous debate recently (Spash, 2020), a dedicated book (Costanza et al., 2020) and not one but two special issues in different journals (Farley and Kish, 2021; Kish and Farley, 2021). Diverging views have resulted in a schism with researchers affiliated to biophysical economics, what some considered the foundation of ecological economics (Ji and Luo, 2020; Melgar-Melgar and Hall, 2020), and led to the establishment of the *BioPhysical Economics and Sustainability* journal or the development of sub-groups as *Exergy Economics*. In its current state, the first lessons for EM are structural: it is time to rethink the core of the discipline, still not defined in a consensual manner¹⁵, and to ask whether it can draw on other heterodox schools of thought such as regulationists, Polanyians, New Developmentalism or institutionalism (Chester and Paton, 2013; Guarini and Oreiro, 2022b; Whalen, 2022). Such question also puts in perspective the poorly studied consequences of different tax revenue compositions on the overall fiscal policy of the government (Walker et al., 2021), the proper integration of the post-Keynesian theory of wage and employment¹⁶ (Stagl, 2014; Strunk et al., 2022), the ties of EM with the Modern Monetary Theory (Alves et al., 2022), the redesign of a novel monetary theory—potentially drawing from the ecology of money (Ament, 2019; Larue, 2020)—and the implementation of practical monetary policies as a modern debt jubilee focusing on countries of the South (Keen, 2022; Svartzman, 2022). Working on the monetary side could also pave the way to answering the remaining and core question to what extent does a “post-growth socio-economic system is incompatible with money created in the form of interest-bearing debt” as per the ‘reformist’ approach of EM on the supposed monetary growth imperative (Svartzman et al., 2020). Furthermore, EM needs to address its relative lack of transdisciplinary, and core question: to what extent it could interact with other fields such as design or public and planetary health (Boehnert, 2018; Victor and Jackson, 2020; Brand-Correa et al., 2022). Other insights are practical, and call for a reflection on the actual limits and possible improvements of current models.

1.2.2. FROM THEORY TO PRACTICE: PROGRESS AND GAPS IN THE MODELS

Several models, either framed under the umbrella of ‘ecological macroeconomics models’ (Hardt and O’Neill, 2017; Saes and Romeiro, 2019), ‘ecological macroeconomic models in the Keynesian tradition’ (Ciarli and Savona, 2019), ‘new economics energy transition models’ (Hafner et al., 2020), ‘macroeconomic transition models’ (Sanders et al., 2022) or part of the ‘energy-environment-economy models’ (Pollitt and Mercure, 2017) or ‘integrated assessment models’ (de Blas et al., 2021) investigate the global monetary and biophysical dynamics of the economy, from the perspective of heterodox economics. Relying on previous literature reviews, I assemble in Table 1.1 a list of all of the models that meet, to the best of my knowledge, the following criteria:

- The model is documented in peer-reviewed literature or working papers, and in English language¹⁷.
- The model integrates at least one biophysical constraint to economic growth: carbon emissions, biodiversity loss, availability of energy or raw materials, etc¹⁸.

¹⁵Röpke (2013) has provided the first and, to our knowledge, sole formal tentative of definition of ecological macroeconomics, highlighting that the “contours are still vague”.

¹⁶Defined here as the determinants of employment (aggregate demand) and wages (balance of power/productivity).

¹⁷Bassi and Shilling (2010) and Campiglio et al. (2015) are excluded due to a lack of publicly available information.

¹⁸Barrett (2018) for instance does explore the stability of a zero-growth economy through a Minskyan model but without any biophysical constraint, and is not considered in our analysis.

- The model is heterodox in the sense that it critically proposes an alternative theoretical framework and practical path away from neoclassical equilibrium economics.
- The model is applied, i.e. is somewhat complex. Models with a too limited number of equations are considered too stylized and therefore not included in the literature review.¹⁹

Model	Sources	Scope	Time scale	SFC	AB	SD	ECM	IO
Augier, 2022	Augier et al. (2022)	Global	2015-2100	✓				
Berg, 2015	Berg et al. (2015)	Global	40 units	✓				✓
Briens, 2015	Briens (2015)	National	2010-2060				✓	✓
Carnevali, 2021	Carnevali et al. (2021)	Global	2025-2040	✓				
Dafermos, 2022	Dafermos et al. (2022)	Global	100 units	✓				
Daumas, 2022	Daumas (2022)	Global	2020-2055	✓	✓			
DEFINE	Dafermos et al. (2017, 2018) Dafermos and Nikolaidi (2019, 2021, 2022)	Global	2015-2115	✓				
Deleidi, 2019	Deleidi et al. (2019)	Global	2016-2030	✓				
DiDomenico2021	Di Domenico (2021)	Global	600 units	✓				✓
DSK	Lamperti et al. (2018, 2019, 2020, 2021)	Global	2000-2100	✓	✓			
Dupont, 2021	Dupont et al. (2021a)	Global	2020-2070					✓
Earth4	Dixon-Decleve et al. (2022)	Global	2020-2100			✓		
EETRAP	Sers and Victor (2018) Monasterolo and Raberto (2017, 2018, 2019)	Global	2015-2050			✓		
EIRIN	Dunz et al. (2021a,b); Ranger et al. (2021) Gourdel et al. (2022); Monasterolo et al. (2022)	National	Variable	✓				
ENGAGE	Gerst et al. (2013)	National	2000-2100		✓			
ERRE	Pasqualino and Jones (2020)	Global	2000-2100	✓		✓		
EURACE	Ponta et al. (2018); Raberto et al. (2018)	Europe	100 years	✓	✓			
EUROGREEN	D'Alessandro et al. (2020); Cieplinski et al. (2021)	Europe	2014-2050	✓		✓		
E3ME-FTT-GENIE	Mercure et al. (2018b,a, 2021); Semieniuk et al. (2022)	Global	2020-2060				✓	✓
FALSTAFF	Jackson and Victor (2015)	Global	100 units	✓		✓		
GEMMES	Bovari et al. (2018a,b, 2020)	Global	2016-2300	✓				
GIBM	Hafner et al. (2021a,b)	National	2016-2050			✓		✓
GINFORS	Lutz et al. (2010)	Multiple	to 2050				✓	✓
Gonzalez, 2018	Gonzalez-Redin et al. (2018)	Global	250 units	✓	✓			
HARMONEY	King (2020, 2021)	Global	150 years	✓				
K+S/DSK	Guerrini et al. (2022)	Global	500 units	✓	✓			
LowGrow	Jackson (2020)	National	2017-2067	✓		✓		
MARCO-UK	Sakai et al. (2018)	National	1976-2013				✓	
MEDEAS	Nieto et al. (2020b)	Multiple	2016-2050			✓	✓	✓
Naqvi, 2015	Naqvi (2015)	Europe	100 years	✓				
Naqvi, 2018	Naqvi and Stockhammer (2018)	Global	50 years	✓	✓			
Rezai, 2018	Rezai et al. (2018)	Global	2010-2310				✓	
Safarzyńska, 2017	Safarzyńska and van den Bergh (2017a,b)	National	1000 years	✓	✓			
Safarzyńska, 2023	Safarzyńska et al. (2023)	Global	2010-2150	✓	✓			
SF	van Egmond and de Vries (2020b,a)	National	1950-2050	✓				
SFCIO-IAM	Sers (2022)	Global	2021-2051	✓				✓
SFFS	Barth and Richters (2019)	Global	400 units	✓				
SIGMA	Jackson and Victor (2016)	Global	100 units	✓		✓		
TranSim	Jackson and Jackson (2021)	National	2015-2070	✓				✓
TRansit	Botte et al. (2021)	Global	1500 units	✓	✓			

TABLE 1.1: Ecological heterodox macroeconomic models, in alphabetical order. A check in a column means that the model is of the type: “SFC”=Stock Flow Consistent, “AB”=Agent Based, “SD”=System dynamics, “ECM”=Econometric, “IO”=Input Output. Some models are not explicitly defined as SFC by their authors although they can be categorized as such.

From this screening, 40 models are selected with some being available under multiple versions (DEFINE, DSK, EIRIN, etc.) and the vast majority being fairly recent. This limited number, along with the diversity of approaches in terms of scope and scale, testifies of the still emerging character of this topic. As noted by Svartzman et al. (2019), “a clear focus on [post-Keynesian’s] stock-flow consistent (SFC) models can be identified”. Two aspects, one theoret-

¹⁹This is the case for the models of Victor and Rosenbluth (2007), Fontana and Sawyer (2013), Rezai et al. (2013), Kemp-Benedict (2014), Fontana and Sawyer (2015), Rosenbaum (2015), Cahen-Fourot and Lavoie (2016), Fontana and Sawyer (2016), Guarini and Porcile (2016), Taylor et al. (2016), Kemp-Benedict and Ghosh (2018), Kemp-Benedict (2018), Monserand (2019), Althouse et al. (2020); Guarini (2020), Luis et al. (2020), Guarini and Oreiro (2022a), Hein and Jimenez (2022), Kennedy (2022), Monserand (2022), Passarella (2022) and Oberholzer (2023).

ical and the other practical, explain this predominance. First is the proximity between post-Keynesian and ecological economics principles (Kronenberg, 2010). Second is the convenience and flexibility of SFC models, as they allow the modeler to represent a complex economy in a simplified mathematical framework with the rigor imposed by the closure of stocks and flows (Godley and Lavoie, 2012; Caverzasi and Godin, 2015; Nikiforos and Zezza, 2018). Another trend, more recent, is the combination of SFC models with input-output (I/O) analysis. Both approaches present different advantages, such as a dynamic representation of monetary flows for the first and a better depiction of past resources and energy consumption for the second. Taken together, they might allow for an improved reflection of the real performance of the productive process as well as the capture of “both direct and indirect effects of a variation in final demand on sectoral production” (Nieto et al., 2020b). Their dual use, however, could ultimately alter their own strengths (Hardt and O’Neill, 2017). Indeed, the usefulness of reproducing past trends to project future ones is questioned in economics, unlike hard sciences such as physics, as practices have become increasingly unconventional and the role of financial agents so predominant that it is difficult to compare the international monetary system of the early 90’s to the current one (Rosser, 2015). In this respect, the integration of agent-based modeling seems a more relevant strategy as it could permit to illustrate the intensification of speculative behaviors that has emerged since the financialization of the economy (Caiani et al., 2016; Di Guilmi, 2017), and would, like I/O, better grasp the sectoral dimension of macroeconomic realities (i.e. the specific nature of certain energy and mining sectors).

Another aspect making the study of ecological SFC models—the latter dubbed Eco-SFC as per Carnevali et al. (2019)—of interest is the models’ various degree of heterodoxy. Sawyer (2020) distinguishes ten criteria that differentiate heterodox from orthodox macroeconomics, which I present thereafter in a revisited form. The number in parentheses are used right next to discuss which criteria are taken into account in Eco-SFC models.

1. *Demand-led*: the economic activity is led by the level of aggregate demand, both in the short and long run (1.1). The use of input-output relationships or Leontief’s production function is preferred to mainstream aggregate production functions as Cobb-Douglas or CES (1.2), which assume the substitutability of heterogeneous nature capital in supply-determined growth theories (Sraffa, 1975).
2. *Explicit endogenous money*: money is endogenously created by banks (commercial and central) when loans are issued, within institutional constraints, and is destructed when loans are paid back (Tobin, 1982; Graziani, 2009).
3. *The key role of investment*: investment involves the creation of new productive capital and determines part of the aggregate level of effective demand: thus creating savings and not the other way around (Keynes, 1936).
4. *Distribution-circled growth*: the functional distribution of income affects the level of investment, and as such aggregate demand (Veblen, 1899; Kalecki, 1935; Pasinetti, 1962; Goodwin, 1967; Kaldor, 1961).
5. *Path dependency and hysteresis*: economic growth is a dynamic, path dependent process fixed in ‘historical’ time, i.e. the initial conditions and the path chosen influence the outcome (Robinson, 1962; Kaldor, 1972). There can therefore be no equilibrium between supply and demand.
6. *Socially-driven prices and wages*: prices (6.1) and wages (6.2) are not determined on a competitive market but are rather conditioned by the cost structure of firms and social

and power relationships as embodied, e.g., in the Phillips curve²⁰ (Eichner, 1976; Steindl, 1976; Phillips, 1958).

7. *Inflation as a social relationship*: inflation originates from the distributional conflict between the owners of capital and the workers. Hyperinflation is explained by self-fulfilling prophecies about exchange rate variations and by the rejection of the domestic currency, for example, in a period of inflation and shortages (Arestis and Sawyer, 2005).
8. *Sectoral balances constrain growth*: the government budget is the opposite of the private domestic and foreign sectors so that the sum of all balances equal zero. In an open economy, exchange rates are influenced by the fluctuations of capital movement (Godley and Wray, 2000).
9. *Fluctuations, cycles and crises*: business cycles emerge from the variation in investment and income distribution (9.1), and are influenced by how investment is financed (9.2). In a context of financialization, the behavior of speculative agents—draining debt and capital from the real economy to bet on the secondary market—is even more destabilizing and accelerates the road to a financial crisis (9.3) (Minsky, 2008; Aliber and Kindleberger, 2017). Capitalism is set to transform, eventually fail, due to its inherent cycles and crises (Marx, 1867; Schumpeter, 1962).
10. *Direct public intervention*: the government (10.1) and the central bank (10.2) have the capacity and the responsibility to regulate the economy in order to seek the stability of economic processes and the prosperity of the greatest number of people, while respecting non-human life (Galbraith, 1985; Mazzucato, 2013). There are however political and social factors constraining their action, leading to economic and social forces to converge or conflict (Polanyi, 1944).

Eco-SFC models are not strictly speaking pure heterodox models, i.e. the vast majority do not respect all these criteria as shown in Table 1.2. They do however share a common group of features found in all or nearly all models: 1.1, 2, 3, 5, 8, 9.1 and 9.2. Another group of criteria is taken into account, but less commonly found: 1.2, 4, 6.1, 6.2, 7, 10.1 and 10.2. Only one is virtually disregarded by all but seven models: the drain of capital to the secondary market for speculative purposes. Dunz et al. (2021a); Gourdel et al. (2022) and Monasterolo et al. (2022) model a market where the financial sector can trade bonds and stocks, thereby reducing liquidity for agents, but do not link it to speculative mechanisms. Gonzalez-Redin et al. (2018) introduce speculator-like agents whose function is to amplify asset price changes in different phases of the economy. To do so, they model the price at which firms sell their goods as dependent on household demand, the biomass supply, and a speculation rate. This speculation rate is itself depending on the total produced output and a Ponzi's behavior factor derived from Keen (2009), who himself does not specify the origin of the function or the empirical basis to support it. Pasqualino and Jones (2020) define the market price as the result of the structure of the costs of the companies, the market dynamics between supply and demand and a speculative surplus resulting from the action of the traders. In practical terms, Pasqualino and Jones (2020) use an additional mark-up to the firms' cost structure that they link to the market price volatility. van Egmond and de Vries (2020b,a) estimate that part of the bank loans are used by households for speculative purpose, but confine themselves to the real-estate market.

²⁰The interpretation of the statistical Phillips curve is that the wage-level depends on the relative bargaining power of workers and firms, which, at high unemployment rate, favours the latter. It is different from the Phillips curve used in mainstream economics textbooks which refer to a relation between the change in the rate of inflation and the unemployment rate, and is less justified than the former interpretation (Kriesler and Lavoie, 2007).

Model	Authors	1.1	1.2	2	3	4	5	6.1	6.2	7	8	9.1	9.2	9.3	10.1	10.2
Augier, 2022	Augier et al. (2022)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		≈	≈
Berg, 2015	Berg et al. (2015)	✓	✓	✓	✓	✓	✓	✓			✓		✓		✓	
Carnevali, 2021	Carnevali et al. (2021)	✓		✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓
Dafermos, 2022	Dafermos et al. (2022)	✓			✓	✓	✓				✓				≈	≈
Daumas, 2022	Daumas (2022)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
DEFINE 1.0	Dafermos et al. (2017)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓			
DEFINE 1.0	Dafermos et al. (2018)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
DEFINE 1.1	Dafermos and Nikolaidi (2019)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
DEFINE 1.1	Dafermos and Nikolaidi (2021)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
DEFINE 1.1	Dafermos and Nikolaidi (2022)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
n/a	Deleidi et al. (2019)	✓	✓	✓	✓	✓	✓	≈	✓	≈	✓	✓	✓		✓	≈
n/a	Di Domenico (2021)	✓	✓	✓	✓	✓	✓	✓	✓	≈	✓	✓	✓		✓	✓
DSK	Lamperti et al. (2018)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		≈	≈
DSK	Lamperti et al. (2019)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		≈	≈
DSK	Lamperti et al. (2020)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		≈	≈
DSK	Lamperti et al. (2021)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		≈	≈
EIRIN	Monasterolo and Raberto (2017)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
EIRIN	Monasterolo and Raberto (2018)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
EIRIN	Monasterolo and Raberto (2019)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
EIRIN	Monasterolo et al. (2022)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
EIRIN	Dunz et al. (2021a)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	≈	✓	✓
EIRIN	Dunz et al. (2021b)	✓	✓	✓	✓		✓	✓	≈		✓	✓	✓		✓	
EIRIN	Ranger et al. (2021)	✓	✓	✓	✓		✓	✓	≈		✓	✓	✓		✓	
EIRIN	Gourdel et al. (2022)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	≈	✓	✓
EIRIN	Monasterolo et al. (2022)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	≈	✓	✓
ERRE	Pasqualino and Jones (2020)	≈		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EURACE	Ponta et al. (2018)	✓	≈	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
EURACE	Raberto et al. (2018)	✓	≈	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
EUROGREEN	Cieplinski et al. (2021)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	≈
EUROGREEN	D'Alessandro et al. (2020)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	≈
FALSTAFF	Jackson and Victor (2015)	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
GEMMES	Bovari et al. (2018a)			✓	✓		✓	✓	✓	✓	✓	✓	✓		≈	
GEMMES	Bovari et al. (2018b)			✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	
GEMMES	Bovari et al. (2020)			✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	
Gonzalez, 2018	Gonzalez-Redin et al. (2018)	✓	≈	≈	✓		✓		≈	✓	✓	✓	≈	≈	✓	
HARMONEY 1.0	King (2020)	✓	≈	≈	✓		✓	✓	✓	✓	✓	✓	✓			
HARMONEY 1.1	King (2021)	✓	✓	≈	✓		✓	✓	✓	✓	✓	✓	✓			
K+S/DSK	Guerini et al. (2022)	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		≈	≈
LowGrow	Jackson (2020)	✓	✓	✓	✓		✓		✓		✓	✓	✓		✓	✓
Naqvi, 2015	Naqvi (2015)	✓	✓	✓	✓	✓	✓				✓	✓	✓		✓	✓
Naqvi, 2018	Naqvi and Stockhammer (2018)	✓	✓	✓	✓	✓	✓				✓	✓	✓		✓	✓
Safarzyńska, 2017	Safarzyńska and van den Bergh (2017a)	≈		✓	≈	✓	✓	✓	✓	≈	≈	✓	✓		✓	
Safarzyńska, 2017	Safarzyńska and van den Bergh (2017b)	≈		✓	≈	✓	✓	✓	✓	≈	≈	✓	✓		✓	
Safarzyńska, 2023	Safarzyńska et al. (2023)	≈		✓	≈	✓	✓	✓	✓	≈	≈	✓	✓		✓	
SF	van Egmond and de Vries (2020b)	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	≈	✓	≈
SF	van Egmond and de Vries (2020a)	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	≈	✓	≈
SFCIO-IAM	Sers (2022)	✓	✓	✓	✓		✓	✓			✓	✓	✓		✓	
SFFS	Barth and Richters (2019)	✓		✓			✓				✓	✓	✓		✓	
SIGMA	Jackson and Victor (2016)	✓		✓	✓		✓		✓		✓	✓	✓		✓	
TRansit	Botte et al. (2021)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
TranSim	Jackson and Jackson (2021)	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓			

TABLE 1.2: Presence of the theorized key features of heterodox macroeconomics in Eco-SFC models. A check (resp. wave) indicates that the feature is explicitly (implicitly) considered by the model.

Overall, our analysis highlights that Eco-SFC models are a promising avenue for post Keynesian and Ecological economists to find common ground and establish a synthesis—as already discussed by Kronenberg (2010); Hardt and O'Neill (2017) and more recently Hein (2023). To do so, I however believe that Eco-SFC models need to recognize and overcome the fact that they are part of an emerging area of research with an incomplete degree of heterodoxy and gaps in knowledge. For instance, attempts to model secondary market speculation and its effects are inconclusive at the macro level, and need to be expanded. This observation seems to be shared by some ecological economists, perhaps more heterodox than the post Keynesians and more open to other—even radical—schools of thoughts (Gerber and Steppacher, 2012; Melgar-Melgar and Hall, 2020; Spash, 2020). Yet, another critical aspect seem missing in the current landscape of Eco-SFC models, and could potentially prevent the assessment of transition pathways: an accurate exploration of the energy depletion in the energy production sector.

1.2.3. ENERGY DEPLETION AS THE MISSING PIECE IN THE ECOLOGICAL MACROECONOMICS PUZZLE

A convergence of both ecological and post Keynesian economics is still somewhat impeded by the variety of themes and sectors considered in current models, and especially regarding the energy depletion interactions with the financial and economic systems, as presented in Table 1.3.

First, it is key to note that Eco-SFC models do not have a preferential approach: some deal with one or two themes whereas others adopt an exhaustive view. They overall tend to favor, in descending order of check marks, issues related to financial stability, the energy transition and climate change, and pay less attention to the resource depletion, the conditions for a sustainable economy, inequalities or the role of innovation. Two pairs of themes stand out by regularly being assessed: financial stability-energy transition and financial stability-climate change, i.e. what can be respectively referred to as the transition risks and the physical risks (Semieniuk et al., 2020; Gambhir et al., 2021). The former are less discussed than the latter, both quantitatively and qualitatively, due to the complex characteristics surrounding climate modelization (large uncertainty, non-linearity and endogeneity—see Campiglio et al. 2018; Battiston et al. 2021; Campiglio and van der Ploeg 2022). To remedy this situation, the models either rely on climate damages function *à la* Nordhaus (2014) or are coupled with rather simple carbon cycle models. Catastrophic climate change and tipping points are only, and scarcely, analyzed by Bovari et al. (2020)²¹ whereas there are reasons to believe that it is of critical importance (Kemp et al., 2022).

In a rather surprising way, inequalities appear as a minor focus, with approximately one third of the models dealing with it. This finding echoes the relative poor integration of the post-Keynesian theory of wage and employment in EM models, critical to elaborate fair socio-ecological transition pathways (Stagl, 2014; Strunk et al., 2022). Moreover, a majority of models focuses on the role of the public sector (government or the central bank) in transition scenarios—either to regulate or rescue the financial sector when climate change (Dafermos et al., 2018). Monetary policies are much more represented and evaluated than fiscal policies, and especially conventional ones than unconventional (employer of last resort, quantitative easing, etc.). Other grey areas include, but are not limited to, gender equity and planetary boundaries—e.g. the loss of biodiversity is absent from all the models even though it can be a major source of financial instability (Crona et al., 2021; Svartzman et al., 2021); the same remark applies to other planetary boundaries as well.

Only a fraction of the models dealing with the energy transition also consider resource depletion, while, conversely, models focusing primarily on resource depletion nearly always deal with the energy transition as well. This underscores the interdependence of the energy transition and resource depletion issues and the fact that models ignoring one when discussing the other risk reproducing one of the criticisms that heterodox schools address to the orthodox ones: the lack of consideration for biophysical processes (Hall et al., 2001; Scricciu et al., 2012; Spash and Ryan, 2012; Spash, 2012; Antal and van den Bergh, 2013; Klitgaard, 2013; Boehnert, 2018; Brand-Correa et al., 2022). Going one step further, only the EIRIN model of Dunz et al. (2021a); Gourdel et al. (2022); Monasterolo et al. (2022) and ERRE model of Pasqualino and Jones (2020) integrate an energy or material-producing sector. Importantly, the most advanced Eco-SFC models interested in representing the interrelated dynamics between the energy constraints and the real and financial spheres of the economy are limited. Jackson (2020) are for instance describing a single country, Naqvi (2015) assumes simplistic resources depletion curves,

²¹ Bovari et al. (2020) rely on Dietz and Stern (2015) damage function, of which one of the latest versions has been criticized for not being in accordance with the scientific literature on tipping points²² (Keen et al., 2022), to which the authors replied that the function was a probable lower bound (Dietz et al., 2022).

Model	Version	RD	CC	CS	ET	FS	IQ	IN	DH	G	B	CB	RoW	M
Augier, 2022	Augier et al. (2022)		✓		✓	✓	✓		✓	≈	✓	≈		
Berg, 2015	Berg et al. (2015)			✓					✓	✓	≈			
Carnevali, 2021	Carnevali et al. (2021)	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	
Dafermos, 2022	Dafermos et al. (2022)		✓	✓					✓	✓				✓
Daumas, 2022	Daumas (2022)				✓	✓				✓	✓	✓		✓
DEFINE 1.0	Dafermos et al. (2017)	✓	✓		✓					✓	✓			
DEFINE 1.0	Dafermos et al. (2018)		✓			✓				✓	✓	✓		
DEFINE 1.1	Dafermos and Nikolaidi (2019)	✓	✓		✓	✓				✓	✓	✓		✓
DEFINE 1.1	Dafermos and Nikolaidi (2021)		✓		✓	✓				✓	✓	✓		✓
DEFINE 1.1	Dafermos and Nikolaidi (2022)		✓		✓	✓				✓	✓	✓		✓
Deleidi, 2019	Deleidi et al. (2019)	✓			✓			✓	✓	✓	✓	✓	✓	
DiDomenico, 2021	Di Domenico (2021)			✓	✓	✓				✓	✓	✓		✓
DSK	Lamperti et al. (2018)		✓			✓			✓	≈	✓	≈		
DSK	Lamperti et al. (2019)		✓			✓			✓	≈	✓	≈		
DSK	Lamperti et al. (2020)		✓		✓	✓			✓	≈	✓	≈		
DSK	Lamperti et al. (2021)		✓		✓	✓			✓	≈	✓	≈		
EIRIN	Monasterolo and Raberto (2017)				✓	✓	✓		✓	✓	✓	✓	✓	✓
EIRIN	Monasterolo and Raberto (2018)				✓	✓	✓		✓	✓	✓	✓	✓	✓
EIRIN	Monasterolo and Raberto (2019)				✓	✓	✓		✓	✓	✓	✓	✓	✓
EIRIN	Monasterolo et al. (2022)				✓	✓	✓		✓	✓	✓	✓	✓	✓
EIRIN	Dunz et al. (2021a)		✓		✓	✓				✓	✓	✓		✓
EIRIN	Dunz et al. (2021b)				✓	✓				✓	✓	✓		✓
EIRIN	Ranger et al. (2021)		✓			✓				✓	✓	✓		✓
EIRIN	Gourdel et al. (2022)		✓		✓	✓	✓		✓	✓	✓	✓	✓	✓
EIRIN	Monasterolo et al. (2022)		✓		✓	✓	✓		✓	✓	✓	✓	✓	✓
ERRE	Pasqualino and Jones (2020)	✓	✓		✓	✓	✓			✓	✓			✓
EURACE	Ponta et al. (2018)				✓					✓	✓	✓		✓
EURACE	Raberto et al. (2018)				✓					✓	✓	✓		✓
EUROGREEN	Cieplinski et al. (2021)	✓	✓				✓		✓	✓	✓			
EUROGREEN	D'Alessandro et al. (2020)	✓	✓				✓		✓	✓	✓			
FALSTAFF	Jackson and Victor (2015)			✓						✓	✓	✓		
GEMMES	Bovari et al. (2018a)		✓	✓		✓				✓	✓			
GEMMES	Bovari et al. (2018b)		✓			✓				✓	✓			
GEMMES	Bovari et al. (2020)		✓			✓				✓	✓			
Gonzalez, 2018	Gonzalez-Redin et al. (2018)	✓				✓				✓	✓			
HARMONEY 1.0	King (2020)	✓		✓							✓			
HARMONEY 1.1	King (2021)	✓		✓							✓			
K+S/DSK	Guerini et al. (2022)		✓			✓			✓	≈	✓	≈		
LowGrow	Jackson (2020)			✓						✓	✓	✓	✓	
Naqvi, 2015	Naqvi (2015)	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓
Naqvi, 2018	Naqvi and Stockhammer (2018)							✓	✓	✓	✓			
Safarzyńska, 2017	Safarzyńska and van den Bergh (2017a)				✓	✓	✓		✓	✓	✓			✓
Safarzyńska, 2017	Safarzyńska and van den Bergh (2017b)				✓	✓	✓		✓	✓	✓			✓
Safarzyńska, 2023	Safarzyńska et al. (2023)	✓	✓	✓	✓					✓	✓			✓
SF	van Egmond and de Vries (2020b)			✓		✓			✓	✓	✓			
SF	van Egmond and de Vries (2020a)			✓		✓			✓	✓	✓			
SFCIO-IAM	Sers (2022)	✓	✓	✓	✓					✓	✓			✓
SFFS	Barth and Richters (2019)	✓		✓						✓	✓			
SIGMA	Jackson and Victor (2016)			✓			✓		✓	✓	✓			
TRansit	Botte et al. (2021)				✓	✓	✓	✓	✓		✓			✓
TranSim	Jackson and Jackson (2021)	✓			✓	✓					✓			✓

TABLE 1.3: Themes and sectors of the ecological stock-flow consistent models. A check in a column means that the model treats the theme: “RD”=Resource Depletion, “CC”=Climate Change, “CS”=Conditions for a Sustainable economy, “ET”=Energy Transition, “FS”=Financial Stability, “IQ”=Inequalities, “IN”=Innovation, or is including the sector: “DH”=Differentiated Households, “G”=Government, “B”=Banks, “CB”=Central Bank, “RoW”=Rest of the World, “M”=Multisectorial firms. A wave indicates that the model implicitly includes the sector. Note that, in my opinion, a model should not aim to cover every theme and integrate every sector: the true value of a model lies in what it is able to ignore in order to shed light on, and possibly provide an answer to, a precise pre-identified question.

and others do not consider pivotal financial actors such as the central bank (Berg et al., 2015; Barth and Richters, 2019; Sers, 2022). As such, and in line with Victor and Jackson (2020), I find that current EM models are not well suited to explore the global systemic risks emerging from the interaction between energy, finance and the economy. In other terms, current EM models are only partially able to assess robust transition pathways as they lack an accurate representation of the interactions between the energy production sector with its inherent energy constraints, the real economy, and the financial sphere.

1.3. THESIS OUTLINE AND MAIN CONTRIBUTIONS

1.3.1. RESEARCH GAP, AIM, OBJECTIVES, QUESTIONS

1.3.1.1. RESEARCH GAP

Based on the above literature, the following research gap is identified.

RG: While recent developments in ecological macroeconomic models have paved the way for an alternative to the impasse of neoclassical frameworks, most of them are still not designed to analyze the systemic risks of the energy depletion for wider systems. What's more, when these elements are addressed, it is often by simplistic assessment of the depletion phenomenon and disregarding impacts on the energy transition.

This gap offers an opportunity for the creation of an innovative model of the energy—finance—economy nexus. The proposed model should rely on transparent and physically realistic assumptions, advancing the somewhat simplistic representation of energy depletion in current ecological macroeconomics models. The specifications of such model would be to have stock-flow monetary consistency, state of the art energy depletion estimates, and robust—yet simple—representation of the energy—finance—economy nexus's most important feedback loops and fragile elements.

1.3.1.2. RESEARCH AIM

From this research gap, the following aim was set:

RA: The aim of the thesis is to understand the processes and consequences of systemic risks emerging from reaching limits, exemplified by the rising energy costs of extraction associated with the depletion of quality fossil fuels and the high capital intensity of renewable energies.

It is however important to recall that the goal is not to produce a very detailed model, which could not be achieved in the time horizon envisaged for this work, and which would in any case be counterproductive in terms of systemic analysis. produce a manageable level of model complexity, both in terms of model development and results analysis.

1.3.1.3. RESEARCH OBJECTIVES AND QUESTIONS

The first objective of the thesis is to analyze the energy depletion of modern economies, with a particular focus on oil liquids and fossil gas. The related research question and sub-research questions follow:

RQ 1: How does long-term resource depletion impact the production of energy?

- RQ 1.1: To what extent the net-energy supply of oil and gas is affected by the use of lower quality energy sources?
- RQ 1.2: What are the effects of resource depletion on the material requirements and associated CO₂ emissions of the hydrocarbon industry?

The second objective of the thesis is to characterize the macroeconomic consequences of the previously determined energy constraints for ecological macroeconomic models. The related research question and sub-research questions follow:

RQ 2: How can macroeconomic modeling take account of energy constraints?

- RQ 1.1: What are the economic consequences of an energy transition scenario compatible with the 1.5°C target of the Paris Agreement?
- RQ 1.2: How can the emerging consensus on energy constraints can pave the way towards improved Integrated Assessment Modeling?

1.3.2. STRUCTURE OF THE THESIS, ARTICLES LIST AND CONTRIBUTIONS

1.3.2.1. STRUCTURE

Chapter 1 is the present introduction. Chapter 2 and Chapter 3 answer the research questions RQ 1 and RQ 2, respectively. Chapter 4 concludes.

1.3.2.2. ARTICLES LIST AND CONTRIBUTIONS

Section 2.1 relies on the published article Delannoy, L., Longaretti, P.-Y., Murphy, D. J., and Prados, E. Peak oil and the low-carbon energy transition: A net-energy perspective. *Applied Energy*, 304:117843, 2021b. doi:10.1016/j.apenergy.2021.117843. This research was led by Louis Delannoy, in charge of the Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing.

Section 2.2 relies on the published article Delannoy, L., Longaretti, P.-Y., Murphy, D. J., and Prados, E. Assessing global long-term EROI of gas: A net-energy perspective on the energy transition. *Energies*, 14(16):5112, 2021a. doi:10.3390/en14165112. This research was led by Louis Delannoy, in charge of the Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing.

Section 2.3 relies on the published article Le Boulzec, H., Delannoy, L., Andrieu, B., Verzier, F., Vidal, O., and Mathy, S. Dynamic modeling of global fossil fuel infrastructure and materials needs: Overcoming a lack of available data. *Applied Energy*, 326:119871, 2022. doi:10.1016/j.apenergy.2022.1

Louis Delannoy was in charge of the Conceptualization, Writing – original draft, Writing – review & editing.

Section 3.1 relies on the published article Jacques, P., Delannoy, L., Andrieu, B., Yilmaz, D., Jeanmart, H., and Godin, A. Assessing the economic consequences of an energy transition through a biophysical stock-flow consistent model. *Ecological Economics*, 209:107832, 2023. doi:10.1016/j.ecolecon.2023.107832. Louis Delannoy was in charge of the Methodology, Data Curation, Formal analysis, Writing – original draft, Writing – review & editing.

Section 3.2 relies on the submitted article Delannoy, L., Auzanneau, M., Andrieu, B., Vidal, O., Longaretti, P.-Y., Prados, E., Murphy, D., Bentley, R., Carbajales-Dale, M., Raugé, M., Höök, M., Court, V., King, C., Fizaine, F., Jacques, P., Heun, M., Jackson, A., Guay-Boutet, C., Aramendia, E., Wang, J., Le Boulzec, H., and Hall, C. Emerging consensus on net energy paves the way for improved integrated assessment modeling. *Submitted to Energy and Environmental Science*, 2023a. This research was led by Louis Delannoy, in charge of the Conceptualization, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration.

The Annex relies on the published article Andrieu, B., Vidal, O., Le Boulzec, H., Delannoy, L., and Verzier, F. Energy intensity of final consumption: the richer, the poorer the efficiency. *Environmental Science & Technology*, 56(19):13909–13919, 2022b. doi:10.1021/acs.est.2c03462. Louis Delannoy was in charge of Writing - Review & Editing, Validation.

CHAPTER 2

ENERGY CONSTRAINTS OF MODERN ECONOMIES

Growth chestnuts have to be placed on the unyielding anvil of biophysical realities and then crushed with the hammer of moral argument.

Herman E. Daly

This chapter presents three studies that advance the understanding of energy constraints of modern economies, especially relating to the resources depletion of oil and gas:

- The first article analyzes the extent to which the net-energy supply of oil products is affected by the use of lower quality energy sources. Its novelty resides in the incorporation of standard EROI (energy-return-on-investment) estimates and dynamic decline functions in the GlobalShift all-liquids bottom-up model, from 1950 to 2050. In doing so, we estimate the energy equivalent needed by the oil industry to drill and extract its products at 15.5% of current production and 50% in 2050 due to the progressive depletion of high-quality reserves.
- The second article adopts a similar approach but analyzes gas, and estimates the energy needed to extract it at 6.7% of current production, and 23.7% for 2050.
- The third article presents a dynamic model of the global fossil fuels infrastructures and materials requirements for each segment of the supply chain, as well as the embedded energy and CO₂ emissions from 1950 to 2050.

2.1. NET ENERGY EXTRACTION FROM OIL LIQUIDS

Delannoy, L., Longaretti, P.-Y., Murphy, D. J., and Prados, E. Peak oil and the low-carbon energy transition: A net-energy perspective. *Applied Energy*, 304:117843, 2021b. doi:10.1016/j.apenergy.2021.117843

ABSTRACT

Since the Pennsylvania oil rush of 1859, petroleum has quickly become the dominant fuel of industrial society. The “Peak Oil” debate focused on whether or not there was an impending production crunch of cheap oil, and whilst there have been no shortages across the globe, a shift from conventional to unconventional oil liquids has occurred. One aspect of this shift was not fully explored in previous discussions—although of some importance in a low-carbon energy transition context: the extent to which the net-energy supply of oil products is affected by the use of lower quality energy sources. To fill this gap, this paper incorporates standard EROI (energy-return-on-investment) estimates and dynamic decline functions in the GlobalShift all-liquids bottom-up model on a global scale. We determine the energy necessary for the production of oil liquids (including direct and indirect energy costs) to represent today 15.5% of the energy production of oil liquids, and growing at an exponential rate: by 2050, a proportion equivalent to half of the gross energy output will be engulfed in its own production. Our findings thus question the feasibility of a global and fast low-carbon energy transition. We therefore suggest an urgent return of the peak oil debate, but including net-energy issues and avoiding a narrow focus on ‘peak supply’ vs ‘peak demand’.

2.1.1. INTRODUCTION

Today, oil is a critical supply chain component for 90% of all industrially manufactured products (Michaux, 2019); as such, it is the backbone of industrial civilization. Its large range of strategic advantages (liquid state, high energy density, numerous applications, etc.) have driven its ever-escalating search and use during the past century. This gargantuan intake not only leveraged our societal development as efficient and powerful machines—conceptualized as energy slaves by Fuller (1940)—were continuously added to the total workforce, but also generated a thirst for oil. The ‘black gold’ now represents one third of the world’s primary energy consumption (BP, 2020). At the interface of geopolitical, economic, social and climatic challenges, oil is essential to the globalized world but in the meantime endangers the planet’s life supporting functions: this is the oil paradox (Sandalow, 2007). Yet, another worrying risk has raised concerns due to the non-renewable nature of oil: its possible contraction as a cheaply extractable energy source which could mark a civilization transformation (Holdren, 2006).

Such a possibility was the subject of an intense discussion during the 2000s, but has since lost academic and political interest. It is in part due to the shale revolution that led the United States

to a new all-time production record. The debate seemed closed until the International Energy Agency (IEA) warned in 2018 of the likelihood of a coming production crunch (IEA, 2018), previously glimpsed at by Fustier et al. (2016). The Coronavirus oil consumption plunge and the subsequent oil prices war between Saudi Arabia and Russia have now put this issue back on the agenda, notably for regions dependent on oil imports such as the EU (The Shift Project, 2020, 2021). As a matter of fact, the number of organizations who envisage global oil demand to peak in the next ten to fifteen years has kept on growing to include energy research groups (Bernstein Energy, BloombergNEF), consulting firms (McKinsey), oil majors (BP, Equinor, Total) and oil intelligence companies (Rystad Energy, GlobalShift, Wood Mackenzie) (Tupaz, 2020).

However, forecasts have for long been confined to a gross energy view and paid little attention to the net-energy, i.e. the energy available after accounting for the cost of its acquisition, usually inclusive of extraction, refinement and delivery. Sticking to the sole gross energy perspective becomes preoccupying as unconventional¹ oil liquids are continuously replacing higher quality conventional ones, and an energy-intensive transition to low-carbon energy sources is needed. However, the fact that changes in resource quality affect the long-term amount of net-energy of oil liquids at global scale has only been discussed and partially analyzed (the relevant literature is reviewed in Section 'Methods'). This study attempts to explore this question and fill the literature gap that exists today. To do so, this article incorporates standard EROI (energy-return-on-investment: ratio of usable energy acquired from a given source of energy to the amount of energy expended to obtain that energy) estimates and dynamic decline functions in the GlobalShift all-liquids bottom-up model at global scale, from 1950 to 2050.

This paper is structured as follows. Section 'Literature review' retraces the peak oil debate history, setting the political and scientific aspects of the dispute. Section 'Methods' describes the chosen Energy Analysis (EA) perspective, the developed methodology and the data used. Section 'Results' presents the results, section 'Discussion' discusses them and section 'Conclusion' draws conclusions.

2.1.2. LITERATURE REVIEW

On the 8th of March 1956, Shell geophysicist Marion King Hubbert presented the results of his latest research at the spring meeting of the Southern District of the American Petroleum Institute (API) in San Antonio, Texas. By compiling past discoveries, production levels and future discovery predictions of the 48 U.S. lower states (excluding Alaska and Hawaii), Hubbert modeled the country's conventional oil production as a bell-shaped curve with the intuition that if individual fields follow such trends, the aggregation at a larger scale from an individual region to the planet as a whole, would produce a similar type of curve (Hubbert, 1956). His results led Hubbert to claim that the country was nearing the extraction of half of its recoverable petroleum resources and that the maximum production level or 'peak' would occur within a few years given the estimate made for the reserves: 1965 for 150 billion barrels and 1970 for 200. More importantly, he warned that the after-peak period would see a permanent decrease of about 5–10% a year.

This position was in contrast to the common belief in cheap oil abundance shared by his contemporaries and would not go without creating conflict, as portrayed by the intense confrontation with USGS (United States Geological Survey) director Vincent McKelvey (Priest,

¹The oil industry identifies two categories of hydrocarbon deposits: conventional and unconventional resources. The distinction between the two types is rooted in the difficulty in extracting and producing the resource, however, there is no consensus as where to draw the line between the two, as it depends on either economic or geological issues (Graefe, 2009).

2014). As years passed, the statistical verification of Hubbert's claims made his theory gain recognition: oil production in the lower 48 states did reach its height in 1970 and declined each year thereafter². The 1970s energy crisis—symbolized by 1973 and 1979 oil crises—pushed the debate into the public domain. Galvanized by his work and strong personality, believers in the peak theory saw in Hubbert a prominent father-like figure (Inman, 2016) whose technocratic political ties exacerbated attention to the debate (Hemmingsen, 2010). It led to a point where the dispute can be seen as the first block of the modern discussion on resources scarcity breached by the Club of Rome "Limits to Growth" report of Meadows et al. (1972) (Hall and Day, 2009). As a result of the general optimism following the collapse in oil prices after the 1980s OPEC quota war, cheap oil production's fate has slowly been put aside. It is only when two long-time oil experts, Colin Campbell and Jean Laherrère, published in 1998 "The End of Cheap Oil" that this issue was brought back on the agenda (Campbell and Laherrère, 1998).

Campbell and Laherrère relied on Hubbert's work and on the PetroConsultants (now IHS Markit) dataset to update the curves on a global scale and warned about the coming peak for conventional oils expecting it to take place around 2005. The term "peak oil"³ was later coined by Colin Campbell in 2000 and popularized in 2001 as the Association for the Study of Peak Oil and Gas (ASPO) was established with the purpose to raise the issue of cheap oil future scarcity. The formation of a dedicated entity, the statistical validation of their claim⁴ combined with the 2007-08 financial crisis—expected to partly result from the oil production incapability to increase (Hamilton, 2012)—exposed once again the question of cheap oil production decline to the world. Books were published⁵, bets were placed, documentaries were screened and articles flourished in scientific journals and on specialized websites such as the now defunct "TheOilDrum" forum to altogether form a vibrant community (Campbell, 2003; Bridge, 2010; Campbell, 2012). Governments themselves seized the matter in a direct—the Belgian Walloon parliament created a "peak oil committee"—or indirect form—reports were commissioned by the British Department of Energy in concert with the Bank of England and the Department of Defense (Michaux, 2019), as well as the U.S. Department of Energy (Hirsch, 2007). Military affiliated institutions, for instance in the U.S. (Parthemore and Nagl, 2010) or Germany (BTC, 2010), and private industries (e.g. the U.K. Industry Task-Force on Peak Oil and Energy Security) also took on the issue.

Oil production models have come to dominate the debate as stakeholders were engaged in a race to guess the peak date. Modeling techniques became the epicenter of the attention⁶ and a myriad of forecasts appeared, ranging from short-term peak, a plateau with possible undulations to long-term or no peak (Sorrell et al., 2010a; Brandt, 2010; Hughes and Rudolph, 2011; Foucher, 2013; Chapman, 2014; Jackson and Smith, 2014; Andrews and Udall, 2015). At some point, it became clear to a number of experts that the time of cheap abundant oil—coined as the first half of the age of oil by Campbell (2015b)—was coming to an end (Greene et al., 2006; Bentley and Boyle, 2008; Salameh, 2008; Rhodes, 2008; Tsoskounoglou et al., 2008; Kjærstad and Johnsson, 2009; Sorrell et al., 2009, 2010b, 2012; Criqui, 2013). Yet, the debate was still raging as misconceptions on oil formation (Tsatskin and Balaban, 2008; Höök et al., 2010), the proper definition and use of reserves (Bentley et al., 2007; Campbell and Gilbert, 2017), the economic aspect of oil (Watkins, 2006; Bentley, 2016), the difference between flow and stock notions

²If the 1970 peak magnitude was nearly 20 percent above Hubbert's high peak prediction, the trends soon caught up with the forecast and only started to drift apart in the early 2000's.

³Peak oil designates the theorized point in time when the maximum rate of extraction of petroleum is reached.

⁴The IEA 2010, 2012 and 2018 reports conceded that the conventional oil peak occurred around 2005-2008 (IEA, 2010a, 2012, 2018).

⁵Among others: Goodstein (2004); Heinberg (2005); Simmons (2006); Clarke (2009); Deffeyes (2009); Ruppert and Campbell (2010).

⁶This sub-debate is still active today. See: Houthakker (2002); Cavallo (2004); Brandt (2007); Holland (2008); Brandt (2010); Reynes et al. (2010); Giraud (2011); Reynolds and Baek (2012); Brecha (2012); Smith (2012); Wang and Feng (2016); Peebles (2017); Jones and Willms (2018); Reynolds (2020).

(Jakobsson et al., 2012), the variability in ultimate recoverable resources estimates (McGlade, 2012) or even the statistical definition of peak oil (Warrilow, 2015) obscured the discussion and created a certain cacophony. These confusions polarized the debate between two radical camps⁷: late or no peak advocates and early peak defenders (so called "peak-oilers") (Chapman, 2014). The latter were cartooned as prophets of doom, Cassandras, catastrophists, fantasists or "chimeras without substance" (Maugeri, 2004; Smil, 2006; Radetzki, 2010; Mann, 2015; Tracy, 2016) though some arguments of the critics have been demonstrated as fallacious (Meng and Bentley, 2008; Brecha, 2013). This however, did not prevent some projections from being too pessimistic. Personal convictions held an important place in the debate too as the discussion was flooded with political ties, private interests and data retention (Bardi, 2009; Atkinson, 2010). Unprecedented clashes took place which meant that—intentionally or not—the two groups did not find common ground to communicate effectively, possibly also due to the challenges surrounding the 'black gold' or the dramatic scenarios once evoked. It altogether hampered the sound development of a systemic political debate (Hemmingsen, 2010; Becken, 2014), which could have tremendous effects if cheap oil production peaks before our society is prepared for it (Hanlon and McCartney, 2008; Frumkin et al., 2009; Curtis, 2009; Korowicz, 2010; Woods et al., 2010; de Almeida and Silva, 2011; Neff et al., 2011; Murphy and Hall, 2011b,a; Lutz et al., 2012; Tverberg, 2012; Bentley et al., 2020).

Accelerating in the 2010s, the Shale Revolution—i.e. the production of oil from unconventional resources and especially American tight oil—marked a turning point in the debate in addition to having crucial economic and geopolitical consequences at the global scale (Auping et al., 2016). Such a production boom can be explained by a unique⁸ and fertile environment: important resources, an hydrocarbon policy which allows the land-owner to possess what lies underneath his estate, a large infrastructure network facilitating the oil and gas sectors expansion, the most important fleet of rigs in the world, the possibility to quickly train qualified oil engineers (thanks to more than one hundred years of practice), direct access to the biggest market worldwide and the connection to an unbridled speculative debt system. Furthermore, it was facilitated by specific triggering components: financial regulations prompted oil majors to invest in shale companies⁹, progress made in horizontal drilling and hydraulic fracturing technologies was significant (Aguilera and Radetzki, 2013; Kim and Lee, 2020) and the shale gas industry was heavily supported by the government for the U.S. to become once again energy self-sufficient (Trembath et al., 2012; Maugeri, 2013; Wang and Krupnick, 2013; Reynolds and Umekwe, 2019). If this boom longevity was questioned since its onset (Hugues, 2013, 2014; Heinberg, 2014), oil production curves still diverged from existing projections, partly because unconventional oil supplies were not previously considered as a viable mitigation strategy and thus were not included in the projections of oil availability (de Castro et al., 2009; Brecha, 2012).

What appeared as a statistical invalidation of peak oil without being strictly so¹⁰, marked a gradual quietening of the debate, symbolized by TheOilDrum closure in 2013, the drop in influence of ASPO, and the reduction in references to this issue in the scientific and public spheres. This loss of interest was furthermore amplified by a number of factors: the loss of fa-

⁷Reducing the peak oil debate to two opposing sides is misleading: a wide spectrum of positions has been observed which can more realistically be attributed to five groups: extreme optimist, optimist, moderate, pessimist, and extreme pessimist (Long, 2018).

⁸The Shale Revolution seems difficult to replicate elsewhere, at least with a similar pace and magnitude (Salameh, 2013; Saussay, 2018; Salygin et al., 2019).

⁹By extending the definition of reserves in 2010, the American Securities and Exchange Commission (SEC) allowed shale companies to overestimate their reserves, making them attractive for major companies (Exxon, Total, Equinor, CNOOC, etc.) that were lacking new discoveries to compensate for their production (Hall and Ramírez-Pascualli, 2013).

¹⁰It is postulated that there can be several 'resource-limited' production maxima of a field or region (Bentley, 2016), leading to model energy sources production through the Multicyclic Hubbert curve or "cycle jumping" technique at global (Nashawi et al., 2010; Wang et al., 2011; Maggio and Cacciola, 2012) or regional scales (Ebrahimi and Ghasabani, 2015; Wang et al., 2016) with varying accuracy (Anderson and Conder, 2011; Tunnell et al., 2020).

mous peak oilers (Matthew Simmons, C. Michael Ruppert, Kenneth S. Deffeyes, etc.), the presence of few extreme positions (Schneider-Mayerson, 2015), an absence of political proposals, a focus on climate change regulation and a fundamental "clash of absolutes" with the mainstream belief in abundance and unlimited technological progress (Bardi, 2019). The establishment of a dedicated journal in 2015 (*The Oil Age*, terminated in 2017) and a special issue outlined in the *Philosophical Transactions of the Royal Society* (Miller and Sorrell, 2014) failed to turn the tide: the peak oil debate shrank to its core authors. The last books (to date) of famous peak oilers (Alekklett, 2012; Campbell, 2013; Bentley, 2016), aiming to provide the next generation with strong scientific grounds for peak oil theory and debate, had finally come to look like a swan song. And while a raft of modelers raised the issue of net-energy reduction due to the transition in quality from conventional to unconventional oil liquids, they were in majority mocked by the public and their work qualified as "overlooked myth" (Lacalle, 2011) or "a nonsense" (Worstell, 2011). This rejection further degraded the scientific relevance of peak oil in the eyes of the public at large and amplified the split with energy scientists who detected in net-energy decrease a real and under-recognized risk (Kreps, 2020; The Pivot Group, 2021).

The mid 2010s finally saw the emergence of the "peak demand" hypothesis which argues that peak oil will be driven by technological developments and policies of carbon dioxide emissions reduction (Kjärstad and Johnsson, 2009; Verbruggen and Marchohi, 2010; Verbruggen and de Graaf, 2013; Höök and Tang, 2013; Dale and Fattouh, 2018). However, the resource-limited peak theory has recently regained importance as the ability of the tight oil industry to double or triple its production (seen as a vital constraint to avoid a supply crunch by 2025 by the IEA in 2018) has been questioned based on economic and geological arguments (Fustier et al., 2016; Rhodes, 2017; Hacquard et al., 2019; Hugues, 2019). Moreover, the 2020 Coronavirus oil consumption plunge and subsequent price war between Saudi Arabia and Russia have strongly undermined the industry capability to quickly recover pre-crisis production levels (Laherrère, 2020a; Nicola et al., 2020). The issue of net-energy from oil liquids in a context of transition to low-carbon energy sources seems thus timely and definitely requires more urgent attention than it currently receives.

2.1.3. MATERIALS AND METHODS

Energy analysis (EA) places the finiteness of the Earth's resources at the heart of its approach. It holds its roots in biophysical economics that sees human societies as thermodynamic or metabolic dissipative systems collecting high quality primary energy before converting it in part as useful energy and rejecting the rest as low-quality energy in the surrounding environment (Georgescu-Roegen, 1971; Odum, 1971; Daly, 1977; Cleveland et al., 1984). Societies evolve and become more complex, thus requiring more and more energy¹¹ which in turn drives complexity growth and so on (Tainter, 1988). EA distinguishes two problems that arise from this way of working. The first is the finite stock of non renewable energy sources: energy extraction rates first grow, reach a peak (precluding further growth driven by this energy source) and decrease, making it in fact a flow issue. The second is the quality of the energy sources, as "humans like most other biological organisms use the highest quality, richest and easiest to obtain resources first" (Martenson, 2014), a concept also known as the "First Best Principle". Both effects combine meaning that at some point societies face diminishing energy sources returns that

¹¹ From this point of view, the society is an "exo-somatic metabolism" which along its evolution, moves off a hunter-gatherer system to let the share of its overall energy consumption required for non-primary biological needs (i.e., for its exo-somatic metabolism) grow in comparison to the share used for the primary biological needs of its people (i.e., for its endo-somatic metabolism) (Raugei and Leccisi, 2016).

push them into an even greater energy quest¹² which, if not fulfilled, can potentially lead them to societal "collapses" characterized by a complexity drop¹³. Economic growth and comfort are not only questioned by lower qualitative and quantitative energy inputs (Ayres and Warr, 2009; Kümmel, 2011; Ayres and Voudouris, 2014; Smil, 2017) but the entire globalized civilization in its present form is at risk of first-order structural perturbations, some of which possibly coming from adverse effects due to induced environmental degradation as climate change. From this perspective, we argue that the one way to perceive systemic risks is to see these through the net-energy prism¹⁴.

Coined in the early 1970s, a derived conceptual framework of the EA discipline known as the Net-Energy Analysis (NEA) allows us to characterize to what extent an energy source constitutes a net-source or a sink for society given the amount of energy required to obtain and deliver useful energy (Murphy, 2014). In other terms, it assesses the energy surplus (also called net-energy gain or NEG) of an energy source, if any. To do so, the NEA firstly sets the boundaries of the studied system, computes the energy provided by the resource at the final stage boundary and subtracts the required energy to make it happen. The NEA methodology translates into:

$$\text{Net energy} = \text{Gross energy} - \text{Energy req. to deliver energy} \quad (2.1)$$

The energy required to deliver energy can be constructed using net-energy indicators, of which a large array exists (Brandt and Dale, 2011; Rana et al., 2020). The most widely known and used is the energy return on (energy) investment EROI or EROEI (Hall, 1972), which can be understood as:

$$\text{EROI} = \frac{\text{Energy delivered}}{\text{Energy req. to deliver energy}} \quad (2.2)$$

Assuming the energy delivered equals the gross energy:

$$\text{Net energy} = \text{Gross energy} \times \left(1 - \frac{1}{\text{EROI}}\right) \quad (2.3)$$

Despite the equations being simple and conceptually elegant, they have proved to be at the source of theoretical and practical difficulties, and EROI in particular is a controversial concept (Hall, 2017). Nevertheless, EROI estimates have been carried out along the years from numerous authors all coming to the same conclusion: unconventional fossil fuel EROI are lower than conventional ones, themselves declining (Murphy and Hall, 2010; Gupta and Hall, 2011; Dale et al., 2012a; Hall et al., 2014; Murphy, 2014; Hall, 2016).

If Hubbert was the first to point out the importance of self-use energy for future global oil supply¹⁵, Murphy (2009) has been the first to conceptualize it under the umbrella of a net Hubbert curve as a back-of-the-envelope calculation. Soon afterwards, Gagnon et al. (2009) assessed for the first time the global oil and gas EROI at the wellhead between 1992 and 2006, based on estimates of energy inputs derived from monetary expenditures of publicly traded companies. After theorizing dynamic functions for EROI (including extraction and processing) (Dale et al., 2011b), Dale et al. (2011a) applied EROI estimates and the previously-mentioned decline

¹²This process is sometimes referred to as the Red Queen effect (Van Valen, 1973; Giraud, 2019), who in Lewis Carroll's "Alice's Adventures in Wonderland" sequel "Through the Looking-Glass" explains to Alice that the faster they run, the more they will need in the coming second to run even faster to stay put.

¹³We follow Tainter's definition of collapse, but the definition of collapse varies from author to author (Middleton, 2019).

¹⁴Strictly speaking, "net-energy" also encompasses the net-energy per unit time i.e. the net-power prism (Odum, 1973; Hall and Klitgaard, 2011).

¹⁵"However, there is a different and more fundamental cost [to oil production] that is independent of monetary price. That is the energy cost of exploration and production. So long as oil is used as a source of energy, when the energy cost of recovering a barrel of oil becomes greater than the energy content of the oil, production will cease no matter what the monetary price may be." (Hubbert, 1982).

functions to different past and future projections for conventional oil. Bentley (2015) has later taken up the subject as a tutorial exercise for students. Campbell (2015a) also incorporated net-energy ratios in his oil and gas forecast model while acknowledging that "input data are far from reliable and there are many places where estimates—and even guesses—are needed", which could be explained by the lower amount of reliable EROI studies and data at that time. On a global level but with a selected pool of oilfields, Brandt et al. (2015a) determined static net-energy returns through an engineering-based model. In the same vein, Tripathi and Brandt (2017) and Masnadi and Brandt (2017) analyzed historical trends of energetic productivity respectively for five large and twenty five super-giant oil fields. Modifying Dale et al. (2011b) dynamic functions, Court and Fizaine (2017) estimated the long-term EROI estimates for coal, oil, and gas global productions but were not interested in net-energy projections. Lamorlette (2020) proposed a prey-predatory model of oil production incorporating extreme parameters in line with Hill (2015) and "most pessimistic calculation in term of remaining liquid fuel" which, in all likelihood, can be called unrealistic. Solé et al. (2018) have dealt with the subject in the most detailed way to date, by applying EROI estimates and associated decline functions to oil liquids at global scale as a starting point to discuss the feasibility of a Renewable Transition (RT). Yet, four points seem particularly critical in their study:

- the authors make use of more than conservative and optimistic IEA oil supply projections that are reasonably questionable at best (Jakobsson et al., 2009; Wachtmeister et al., 2018);
- the projections date from 2014, when the Shale Revolution was only beginning, thus lowering the forecast's reliability;
- EROI estimates are disputable: some quantities are badly or arbitrarily chosen, the system boundaries are not specified;
- the sensitivity of the results against EROI scenarios is not assessed. Coeytaux (2019) explored this topic as a blog post and estimated the net-energy peak to occur 2 years in advance.

Several studies of EROI and net-energy yield for oil have been conducted on a national scale. Cleveland et al. (1984) were the first to estimate the U.S. net-energy yield from oil production. Cleveland (2005) extended this work by discussing the overall pattern of oil production and attached EROI from 1954 to 1997. Gately (2007) modeled the EROI and net-energy output of offshore oil in the gulf of Mexico. Brandt (2011) explored California net oil production from 1955 to 2005. Guilford et al. (2011) assessed the long term EROI for U.S. oil and gas including discovery and production. Safronov and Sokolov (2014) studied crude and light oil products in Russia. Subsequently, the focus of studies on oil EROI has been oriented towards China, as energy security concerns have escalated. Hu et al. (2011) began by analyzing the EROI of the Daqing oil field. Hu et al. (2013) used a multi-cyclic generalized model and a linear trend extrapolation method to predict the EROI of conventional fossil fuels. Kong et al. (2016a) studied the standard EROI of oil and gas from 1996 to 2015. Wang et al. (2017a) reviewed the physical fossil fuels supply and associated EROI. Kong et al. (2018b) analyzed EROI for oil and gas exploration and light oil products. Kong et al. (2018a) calculated the net-energy impact of substituting imported oil with coal-to-liquid from a life-cycle perspective. Feng et al. (2018a) approached point-of-use EROI of fossil fuels using a dynamic function for projections and subsequently determined the future net-energy yield from 1996 to 2030. Feng et al. (2018b) followed by simulating economic Gross Domestic Product (GDP) trends in China using net-energy production function. Cheng et al. (2018) calculated EROI time series of onshore and

offshore domestic oil and gas. In Iran, Salehi et al. (2020) studied the evolution of oil and gas EROI.

Other notable works exist in the domain but attach more importance to how EROIs affect the global energy transition. García-Olivares et al. (2012) proposed a global renewable energy mix under two limiting factors: materials availability and EROI. Fizaine and Court (2015) investigated how energy requirement associated with metal extraction could impact the energy-return-on-investment (EROI) of different renewable and nuclear technologies. Based on Csala (2016), Sgouridis et al. (2016) modeled feasible transition pathways to achieve different net-energy levels. King and van den Bergh (2018) addressed the implications of energy-return-on-investment for a low-carbon energy transition that limits potential climate change to 2°C. Vidal et al. (2018) described the material and energy costs associated with three different scenarios of a low-carbon energy transition. Rye and Jackson (2018) reviewed EROI system dynamics models. Manjong (2018) determined net-energy transition for Ghana, employing EROI dynamical evolution as a function of technological progression and resource quality. Brockway et al. (2019) estimated the global primary and final stage EROI ratios of fossil fuels, which could serve as the basis of a net-energy analysis, on a limited time-frame (1995–2011) but with an acclaimed rigor (Carbajales-Dale, 2019). White and Kramer (2019) explored possible forward projections of EROI in a non-scarce-energy future. Diesendorf and Wiedmann (2020) discussed the EROI aspects of a large scale transition to renewable sources for electricity supply, considering storage. Based on the WoLim model (Capellán-Pérez et al., 2014), Capellán-Pérez et al. (2019) assessed the net-energy and material investments necessary for a transition to renewable energies. They pursued by developing the integrated assessment model MEDEAS, which combines global biophysical and socioeconomic constraints relying on dynamic EROIs (Capellán-Pérez et al., 2020; Solé et al., 2020). Finally, Jackson and Jackson (2021) modeled the economic and financial impacts of declining energy return on investment in the energy transition. In addition to this literature, various works on net-energy ratios of specific energies appeared (Rana et al., 2020).

In summary and although being called out for more than a decade, researchers have to date and to the best of the authors' knowledge not explored in sufficient detail the impact of declining EROIs on the net-energy production of oil liquids on a global scale and in a long-term perspective. This study attempts to explore this question and fill the literature gap that exists today. To do so, the following three stages methodology is carried out.

First of all, a model presenting extended past and future production of oil liquids is chosen on the basis of a number of inclusion criteria. Secondly, conversion factors are applied to oil production volumes to quantify the gross energy of all liquids. Thirdly, EROIs scenarios are constructed relying on literature-based EROI estimates and decline functions for each type of oil. Net-energy curves can finally be computed and the sensitivity of the results to the developed EROI scenarios can be assessed.

2.1.3.1. OIL PRODUCTION MODELS SELECTION

Identified oil supply models have been evaluated according to eight criteria:

1. Language: either French or English;
2. Scale: global, i.e. covering the entire world;
3. Age: published after 2015 given the Shale Revolution importance;
4. Scope: all oil liquids are included to cope with a systemic perspective;

5. Granularity: production is subdivided per oil liquid;
6. Time coverage: the model provides with past and future oil production (at least 2050 and beyond);
7. Reliability: as experienced during the first two phases of the peak oil debate, models have sometimes proved to be based on invalid hypotheses, to involve methodological flaws and/or politically driven assumptions, from all sides (Jakobsson et al., 2009; Aleklett et al., 2010; McGlade, 2014; Laherrère et al., 2016a,b, 2017; Wachtmeister et al., 2018). Different options to compare a model reliability exist (Brandt, 2010; Sorrell et al., 2010a; Foucher, 2013; Peebles, 2017) but the one chosen here is to solely consider models from oil intelligence companies as they have access to sensible private data. This choice is also supported as they use field-scale bottom-up¹⁶ models that combine both physical and economic aspects of oil production, seen as "the most promising avenue" for oil supply models (Brandt, 2010);
8. Access: the entire set of yearly data is accessible at zero or relatively low cost;

Models fulfilling the first three criteria are presented in Table 2.1. The chosen model is from GlobalShift (although not free, the access cost is rather modest), and presents for each oil-producing country past and projected oil production from 1950 to 2050, as well as estimates of reserves and drilled wells. Projections are available at regional, geopolitical and global scales. GlobalShift distinguishes onshore fossil oils (field oils, Natural Gas Liquids or NGLs, Shale/Tight Oils or STOs, extra-heavy oils i.e. from oil sands), onshore manufactured oils (mined shale oils, Gas-To-Liquids or GTLs, Coal-To-Liquids or CTLs, Biomass-To-Liquids or BTLs or biofuels, refinery gains) and offshore oils (0-500m, 500-1000m, 1000-2000m and 2000+ meters). Forecasts are evidence-based, validated using geological, engineering, investment and other (environmental, political, economic and social) criteria. For a recent description of GlobalShift Ltd.'s all-liquids forecast model, see Smith (2015) or the GlobalShift website.

2.1.3.2. ENERGY CONVERSION FACTORS

Once the oil production is constructed, it is essential to convert from a daily volumetric unit (production projections are usually expressed in thousands or millions of barrels per day) to a daily energy unit in order to quantify the energy production from all oil liquids. The process is twofold. First, the share of oil liquids destined to meet other needs than energy production (chemicals, plastics, anti-freeze products, detergents, etc.) is removed. This share is estimated to be 40% for NGLs (Solé et al., 2018) and 8% for all other liquids except biofuels, in accordance with GlobalShift estimates. Secondly, energy conversion factors are applied considering the different energy content of oil liquids. We make the conservative assumption that the share and the factors will remain constant over time. GlobalShift estimates of these energy conversion factors take into account the methodological choices adopted to define the various categories of oil liquids. These estimates lead to 4.06 GJ/bbl for NGLs and 5.9 GJ/bbl for all other liquids. These are of course rough factors only and the absolute figures will theoretically differ by regions according to the API gravity¹⁷ of the local oils. Yet, they remain a solid basis as the gravity of each national oil is unknown or only partially known.

¹⁶Models can be categorized in three types: 'field-aggregate', 'bottom-up by field' and others (system dynamics, hybrid, etc.) (Brandt, 2010).

¹⁷Oil API specific gravity is the inverse ratio to normal specific gravity (SG). It measures how heavy or light oil is compared to water: if it is greater than 10, oil floats on water and the oil is called light; if it is less than 10, it sinks and the oil is called heavy. This property indicates the proportion of small and large molecules, which relate to the expected Higher Heating Value (HHV) of the petroleum product (Demirbas and Al-Ghamdi, 2015; EIA, 2019), and the ability of the oil to be refined (in fact the quantity of processes needed to refine it to given specifications).

Authors	Crit4	Crit5	Crit6	Crit7	Crit8	Score
GlobalShift	AL	✓	1950-2050	✓	✓	8
Rystad Energy	AL	✓	1900-2100	✓	×	7
IHS Markit	AO	✓	1850-2100	✓	×	6
Laherrère	AL	×	1900-2150	×	✓	6
Mohr et al.	AO	✓	1850-2300	×	✓	6
Dittmar	AL	✓	2020-2050	×	✓	5
DNV GL	AO	×	1980-2050	✓	×	5
EIA	AO	×	1973-2019	×	✓	5
ExxonMobil	AL	✓	2000-2040	×	×	5
Hosseini and Shakouri	AO	×	2013-2025	×	✓	5
IEA	AL	×	1971-2040	×	×	5
McGlade	AO	✓	2005-2035	×	✓	5
Norouzi et al.	AO	×	1977-2040	×	✓	5
BP	AL	×	2000-2050	×	×	4
Equinor	AL	×	1990-2050	×	×	4
OPEC	AL	✓	2019-2045	×	×	4
Total	AL	×	2000-2050	×	×	4
Shell	AO	×	2000-2100	×	×	3
WEC	AO	×	2015-2060	×	×	3

TABLE 2.1: Models identified respecting the first three inclusion criteria, sorted in descending order by score (i.e. the total number of criteria met). AO refers to All Oils (conventional oil plus NGLs, EOR, extra-heavy oil, light-tight oil and mined shale oil) and AL refers to All oil Liquids ('all-oil' plus all other liquids such as gas-to-liquids, coal-to-liquids, biofuels, etc.). The access criteria score relies on private communications with the authors, when applicable.

Energy Inputs	Extraction	Processing	End-use
Direct energy and material	$EROI_{1,d}$	$EROI_{2,d}$	$EROI_{3,d}$
Indirect energy and material	$EROI_{std}$	$EROI_{2,i}$	$EROI_{3,i}$
Indirect labor consumption	$EROI_{1,lab}$	$EROI_{2,lab}$	$EROI_{3,lab}$
Auxiliary services consumption	$EROI_{1,aux}$	$EROI_{2,aux}$	$EROI_{3,aux}$
Environment	$EROI_{1,env}$	$EROI_{2,env}$	$EROI_{3,env}$

TABLE 2.2: Two-dimensional EROI nomenclature: boundaries for energy inputs and outputs. Source: Murphy et al. (2011).

2.1.3.3. EROIS SCENARIOS

For this analysis, we employ the standard EROI (noted $EROI_{std}$) which accounts for the energy used in the extraction process, measuring the energy out at the well-head over the energy spent in the process (Hall et al., 2014). The desired energy level includes direct and indirect energy and material inputs. This choice is motivated by the will to reduce the boundary statistical uncertainty (the more steps taken, the more uncertain is the estimated EROI) and the consideration of an in-between energy costs level (Murphy et al., 2011), as presented in Table 2.2.

To account for the uncertainty in EROI values and the evolution over time as well as assess the robustness of our analysis, we used a modeling approach that combines (i) a literature-based desk-research of an EROI estimate (low, medium or high) (ii) a decline function (7 different functions are considered) starting at a (iii) decline year (three decline year hypotheses are considered). The resulting panel of 39 scenarios is presented in Table 2.3 and implemented to estimate a set of key outputs: the year of the peak, the magnitude of the peak (in petajoule per day, PJ/d), the yearly net-energy increase from 2015-2019 to the peak (in %/yr), the yearly net-

energy decrease from the peak to 2050 (in %/yr), the ratio of the decrease/increase rates and the weighted average EROI.

EROIs estimates A literature review selection on standard EROI is carried out on the basis of several criteria such as the publication date (less than 5 years preferred, less than 10 years if nothing else) or the respect of the right energy inputs and energy outputs. This allows the attribution of a low, medium and high estimate for each oil liquid. If the desired boundary or energy level is not found in the current literature, the closest estimate is searched for. For manufactured oil (biofuels, CTL, GTL), it would not make sense to exclude the processing stage that gives oil liquids and as such, it is included. The results and sources are presented in Table 2.4 and are followed by a presentation of the hypotheses per oil liquid.

Onshore field oil and shallow offshore (0-500m) yearly estimates have been obtained from a modified version of the base prospective model of Court and Fizaine (2017) (noted $EROI_{CF}$, see appendix for more information). No decline function is thus associated to these liquids. The Ultimately Recoverable Resources (URR) for conventional of McGlade and Ekins (2015) and Miller and Sorrell (2014) are used to compute $EROI_{CF,1}$ and $EROI_{CF,3}$, corresponding to the low and high estimates, respectively. The URR used for the medium hypothesis is the average of the two previous ones and leads to the computation of $EROI_{CF,2}$.

Onshore and offshore NGL are assumed equivalent. As no paper respecting the previously established screening rules has been found in the literature, the low estimate has been taken from Campbell (2015a), the high from Solé et al. (2018) and the medium is the average of the two.

Shale tight oil estimates derive from Brandt et al. (2015b) who evaluate standard net-energy-yields at the Bakken tight oil formation, but including processing (papers respecting the previously established screening rules have not been found in the literature). The low and high estimates are the interquartile range for the base case and the medium estimate is the mean value.

Tar sands estimates are obtained from Wang et al. (2017c) who assessed the resource EROI in Canada (the largest tar sands producing country in the world) from 2009 to 2015. We assume the overall contribution of tar sands to be made at 60% by in-situ techniques (EROI of 3.2-5.4) and at 40% by mining (EROI of 3.9-8) based on CER (2017). The medium estimate is an average of extreme values, weighted by contribution.

Mined shale oil estimates are taken from a review from Cleveland and O'Connor (2011) (low estimate) and a company estimation (Aarna and Lauringson, 2011) for the high estimate. The medium estimate is the average of both.

Biofuels estimates are obtained from Prananta and Kubiszewski (2021), who carried out a meta-analysis of biofuel Energy Return on Investment covering 44 studies across 13 countries. This choice was made as an important controversy exists in the EROI of biofuels (Hall et al., 2011). The low and high estimates respectively correspond to the values of the first and the second generation of biofuels. The medium estimate is the average of both.

CTL estimates are approached by the values of Kong et al. (2018a). The low, medium and high estimates represent the low, average and high values of the EROI without internal energy inputs or environmental inputs. Without this restriction, the EROI is lower than 1.

CTL estimate is used for GTL as no paper respecting the previously established screening rules has been found in the literature for gas-to-liquids oil.

Offshore oils estimates are computed using Jones (2013) equation: $EROI(h) = 5.5 \times 10^5 / (25 \times h)$ with h being equal to 750m, 1500m and 2500m for the three categories in ascending depth order. Low and high estimates are respectively a decrease/increase of 20% of the computed value, arbitrarily chosen as such to cover a wide enough range and evaluate the related

EROI estimates	Decline year y_D	Decline function	Scenario
High	Constant scenario	DF1	H1
	2015	DF2	H2
		DF3	H3
		DF4	H4
		DF5	H5
		DF6	H6
		DF7	H7
	$y_{prod}=0.03$	DF2	H8
		DF3	H9
		DF4	H10
		DF5	H11
		DF6	H12
		DF7	H13
Medium	Constant scenario	DF1	M1
	2015	DF2	M2
		DF3	M3
		DF4	M4
		DF5	M5
		DF6	M6
		DF7	M7
	$y_{prod}=0.03$	DF2	M8
		DF3	M9
		DF4	M10
		DF5	M11
		DF6	M12
		DF7	M13
Low	Constant scenario	DF1	L1
	2015	DF2	L2
		DF3	L3
		DF4	L4
		DF5	L5
		DF6	L6
		DF7	L7
	$y_{prod}=0.03$	DF2	L8
		DF3	L9
		DF4	L10
		DF5	L11
		DF6	L12
		DF7	L13

TABLE 2.3: Summary of all 39 scenarios considered for the scenarios-based sensitivity analysis.

Oil liquid	Low	Medium	High	Source	EROI
Field oil	$EROI_{CF,1}$	$EROI_{CF,2}$	$EROI_{CF,3}$	Miller and Sorrell (2014) Court and Fizaine (2017)	$EROI_{1,lab}$
Onshore NGL	5	6.35	7.7	Campbell (2015a) Solé et al. (2018)	$EROI_{2,d}$
Shale tight oil	24.3	30.6	35.7	Brandt et al. (2015b)	$EROI_{2,i}$
Tar sands	3.48	4.96	6.44	Wang et al. (2017c)	$EROI_{stnd}$
Mined shale oil	6.37	10.75	15.12	Cleveland and O'Connor (2011) Aarna and Lauringson (2011)	$EROI_{stnd}$
Biofuels	2.32	3.12	3.92	Prananta and Kubiszewski (2021)	$EROI_{stnd}$
CTL	1.1	1.4	1.8	Kong et al. (2018a)	$EROI_{2,d}$
GTL	1.1	1.4	1.8	Kong et al. (2018a)	$EROI_{2,d}$
Offshore 0/500m	$EROI_{CF,1}$	$EROI_{CF,2}$	$EROI_{CF,3}$	Miller and Sorrell (2014) Court and Fizaine (2017)	$EROI_{1,lab}$
Offshore 500/1000m	23.5	29.3	35.2	Jones (2013)	$EROI_{stnd}$
Offshore 1000/2000m	11.7	14.7	17.6	Jones (2013)	$EROI_{stnd}$
Offshore 2000m+	7.0	8.8	10.6	Jones (2013)	$EROI_{stnd}$
Offshore NGL	5	6.35	7.7	Campbell (2015a) Solé et al. (2018)	$EROI_{2,d}$

TABLE 2.4: EROI estimates (X:1) for each oil liquid. $EROI_{CF}$ refers to the yearly estimate of the modified base prospective estimates of Court and Fizaine (2017). The EROI nomenclature follows Murphy et al. (2011). The yearly EROI estimates for field oil and shallow offshore oil are presented in Figure 2.6.

impacts on the final results.

EROIs decline functions EROI is theorized to depend on time as the energy production evolves due to physical depletion and technological improvement factors (Dale, 2011; Court and Fizaine, 2017). The functional dependence of EROI on time for non-renewable energy sources is assumed to start at some high level, grow rapidly to a maximum and gradually decline to reach an asymptotic limit of one. That said, those mathematical formulation of the time dependence applies to the entire exploitation history of a resource. They are thus considered inadequate for the GlobalShift data, which covers a limited portion of the resource exploitation history (1950 - 2050) and includes different resources (for instance, EROI of CTL and GTL respectively depend on the resource exploitation ratio of coal and gas).

On the basis of Dale (2011), Heun and de Wit (2012), Court and Fizaine (2017) and Solé et al. (2018), we hence define seven decline functions: the first is constant (i.e., no decline, a conservative estimate), and the remaining six start declining at the decline year. They apply for each liquid except for onshore field oil and offshore shallow oil that have yearly values. Following the modification introduced by Court and Fizaine (2017), it is assumed that EROIs cannot reach a value of less than 1 as such a value at the well-head would imply pure energy loss. This last assumption is important but is supported by the use of a modified version of Court and Fizaine (2017) model for onshore field oil and offshore shallow oil (see Appendix). The decline functions and their mathematical formulation are presented in Table 2.5.

EROIs decline years For each of the non-constant decline functions, two decline-years are used: 2015 (i.e., a nearly common year of publication for all selected papers, the idea being that these papers quote the current EROI at the time of publication) and the year when the production of the oil liquid reached or will reach 3% of the total gross energy production (in energy content and not volumes). This decline-year noted $y_{j,prod=0.03}$ is chosen as such to represent a domino decline year for each oil linked to the resources production history in the vein of Court and Fizaine (2017). It is to 2050 for the offshore NGL, offshore 500/1000m, CTL and mined shale

Decline function	Definition	Mathematical formulation
DF1	Constant	$EROI_j(y) = EROI_j(y_0)$
DF2	Constant and linear decline _I	$EROI_j(y) = \begin{cases} EROI_j(y_0), & \text{if } y \leq y_D \\ EROI_j(y_0) - \delta_I \times (y - y_D), & \text{otherwise} \end{cases}$
DF3	Constant and linear decline _{II}	$EROI_j(y) = \begin{cases} EROI_j(y_0), & \text{if } y \leq y_D \\ EROI_j(y_0) - \delta_{II} \times (y - y_D), & \text{otherwise} \end{cases}$
DF4	Constant and geometric decline _I	$EROI_j(y) = \begin{cases} EROI_j(y_0), & \text{if } y \leq y_D \\ \gamma_I \times EROI_j(y - 1), & \text{otherwise} \end{cases}$
DF4	Constant and geometric decline _{II}	$EROI_j(y) = \begin{cases} EROI_j(y_0), & \text{if } y \leq y_D \\ \gamma_{II} \times EROI_j(y - 1), & \text{otherwise} \end{cases}$
DF6	Constant and exponential decline _I	$EROI_j(y) = \begin{cases} EROI_j(y_0), & \text{if } y \leq y_D \\ EROI_j(y_0) - e^{-\frac{y-y_D}{\tau_I}}, & \text{otherwise} \end{cases}$
DF7	Constant and exponential decline _{II}	$EROI_j(y) = \begin{cases} EROI_j(y_0), & \text{if } y \leq y_D \\ EROI_j(y_0) - e^{-\frac{y-y_D}{\tau_{II}}}, & \text{otherwise} \end{cases}$

TABLE 2.5: Summary of EROI decline functions (DF), $EROI_j(y_0)$ being the initial EROI value at the year 1950 for the oil liquid j . They apply as long as $EROI_j(y)$ is greater or equal to 1, which is the minimum value EROI can hypothetically reach. The models’ constants derive from the authors and the scenarios of Heun and de Wit (2012) with $\delta_I, \delta_{II}, \gamma_I, \gamma_{II}, \tau_I$ and τ_{II} being respectively equal to 0.25 year⁻¹, 0.125 year⁻¹, 0.95, 0.975, 43 years and 116 years.

oil. The corresponding decline years are 1994, 2007, 2013, 2014, 2026, 2028 and 2042 for onshore NGL, offshore 1000/2000m, tar sands, shale tight oil, offshore 2000m+, biofuels and GTL, respectively.

2.1.4. RESULTS

2.1.4.1. NET VS. GROSS ENERGY FROM OIL LIQUIDS

According to GlobalShift (2020), the oil liquids production for energy purposes should peak in 2034 with a magnitude of 551 PJ/d. Removing the energy necessary for the liquids extraction and production (including direct plus indirect energy and material costs), we find that the net-energy reaches a peak in 2024 of 415 PJ/d, with respective standard deviations over all scenarios being equal to 6.6 yr and 26.7 PJ/yr. This first result should not be interpreted as the announcement of a coming peak, but as an indication that by 2024, the production of oil liquids will require an amount of energy equal to 25% of its energy production. Yearly increase has been diminished by 69% (from 1.26%/yr to 0.39%/yr) while the yearly decrease has been lowered by 28%. Most notably, the ratio of the decrease rate over the increase has experienced an increase of 445%: from 1.28 to 6.97. If the year of the peak and the magnitude matter, this ratio seems to be the most crucial factor as it implies important and accelerated energy needs from the oil liquids sector. In particular, the energy required for energy production will reach a staggering proportion of 50% by 2050. The contribution in terms of gross energy of the oil liquids is led by onshore field oil (63%) followed by offshore shallow oil (20%), while the rest does not exceed 3% per oil liquid. For instance, shale tight oil and oil sands input are limited to small fractions of 3% and 2%. The contribution in terms of net-energy is close, with a weighted average total difference of 0.1%. However, unconventional oils begin to grow in proportion starting from the shale revolution and the yearly contribution undergoes important changes: onshore field oil and shallow offshore are expected to equal about 51% of the gross energy production in 2050. Figure 2.2 presents the average oil liquids net-energy production from 1950

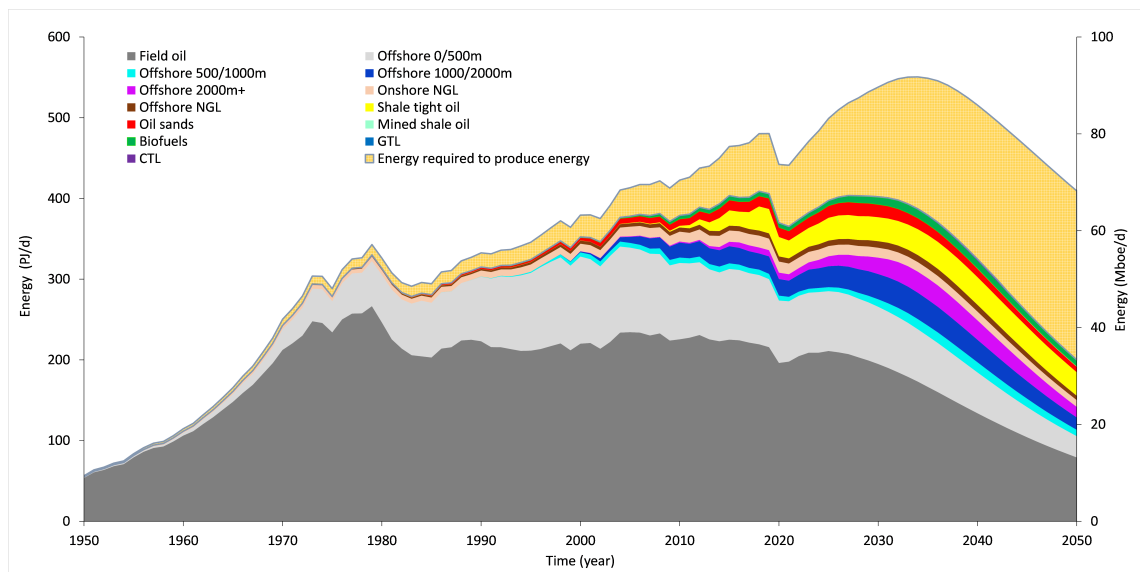


FIGURE 2.1: Average oil liquids net-energy production from 1950 to 2050, compared to the gross energy.

to 2050.

The weighted average EROI (based on the gross energy contribution) experiences a steady decline from its initial maximum value of 44.4 to its apparent final plateau of 6.7. This reduction is predominantly led by the decrease in EROI of onshore field oil and shallow offshore, until both curves drift apart, from 2013 onwards, as Figure 2.2 shows. Let us also note that each EROIs tends to decrease, but at different rates, which is explained by the different decline-years (see for instance the difference between shale tight oil and offshore 500/1000m).

The energy required for the production of oil liquids grows from 1.5 PJ/d in 1950 to 210 PJ/d in 2050, with an exponential increase until reaching an apparent plateau. This represents 15.5% today of the gross energy production, and is projected to reach 50% by 2050, as illustrated in Figure 2.3. In other terms, an amount equivalent to half of the energy production of oil liquids will be necessary in 2050 in order to keep producing. Nevertheless, the precise breakdown by energy sources remains to be treated in future research.

2.1.4.2. SCENARIOS-BASED SENSITIVITY ANALYSIS

EROIs estimates As one could expect, reduced EROI estimates induce a lower peak year: the high, medium and low hypothesis respectively correspond to a peak year of 2030, 2024 and 2017, respectively. In a similar fashion, the net-energy peak magnitude reaches 444, 417 and 383 PJ/d, while the 1950 - 2050 average EROI goes from 24.4, 22.7 and 20.5. Dividing the difference between high and low outputs by the medium output, we find that the peak magnitude and average EROI have similar uncertainties (15% and 17% respectively). Let us note that these results are also in line with the dominance of onshore field and offshore shallow oil in the overall gross energy production (83% of the total contribution). To assess future projection uncertainties, one should focus on these two sources of oil liquids first, short of a major technological revolution making another source much more accessible than it presently is.

EROIs decline years The decline years present more similar features than the EROI estimates. The constant scenarios (H1, M1 and L1 in Table 2.3) reach on average a peak of 427 PJ/d in 2027 with a decrease/increase ratio of 2.8 and an average EROI of 23.4. Other decline-years

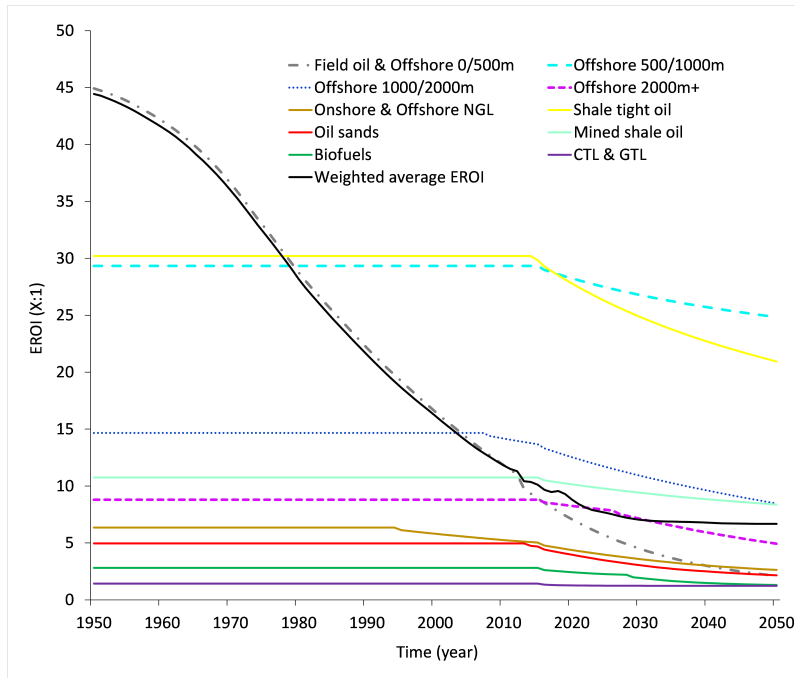


FIGURE 2.2: Evolution of each liquid standard EROI and the weighted average EROI, from 1950 to 2050.

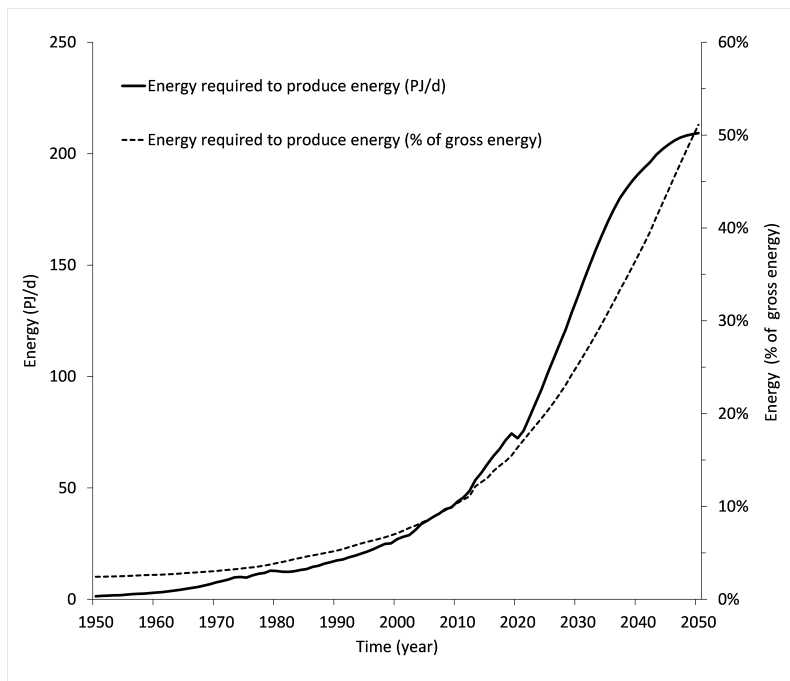


FIGURE 2.3: Evolution of energy required to produce oil liquids, from 1950 to 2050.

Output assessed	Gross en.	Net en.	$\frac{ x_{gross} - x_{net,avg} }{\sigma_{net}}$	Scale
Peak year	2034	2023.6	1.6	+
Peak magnitude	551	415	5.1	++
Pre-peak increase	1.26	0.39	5.7	++
Post-peak decrease	1.60	2.04	1.4	+
Decrease/increase ratio	1.28	6.97	1.7	+

TABLE 2.6: Comparison between gross and net-energy outputs to estimate the robustness of the results.

hypotheses lead to a peak of 414 PJ/d in 2023, with a decrease/increase ratio of 3 and an average EROI of 22.4. The difference between the first decline-year hypothesis (2015) and $y_{j,prod=0.03}$ is rather negligible in terms of peak year, magnitude or average EROI, but not for the ratio. Two lessons can be drawn from this. Firstly, decline-years have lower impact on the assessed outputs than the EROI estimates. Secondly, taking in consideration decline functions for all liquids (except field oil and shallow offshore oil that already have yearly values) generates an earlier, lower and steeper peak, but with rather close outputs. Still, these results highlight the significance of incorporating decline functions to net-energy forecasts and not solely sticking to static estimates of EROIs.

EROIs decline functions In a logical way, outputs that induce a steeper EROI decline have resulted in higher reductions in net-energy peak, and higher decrease/increase ratios. We find that the exponential and geometric decline functions are the most optimistic whereas the linear function hypothesis leads to small average EROI values. Putting aside the linear function, the EROI plateau previously identified reaches 12. This is an important finding as our data could be used in future energy transition models integrating a net-energy perspective.

2.1.4.3. ROBUSTNESS OF THE RESULTS

In order to analyze the robustness of the results, we constructed a 3-level robustness scale. "0" indicates that the evaluation of the net-energy does not give a significant qualitative and quantitative variation compared to the gross energy (when the difference between gross and net-energy output values is less than half of the average standard deviation of net-energy), "+" indicates a qualitative significance (when the difference is of the order of the standard deviation) and "++" a qualitative and quantitative significance (roughly speaking, when the difference is more than twice the standard deviation). From this scale, it appears that net-energy is clearly robust for the peak magnitude and the pre-peak net-energy increase rate, both on the qualitative and quantitative fronts. It is also qualitatively significant for the peak year, the post-peak decrease rate and the decrease/increase ratio. The results testify that, in all likelihood, relative trends are independent of our choice of gross energy data. Table 2.6 gives the robustness evaluation outputs.

Moreover, and even though the expected peak date and production may differ somewhat from one set of data to another, the EROI trend models as quantified in this work do not (as our quantification of these trends are independent of the type of future production projection used). Furthermore, when comparing the volumetric projection of the three all liquids models with the highest model score (GlobalShift, Rystad Energy, Laherrère), one can note the overall similarity in terms of peak year and magnitude trends (Figure 2.4). This assertion is furthermore reinforced when integrating projections discussed in the introduction, although which yearly values were not made available to us.

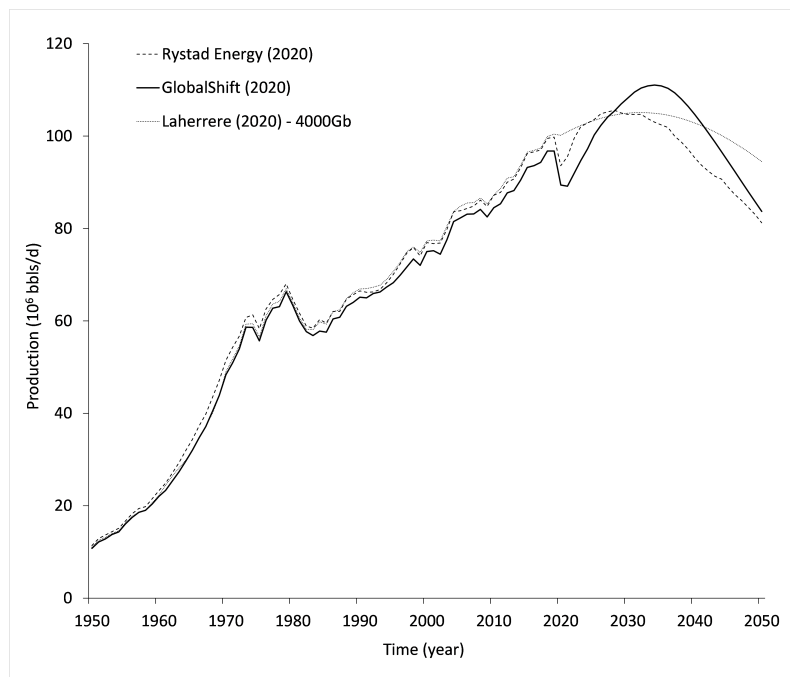


FIGURE 2.4: Comparison of the three oil production models with the highest model score made available to us, see Table 2.1.

2.1.5. DISCUSSION

2.1.5.1. IMPLICATIONS FOR A GLOBAL AND FAST LOW-CARBON ENERGY TRANSITION

This study uses GlobalShift's all oil liquids projection and a panel of standard EROI scenarios to characterize the dynamic evolution of the primary stage net-energy along the transition from high quality conventional to low-quality unconventional resources. Several key findings appear.

Firstly, the gross energy production from oil liquids is likely to peak in the next 10 to 15 years. The overall contribution of unconventional liquids is relatively low until the mid 2010's, when their gross energy production starts to increase to reach about half of the conventional at its peak. (Figure 2.5). If the shale tight oil has been able to compensate for the production plateau of conventional oils since the mid 2000's, no other liquid is expected to take off and become the next backstop energy source.

Secondly, the energy necessary for the production of oil liquids is estimated to equal 15.5% of the oil energy production today, and is expected to grow exponentially to reach 50% in 2050. We thus foresee an important consumption of energy to produce future oil liquids, a phenomenon relating to "energy cannibalism" (Pearce, 2008). We point out that our model features are robust on the qualitative side, and for some on both on the qualitative and quantitative fronts. Moreover, the comparison of gross energy models shows that a gross peak is expected by 2035 with approximately similar shapes, even though GlobalShift demonstrates a steeper decline. In other terms, it means that the relative trends from our results are in all likelihood, independent of the choice of gross energy data. Finally, the weighted average EROI of oil liquids is expected to reach a low plateau of 6.7.

On the one hand, we clearly have too much fossil fuels stock to respect ambitious climate targets (McGlade and Ekins, 2015). On the other hand, the flow from oil liquids (which might be needed for the transition while maintaining a growing economy) may be constraining, espe-

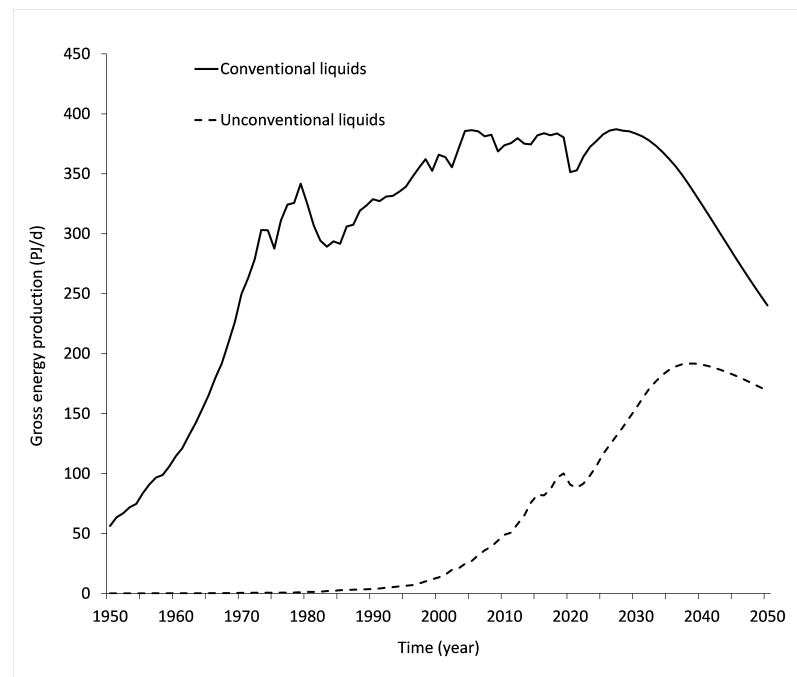


FIGURE 2.5: Gross energy production from conventional (onshore field oil, shallow offshore and NGL) and unconventional oil liquids (others).

cially from a net-energy perspective. In this context, two different energy transition scenarios may be envisaged and discussed in light of the 2°C maximum climate target of the Paris Agreement.

The first are rapid transition scenarios to low-carbon energies, which, as their deployment is only one component of fossil fuel use, appear to be marginally affected by a net-energy reduction from oil liquids. However, such scenarios bear possibly unrealistic deployment rates of low-carbon energy and derived end-use technologies (for example in terms of structural metals or minerals production increase and associated costs) and/or emission trajectories (due to the transition itself and potential rebound effects¹⁸). (Geo)economic realism, the delays required for large scale deployment of nuclear power plants, the self-sustainability of renewables or the technological limits that they generate in the electrical grid are other constraints. These limitations consequently question the feasibility and validity of rapid transitions scenarios (Kramer and Haigh, 2009; Smil, 2010; Solomon and Krishna, 2011; Loftus et al., 2014; Sovacool, 2016; Grubler et al., 2016; Smil, 2016; Fouquet, 2016; Napp et al., 2017; Smil, 2017; Vidal, 2018). It thus seems more reasonable to think that (or at least question whether) fast scenarios on the one hand are limited upstream by the rate of deployment, and on the other hand, the energy flow may be constrained downstream.

The second types of scenarios are slower low-carbon energy transitions, but they come up against the availability of cheap oil liquids in the 2030's. They would thus impose a decrease in oil consumption, with consequent adverse effects. For instance, a period of economic doldrums can happen as large scale and long-term decoupling seems impossible (Hickel and Kallis, 2019; Parrique et al., 2019; Haberl et al., 2020; Vadén et al., 2020a,b; Mastini et al., 2021). Such scenario could also mean an abandonment of the previous climate target and would further accentuate the "carbon crunch" effect (Figueres et al., 2017): the more we wait (n years to start

¹⁸According to Brockway et al. (2021), the rebound effect of energy efficiency is largely underestimated and might offset half of the savings made.

curbing GHG emissions), the less time we have for any given carbon and climate warming target (reduction of available time by $2n$ years).

The question is: is there a window between the two types of scenarios? Does this window force choices/shocks on critical/priority areas and the role of nuclear energy in the transition? If so, of what kind? What are the links with investment inertia in the sector concerned, but also in the primary mining and secondary (renewable) sectors concerned? Do these inertias lead to price or financial instabilities? If so, according to which broad categories of scenarios? With what implications for all critical sectors? Another "crunch" appears at this level: no growth (or less than 2% of global growth) might generate a global economic shock and new questions about critical/priority sectors.

2.1.5.2. ON THE DEBATE'S FUTURE AND THE PITFALL OF THE PEAK SUPPLY VS. PEAK DEMAND DISPUTE

However, we anticipate that these questions—beyond the scope of the present article—might be superseded by another side of the discussion. As the peak oil debate has been dormant over the last decade or so, focus has been directed onto the peak supply vs. peak demand confrontation. Proponents of the second hypothesis have gradually taken over, benefiting from the deterioration of the peak oil debate and from the shale revolution. We argue that the point is not here and by restraining ourselves to this dual confrontation, we would only repeat the pitfalls of the preceding peak oil debate. Oil is a commodity like no other as it is the lifeblood of our society with intricate political interests. A contracting range exists between oil prices high enough so that extraction and development are viable, and low enough to let consumers have access to it (Murphy, 2014). From this perspective, peak oil will never be either totally peak supply nor peak demand, but a mix of both in proportions that are difficult to measure and project. Given the issues at stake, we therefore urge for a renewal of the peak oil debate in the larger context of energy transitions.

2.1.5.3. LIMITATIONS AND FUTURE WORK

This study presents a quantitative analysis of the differences between net and gross energy production of all oil liquids. However, the methodology adopted suffers from a number of limitations that we now discuss. The first one concerns the uncertainty of GlobalShift's gross energy forecast, exacerbated today by geopolitical tensions surrounding the resumption of oil production in a COVID-recovery and climate emergency context. Globalshift's model currently assumes that demand for oil will continue on a 'business-as-usual' basis, which may not be the case if very strong climate-change restrictions—such as significant levels of carbon pricing—are implemented. Like other detailed bottom-up modellers, Globalshift recognises that if the oil price goes really quite high, then more unconventional oil can certainly come on-stream from some countries. These countries, though probably not too many, have potentially quite large recoverable resources of unconventional oils, including Canada (tar sands oil), Venezuela (heavy oil), Argentina, Russia and China ('light-tight' shale oil from fracking), and the U.S. (mined shale oil). But under most scenarios, much of this unconventional oil only comes on-stream fairly slowly after current resource-limited oil production peaks (the U.S. shale oil boom being the exception because of good resources, advanced technology, ample speculative finance, and beneficial land/resource ownership rules, as discussed). Globalshift does include such production in its forecasts, but points out that it is hard to be certain about future rates of production from new—and possibly quite expensive in most cases—oil resources. Moreover, it is difficult to assess GlobalShift's model robustness as similar bottom-up models require a great deal of data

and assumptions (Jakobsson et al., 2014). We have pointed out earlier, though, that because all gross production models share similar features (similar overall production projection shape) the results obtained here should be qualitatively correct, and in all likelihood semi-quantitatively correct in net vs gross relative difference. Still, the most robust conclusions drawn from this study (small relative shift for the peak year and substantial relative decrease for the peak production) do depend, once translated in absolute terms, on the gross production features, and most importantly, the expected peak date. Having a feel for the uncertainty of this feature would definitely help us to sharpen our conclusions. A second limitation lies in the use of the GlobalShift model. Even though it is a field scale model, the restricted granularity level made available to users has precluded us from implementing a more precise type of depletion analysis (Höök et al., 2009). On the other hand, other field scale models are usually sold at a very high price by oil intelligence companies that may have restricting publishing policies, which is not the case of GlobalShift. Unlike climate change related information, the public release of oil data conflicts with forceful private interests and internal security matters. Thus, building reliable projections is a complex and intricate task, as obtaining trustworthy data on oil availability is difficult.

Thirdly, a limitation arises from EROI assumptions on estimates, decline functions and decline years. Indeed, selecting EROI estimates on the basis of drastic inclusion criteria has proven to be difficult to respect and altogether make estimates questionable (Raugei, 2019). The use of decline functions and decline years although based on the literature may also have induced uncertainty in the results, as the dynamic evolution of EROI is still an emerging topic. It could be pointed out that an incline function could have been taken in consideration for unconventional oil. However, we believe that incline functions for unconventional oils at a global scale appear very unlikely for extraction¹⁹ and not significant as conventional oil represents more than 80% of the overall gross energy production. These two categories have better known EROIs than the others and necessarily limits quite substantially the usefulness of further sensitivity analysis and enhance the reliability of the results obtained. Nonetheless, we implemented constant scenarios without decline functions and scenarios with late decline years to balance for a hypothetical growth. More largely, uncertainties surrounding EROI are partly reduced by the set of scenarios and the sensitivity analysis. Fourthly, the existing literature on EROI has prevented the comparison between standard and societal EROI, a more meaningful viewpoint (Brockway et al., 2019). However, restraining ourselves to standard EROI has made the comparison between each EROI more reliable (the basis of comparison being clearer and closer to the physical extraction and other processes, and therefore less open to interpretation). Finally, the major limitation of this study resides in its prospective nature: the scenarios presented will in all likelihood not depict reality. And it should be kept in mind that this is not the objective of this article, as we are more interested in estimating the impact of net-energy relative to gross energy rather than guessing the timing and magnitude of a peak.

The assessment of more precise policy reactions to peak oil would constitute a useful improvement; this aspect is not sufficiently developed in the GlobalShift model—a deliberate modelling choice²⁰. This can be done by (i) predicting oil producing countries' reaction to peak oil (ii) developing policy reaction scenarios from oil demanding countries (Correljé and van der Linde, 2006). This distinction is key as friendly or hostile behaviors can emerge from the peak, with producing countries adapting to consumption per geopolitical affinity or reducing oil exports under the double constraint of both a peak in oil production and an increase in domestic

¹⁹See for example the long-term evolution of mine-mouth net-energy return and net external energy return of oil sands (Brandt et al., 2013).

²⁰Globalshift acknowledges there are many possible futures, their model is an attempt at a "most likely" version under present day economic, environmental etc. expectations, to be used to develop more nuanced predictions.

oil consumption²¹ (Matutinović, 2009; Verbruggen and de Graaf, 2013; Bradshaw et al., 2019).

2.1.6. CONCLUSIONS

Our society can be described as a thermodynamic system that profoundly relies on abundant cheap energy sources such as petroleum to thrive. However, the rapid growth in use of this non-renewable fossil fuel has undermined its future availability, leaving little doubt that an all-oil liquids peak will take place in the next 10 to 15 years. Given the societal dependence on oil and the difficulties in achieving a transition to low-carbon energies in time, such a peak is likely to have deep consequences that are not yet fully understood and which might handicap the transition itself.

When removing the energy necessary for these liquids' acquisition, this peak is not only sooner or reduced in terms of magnitude but also—and perhaps more importantly—carries a greater ratio between the decrease post-peak and the increase pre-peak rates. The total energy needed for the oil liquids production thus continually increase from a proportion equivalent today to 15.5% of the gross energy produced from oil liquids, to half in 2050. We thus foresee an important consumption of energy to produce future oil liquids. If our approach is subject to various uncertainties, the gaps between net and gross energy are statistically significant to uphold that our results are qualitatively and to some extent quantitatively robust. This conclusion is further supported when most robust oil production models are compared with one another.

Our findings question the feasibility of a global and fast energy transition, not in terms of stocks of energy resources, but in terms of flows. They imply that either the global energy transition takes place quickly enough, or we risk a worsening of climate change, a historical and long-term recession due to energy deficits (at least for some regions of the globe), or a combination of several of these problems. In other terms, we are facing a three-way conundrum: an energy transition that seems more improbable every passing year, increasing environmental threats and the risk of unprecedented energy shortages and associated economic depression in less than two decades. This leaves no room for approximation and poor judgment. Given the issues at stake, we therefore urge a renewal of the peak oil debate in the larger context of energy transitions but including consideration of net-energy, wise energy consumption and avoiding focusing simply on 'peak supply' vs. 'peak demand'. We see this conclusion not simply as a cautionary note, but as a call to scientific and political responses.

APPENDIX - MODIFIED BASE PROSPECTIVE MODEL OF COURT AND FIZAINE (2017)

Following Dale et al. (2011b), Court and Fizaine (2017) define the EROI of a non-renewable energy resource as:

$$\text{EROI}(\rho) = \varepsilon F(\rho) = \varepsilon G(\rho)H(\rho) \quad (2.4)$$

With ρ being the exploited resource ratio (historical cumulative production over the Ultimate Recoverable Resource, ratio comprised between 0 and 1) and ε a scaling factor which represents the maximum potential EROI value (never formally attained). The function $G(\rho)$ represents a technological component that increases EROI and $H(\rho)$ represents the physical component that diminishes EROI as resources are depleted. They read:

²¹This theory is also known as the "export land model" and is based on the work of Jeffrey Brown (Tverberg, 2010).

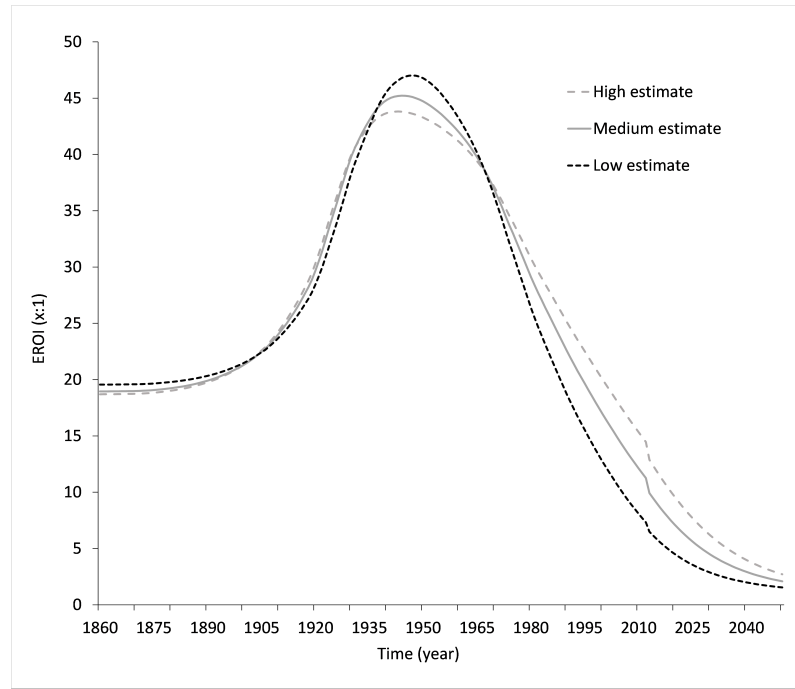


FIGURE 2.6: Yearly EROI estimates for conventional oil, from a modified Court and Fizaine model (Court and Fizaine, 2017). The drop-off towards 2012 is linked to the reconciliation of the EROI calculation with the historical and prospective rho.

$$G(\rho) = \Psi + \frac{1 - \Psi}{1 + \exp(-\psi(\rho - \tilde{\rho}))} \quad (2.5)$$

$$H(\rho) = \exp(-\varphi\rho) \quad (2.6)$$

Ψ represents the initial EROI with immature technology, ψ the rate of technological learning, $\tilde{\rho}$ the exploitation ratio for maximum growth rate of EROI and φ the rate of degradation of the resource. From historical estimates of EROI obtained with a price-based methodology (especially suited for conventional oil only), Court and Fizaine (2017) find the best fit values of Ψ , ψ , $\tilde{\rho}$ and φ using a minimization procedure of the sum of square root errors. However, the production ratio ρ is found using an URR that includes conventional and unconventional oils, and is therefore not relevant to our analysis of on conventional oil only. Thus, a modified version of yearly EROI estimates is computed using a similar method but with a URR of 15,000 GJ for the low estimate McGlade and Ekins (2015), 24,665 GJ for the high Miller and Sorrell (2014) and 19,833 GJ (the average of both) for the medium hypothesis. Figure 2.6 presents the different yearly EROI estimates for each high, medium and low URR hypotheses.

2.2. NET ENERGY EXTRACTION FROM GAS

Delannoy, L., Longaretti, P.-Y., Murphy, D. J., and Prados, E. Assessing global long-term EROI of gas: A net-energy perspective on the energy transition. *Energies*, 14(16):5112, 2021a. doi:10.3390/en14165112

ABSTRACT

Natural gas is expected to play an important role in the coming low-carbon energy transition. However, conventional gas resources are gradually being replaced by unconventional ones and a question remains: to what extent is net-energy production impacted by the use of harder to reach energy sources? This aspect of the energy transition was only partially explored in previous discussions. To fill this gap, this paper incorporates standard energy-return-on-investment (EROI) estimates and dynamic functions into the GlobalShift bottom-up model at a global level. We find that the energy necessary to produce gas (including direct and indirect energy and material costs) corresponds to 6.7% of the gross energy produced at present, and is growing at an exponential rate: by 2050, it will reach 23.7%. Our results highlight the necessity of viewing the energy transition through the net-energy prism and call for a greater number of EROI studies.

2.2.1. INTRODUCTION

Energy is the backbone of any society's economic development and, accounting for 84% of the current global primary energy consumption, fossil fuels are the largest contributors (BP, 2020). However, the current energy mix leads to two problems: (i) fossil fuels are, by their very essence, non-renewable, meaning that cheap reserves will eventually dwindle; (ii) environmental impacts (water consumption, land-use change, induced seismic activity, public health and safety risks, etc.) and the CO₂ emissions released by their ever-escalating use threaten every aspect of human societies as well as a large part of the living world (Costa et al., 2017; IPCC, 2021). In this context, a rapid and global transition to low-carbon energy sources is deemed a necessity, although not without scrutiny of its feasibility (Loftus et al., 2014; Heard et al., 2017; Smil, 2017; Napp et al., 2017; Brown et al., 2018; King and van den Bergh, 2018; Sers and Victor, 2018; Vidal, 2018; Jewell and Cherp, 2019; Capellán-Pérez et al., 2020; Nieto et al., 2020b; Moriarty and Honnery, 2020; Dupont et al., 2021b).

Natural gas is expected to play an important role in this transition, at least in the short- and middle-term (Smil, 2015; Gürsan and de Gooyert, 2021). Its numerous strategic advantages (abundance, versatility, high gravimetric energy density, etc.) drove a steady 3.4% consumption increase since 2000, which is likely to persist for the current decade (BP, 2020). To meet this growing demand, the industry turned to unconventional gas resources²². This shift be-

²²The distinction between conventional and unconventional resources is rooted in the difficulty of extracting and producing the resource; however, there is no consensus on where to draw the line between the two, as it depends on either economic or geological issues, especially in the U.S., where, in 2018, shale gas made up 70% of the total production according to the U.S. Energy Information Administration (accessed on 07-15-2021)

comes interesting from a net-energy perspective (i.e. the energy available after accounting for the energy cost of its acquisition, usually inclusive of extraction, refinement and delivery), as unconventional production methods are usually more energy intensive, and energy returns tend to diminish over time.

2.2.1.1. GROSS AND NET ENERGY

The Net Energy Analysis (NEA) is a conceptual framework drawn up in the early 1970s, when energy-related concerns emerged after the oil crisis (Murphy, 2014). According to the NEA, the net-energy is the main driver of the economic development of societies and should become the standard basis of political decisions (Carbajales-Dale et al., 2014). To this end, the NEA derives the value of the energy surplus of a given system, if any, using the following equation:

$$\text{Net energy} = \text{Gross energy} - \text{Energy required to deliver energy} \quad (2.7)$$

The energy required to deliver energy can be computed through net-energy indicators, of which a large array exists (Rana et al., 2020). The most well-known and used is the energy return on (energy) investment (EROI or ERoEI). Developed in 1972 (Hall, 1972, 2017), EROI is the ratio between the usable energy acquired from an energy carrier and the amount of energy expended to obtain that energy. When the EROI is equal or less than one, the considered energy system becomes an “energy sink”. If it is superior to one, it is an “energy source”. It reads:

$$\text{EROI} = \frac{\text{Energy delivered}}{\text{Energy required to deliver energy}} \quad (2.8)$$

Combining Equations (2.7) and (2.8), and assuming the gross energy equals the energy delivered:

$$\text{Net energy} = \text{Gross energy} \times \left(1 - \frac{1}{\text{EROI}}\right) \quad (2.9)$$

Despite the conceptual elegance and simplicity of previous equations, EROI has been at the center of theoretical and practical disputes, with the main one being the clear delimitation of energy output boundaries and energy input levels (Raugei, 2019). This made the realistic comparison of EROI from different sources difficult (Buchanan, 2019). A first tentative attempt to solve EROI associated issues was made by Murphy and Hall (2011a) with a protocol proposition identifying standard boundaries for energy inputs and outputs; see Table 2.7. If several controversies remain (Carbajales-Dale, 2019), EROI has proved itself to be a powerful indicator when correctly applied. It also attracted a great deal of attention starting from the 2010s, as the energy transition from high-energy-yield fossil-fuels to low-energy-yield renewables might put pressure on the energy production system (Hall et al., 2014; King and van den Bergh, 2018; White and Kramer, 2019).

Another relevant area of study in the recent literature is the difference between energy return on investment and power return on investment. Energy return on investment sums the energy inputs and outputs over the life of the energy technology/resource, while power return on investment calculates the energy returns in a set period of time. For example, Court and Fizaine (2017) report EROI values but, as Carbajales-Dale (2019) points out, what they really calculate are power returns. The denomination Power Return On Investment (PROI) might theoretically be a better fit here, as we refer to a quantity of energy per year. However, we decided to stick to “EROI”, as we are modeling energy returns—not calculating them—on the basis of studies which employed “EROI”.

Energy Inputs	Extraction	Processing	End-Use
Direct energy and material	$EROI_{1,d}$	$EROI_{2,d}$	$EROI_{3,d}$
Indirect energy and material	$EROI_{std}$	$EROI_{2,i}$	$EROI_{3,i}$
Indirect labor consumption	$EROI_{1,lab}$	$EROI_{2,lab}$	$EROI_{3,lab}$
Auxiliary services consumption	$EROI_{1,aux}$	$EROI_{2,aux}$	$EROI_{3,aux}$
Environment	$EROI_{1,env}$	$EROI_{2,env}$	$EROI_{3,env}$

TABLE 2.7: Two-dimensional EROI nomenclature: boundaries for energy inputs and outputs. Source: Murphy and Hall (2011a).

2.2.1.2. EROI OF GAS AT GLOBAL SCALE

Several studies have been conducted to estimate the net-energy and EROI of gas at a global level, in various contexts. Gagnon et al. (2009) were the first to assess the global trends in oil and gas at the wellhead, but for a restricted time frame (1992–2006). Brandt et al. (2015a) applied a detailed field-level engineering model of oil and gas production to 40 oilfields to determine net-energy return ratios. Relying on the mathematical formulations of EROI evolution over time of Dale (2011), Court and Fizaine (2017) assessed the long-term EROI trends of coal, gas and oil. However, they relied on estimates of Ultimately Recoverable Resources (URR), potentially outdated due by the Shale Revolution. Brockway et al. (2019) estimated the global primary-stage and final-stage EROI for fossil fuels using an input–output approach, but solely between 1995 and 2011. Finally, Capellán-Pérez et al. (2019) explored the dynamic evolution of EROI in scenarios of global transition to renewable energies from 1995 onwards, but assuming the EROI of non-renewable energy sources (oil, gas, coal and uranium) to be constant over time.

2.2.1.3. EROI OF GAS AT LOCAL, REGIONAL OR NATIONAL SCALE

Other notable works exist but have been conducted at the local, regional or national scale. Gately (2007) presented estimations of EROI ratios for U.S. offshore extraction in the Gulf of Mexico. Guilford et al. (2011) explored the long-term EROI of U.S. oil and gas discovery and production. Moerschbaecher and Jr. (2011) looked at the financial and energy return on investment of ultra-deepwater oil and gas production in the Gulf of Mexico. Freise (2011) analyzed the EROI of conventional Canadian natural gas production. Sell et al. (2011) examined the EROI for tight gas wells in the Appalachian basin (U.S.). Poisson and Hall (2013) calculated the time series of EROI for Canadian oil and gas, from 1990 to 2008. Aucott and Melillo (2013) provided an analysis of natural gas EROI in the Marcellus Shale. Dale et al. (2013) also studied the Marcellus shale, collecting information from operating companies to model greenhouse gas emissions, energy consumption (and EROI), as well as water consumption. Nogovitsyn and Sokolov (2014) tackled the EROI of the production of gas in Russia, relying on annual reports from Russian companies. Yaritani and Matsushima (2014) used a Monte Carlo approach to estimate expected ranges of EROI values. Moeller and Murphy (2016) calculated the EROI of the Marcellus Shale using a hybrid lifecycle analysis approach. Siazik et al. (2017) computed the EROI for natural gas hydrates in laboratory conditions. de Luna Marques et al. (2018) quantified the EROI of biogas produced from microalgae.

An important part of the published literature is devoted to the evolution of primary energy consumption mixture in China. Hu et al. (2013) conducted an assessment of China’s conventional fossil fuels’ EROI, past and projected. Kong et al. (2016b) modeled the net-energy advantages and drawbacks of coal-based synthetic natural gas vs. imported natural gas in China. Kong et al. (2016a) followed and computed the energy return of China domestic production of

oil and gas, compared to their imports. Lior (2016) determined the exergy and energy returns on investment of an hydro-fractured shale gas well. Wang et al. (2017b) reviewed the physical supply and projections of EROI of fossil fuels in China, including natural gas. Wang et al. (2017c) developed a hybrid lifecycle inventory model to estimate the EROI of shale gas development for China. Kong et al. (2017) estimated the EROI, energy payback time and greenhouse gas emissions of a coal seam gas project, situated in the Qinshui basin (China). Kong et al. (2018b) represented the EROI of natural gas hydrates in the South China Sea. Kong et al. (2018a) re-evaluated China's natural gas imports using an integrative approach from 2009 to 2015. Cheng et al. (2018) analyzed domestic and imported oil and gas EROI for China. Chen et al. (2020) extended previous EROI estimates of China shale gas extraction, considering labor, auxiliary services and environmental factors.

In summary, despite the crucial need to address this problem, which has been present for more than a decade, researchers have, to date and to the best of the authors' knowledge, partially explored the impact of declining EROIs on the net-energy production of gas at a global level and from a long-term perspective. This study attempts to explore this question and fill the literature gap that exists today.

2.2.2. MATERIALS AND METHODS

To do this, the following methodology is carried out. First of all, a model presenting extended past and future production of gas (conventional and unconventional) is chosen on the basis of a number of inclusion criteria. Conversion factors are applied to gas production volumes to quantify the gross energy. Secondly, EROI scenarios are constructed, relying on published EROI estimates and dynamic functions for each type of gas. Net-energy curves can finally be obtained, and the sensitivity of the results to the developed EROI scenarios can be assessed.

2.2.2.1. GAS PRODUCTION MODEL

The process of selecting a model to present the past and future production of gas is twofold. First, we carried out a literature review in order to identify recent models (published after 2010) and applied at a global scale. Second, we chose a single model on the basis of several criteria: (i) the time coverage should be long enough to retrace past and future production, (ii) the production should be subdivided per type of gas, (iii) the access to the yearly values should be free or at low cost, (iv) the model should be reliable. This last criteria is particularly difficult to assess but, in order to reduce uncertainties, we chose to solely consider models from oil and gas intelligence companies. Not only do these companies have access to sensible private data, they also provide field-scale bottom-up models that combine both the physical and economic aspects of production. However, two drawbacks exist: the possible high price and the restrictions placed on publishing. The set of identified models forecasting global gas supply is presented in Table 2.8.

On the basis of each model score (i.e., the total number of criteria met) we chose GlobalShift's model (although not free, the access cost is rather modest and the publishing policy is not restrictive). For every gas-producing country, their model includes past and projected production from 1950 to 2050, as well as estimates of reserves and wells. Projections are compiled at regional, geopolitical and global scales. GlobalShift differentiates between onshore gas (field gases, Shale/Tight Gases or STGs and Coal Bed Methanes or CBM) and offshore gas (0–500 m, 500–1000 m, 1000–2000 m and 2000+ meters). The production data do not comprise un-sold vented, flared, and re-injected gases, as well as gases used on site. For a recent description

Authors	Time	Subdivision	Access	Reliability	Score
Smith (2015)	1950–2050	✓	✓	✓	3
Maggio and Cacciola (2012)	1940–2060	✓	✓	×	2
Mohr et al. (2015)	1900–2300	✓	✓	×	2
DNV GL (2020)	1980–2050	×	✓	×	1
GEFC (2021)	2000–2050	✓	×	×	1
IEA (2020a); Tan et al. (2018)	1995–2040	✓	×	×	1
Kontorovich et al. (2014)	1900–2040	×	✓	×	1
Laherrère (2020a)	1900–2150	×	✓	×	1
Valero and Valero (2010)	1900–2150	×	✓	×	1
Wang and Bentley (2020)	1990–2050	×	✓	×	1
Kober et al. (2020)	1970–2060	✓	×	×	1
Zou et al. (2016)	1800–2200	×	✓	×	1
BP (2020)	1900–2050	×	×	×	0
EIA (2021); Azari et al. (2018)	1980–2054	×	×	×	0
OPEC (2020)	2019–2045	×	×	×	0

TABLE 2.8: Identified models forecasting global gas supply, sorted by descending score (total number of criteria met).

Country	Conversion Factor (PJ/bcm)	Production in 2018 (Mtoe)
United States	38.53	719.0
Russia	38.23	606.6
Iran	39.36	190.6
Canada	39.07	154.7
Qatar	41.40	147.4
China	38.93	135.3
Norway	39.47	106.4
Australia	39.76	101.2
Algeria	39.57	82.6
Saudi Arabia	38.00	79.1

TABLE 2.9: Indicative Gross Heating Value of natural gas of the ten major producing countries. Source: IEA (2021a).

of GlobalShift Ltd.’s forecast model, see Smith (2015) or the GlobalShift website (accessed on 07-15-2021).

Once the gas production is commissioned, it is essential to convert from a daily volumetric unit (expressed in billions of cubic meters) to a daily energy unit in order to quantify the gross energy production. Making the conservative assumption that this factor will remain constant over time, and using GlobalShift estimates for consistency matters, we assume each billion cubic meter of gas to equal 39.7 PJ (private communications). This is, of course, a rough factor only, and the absolute figures will theoretically differ by region according to the properties of the local gas, as presented in Table 2.9. However, it remains a solid basis for when the properties of the gas of each nation are only partially known or completely unknown.

2.2.2.2. EROIs YEARLY VALUES

To account for the uncertainty in EROI values and their evolution over time, as well as to assess the robustness of our analysis, we used a modeling approach that combines (i) a literature-based EROI estimate (low, medium or high) and (ii) a dynamic function (13 different functions are considered). The resulting panel of 39 scenarios is used to estimate a set of key out-

Gas Type	Low	Medium	High	Source	EROI
Field gas	$EROI_{CF,1}$	$EROI_{CF,2}$	$EROI_{CF,3}$	McGlade (2015) Court and Fizaine (2017) Wang and Bentley (2020) Aucott and Melillo (2013)	$EROI_{1,lab}$
Shale-Tight gas	32	51.9	82	Lior (2016) Wang et al. (2017c) Chen et al. (2020)	$EROI_{stnd}$
Coal Bed Methane	10	12.5	15	Kong et al. (2017)	$EROI_{stnd}$
Offshore 0–500 m	$EROI_{CF,1}$	$EROI_{CF,2}$	$EROI_{CF,3}$	McGlade (2015) Court and Fizaine (2017) Wang and Bentley (2020)	$EROI_{1,lab}$
Offshore 500–1000 m	34.2	42.8	51.3	Jones (2013)	$EROI_{stnd}$
Offshore 1000–2000 m	23.05	29.6	39.2	Gately (2007)	$EROI_{stnd}$
Offshore +2000 m	11.9	16.4	27.1	Moerschbaeher and Jr. (2011) Moerschbaeher and Jr. (2011)	$EROI_{stnd}$

TABLE 2.10: EROI estimates (X:1) for each gas type. $EROI_{CF}$ refers to the yearly estimate of the modified model of Court and Fizaine (2017). The EROI nomenclature follows Murphy and Hall (2011a).

puts: the year of the peak, the net-energy production peak (EJ), the yearly net-energy increase from 2015–2019 to the peak (EJ/year), the yearly net-energy decrease from the peak to 2050 (EJ/year), the ratio of the decrease/increase rates and the weighted average EROI.

EROIs Estimates For this analysis, we employ the standard EROI ($EROI_{stnd}$) which accounts for the energy used in the extraction process, measuring the energy out at the well-head over the energy spent in the process (Murphy and Hall, 2011a). The desired energy level includes direct and indirect energy and material inputs. This choice is determined by the willingness to reduce statistical uncertainties (the more steps and the more flows taken, the more uncertain the result). It is also in line with the existing EROI literature, and not as significant as for oil or renewables.

Desk research has been carried out to determine the right parameters. It has allowed us to attribute a low, medium and high estimate for each gas. If the desired EROI is not found in the published literature, the closest estimate is searched and adopted. The results and sources are presented in Table 2.10.

Onshore field gas and shallow offshore (0–500 m) yearly estimates were obtained from a modified version of the base prospective model of Court and Fizaine (2017) (noted $EROI_{CF}$). No dynamic function is thus associated with these gases. The Ultimately Recoverable Resources (URR) estimates for conventional gas from McGlade (2015) and Wang and Bentley (2020) are used to compute $EROI_{CF,1}$ and $EROI_{CF,3}$, corresponding to the low and high estimates, respectively. The URR used for the medium hypothesis is the average of the two previous ones and leads to the computation of $EROI_{CF,2}$.

Shale–Tight gas estimates are derived from a compilation of sources (Aucott and Melillo, 2013; Lior, 2016; Wang et al., 2017c; Chen et al., 2020). The low estimate is the first quartile of the collected values, the high estimate of the third quartile and the medium, taken as the average.

A Coal Bed Methane estimate is taken from Kong et al. (2017). Low and high estimates are, respectively, a decrease/increase of 20% of the given value, arbitrarily chosen to cover a wide enough range, and evaluate the relative impacts on the final results.

Offshore 500–1000 m estimates rely on Gately (2007). First, the EROI for the combined production of oil and gas is obtained by averaging the last 5 years of energy returns values of the 201–900 m water depth T1 and T3 energy boundaries (in order to simulate a T2, equivalent to

the standard EROI). A multiplier of 0.8 and 1.2 is applied to compute low and high estimates, respectively. Then, the EROI of oil production for this specific depth is collected from Delannoy et al. (2021b). Finally, and knowing the energy production proportions of gas and oil in the Gulf of Mexico, data from the U.S. Energy Information Administration website (accessed on 07-15-2021), we can compute the EROI of gas alone.

In a similar fashion, EROI values for the offshore +2000 m are retrieved using Moerschbaecher and Jr. (2011). Low, medium and high EROI estimates for oil and gas combined, as well as for oil alone, are retrieved, and, knowing the share of energy produced in the Gulf of Mexico (46% of gas and 54% of oil in 2009 from the EIA), we can compute the EROI of the gas produced.

Offshore 1000/2000 m estimates correspond to the average between the offshore 500–1000 and offshore +2000 m categories.

EROIs Dynamic Functions EROI is theorized to vary over time as the energy production evolves due to physical depletion and technological improvement factors. More precisely, functional forms of EROI for non-renewable energy sources are assumed to start steadily, grow rapidly to a maximum and gradually decrease to reach an asymptotic limit of one (Dale, 2011; Court and Fizaine, 2017). However, those mathematical formulae are defined over the entire exploitation-history of a resource. They are thus considered inadequate for the GlobalShift's model of gas production, which covers a limited portion of the resource exploitation-historic (1950–2050).

We hence define thirteen decline functions: one is constant, six experience a decrease starting from 2018 and six others experience an increase between 2018 (noted y_D) and 2025 (noted y_B) before decreasing at the same rate (referred afterwards as a “bump”). This bump aims to simulate a hypothetical short-term increase in EROI, possibly coming from a technological breakthrough. Dynamic functions apply to each gas except for onshore field gas and offshore shallow gas, which have yearly values. In order to follow Court and Fizaine (2017) functional forms, we assume that EROI cannot reach a value inferior to 1 at the well-head because that would imply pure energy loss. The decline functions and their mathematical formulation are presented in Table 2.11.

We derive the models' constants from the scenarios Delannoy et al. (2021b), who rely on Heun and de Wit (2012), themselves using Gagnon et al. (2009) global study: δ_I , δ_{II} , γ_I , γ_{II} , τ_I and τ_{II} respectively correspond to 0.25 year^{-1} , 0.125 year^{-1} , 0.95, 0.975, 43 years and 116 years.

2.2.3. RESULTS

2.2.3.1. NET VS. GROSS ENERGY FROM GAS

The gross energy peak in gas is expected to take place in 2040, with a magnitude of 249 EJ. The increase rate prior to the peak is estimated to 4.3 EJ/year, and the post-peak decrease rate to 2.55 EJ/year. The decrease/increase rates ratio equals 0.59, which highlights the fact that gas is produced faster before the peak than after. The net-energy peak of gas is predicted for 2037 to be in the order of 210 EJ. The energy necessary for gas production at the peak, therefore, represent 40 EJ, or 15.9% of the gross energy peak magnitude. The net-energy increase rate reaches 3.5 EJ/year, and the decrease rate 3.1 EJ/year. The net-energy decrease/increase ratio is 0.92, a rise of 54% compared to the gross energy. If the year of the peak and the magnitude matter, this ratio seems to be the most key factor, as it implies that the gas production sector will need important and accelerated energy inputs to keep producing. Finally, the energy contribution over the 1950–2050 period per type of gas is led by field gas (48%), followed by offshore shallow

	Definition	Mathematical Formulation
DF1	Constant	$EROI(y) = EROI(y_0)$
DF2	Linear decrease	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ EROI(y_0) - \delta_I \times (y - y_D), & \text{for } y \geq y_D \end{cases}$
DF3	Linear decrease	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ EROI(y_0) - \delta_{II} \times (y - y_D), & \text{for } y \geq y_D \end{cases}$
DF4	Geometric decrease	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ \gamma_I \times EROI(y - 1), & \text{for } y \geq y_D \end{cases}$
DF4	Geometric decrease	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ \gamma_{II} \times EROI(y - 1), & \text{for } y \geq y_D \end{cases}$
DF6	Exponential decrease	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ EROI(y_0) - e^{-\frac{y-y_D}{\tau_I}}, & \text{for } y \geq y_D \end{cases}$
DF7	Exponential decrease	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ EROI(y_0) - e^{-\frac{y-y_D}{\tau_{II}}}, & \text{for } y \geq y_D \end{cases}$
DF8	Linear bump	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ EROI(y_0) + \delta_I \times (y - y_D), & \text{for } y_D \leq y < y_B \\ EROI(y_0) - \delta_I \times (y - y_D), & \text{for } y \geq y_B \end{cases}$
DF9	Linear bump	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ EROI(y_0) + \delta_{II} \times (y - y_D), & \text{for } y_D \leq y < y_B \\ EROI(y_0) - \delta_{II} \times (y - y_D), & \text{for } y \geq y_B \end{cases}$
DF10	Geometric bump	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ (1 - \gamma_I) \times EROI(y - 1), & \text{for } y_D \leq y < y_B \\ \gamma_I \times EROI(y - 1), & \text{for } y \geq y_B \end{cases}$
DF11	Geometric bump	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ (1 - \gamma_{II}) \times EROI(y - 1), & \text{for } y_D \leq y < y_B \\ \gamma_{II} \times EROI(y - 1), & \text{for } y \geq y_B \end{cases}$
DF12	Exponential bump	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ EROI(y_0) + e^{-\frac{y-y_D}{\tau_I}}, & \text{for } y_D \leq y < y_B \\ EROI(y_0) - e^{-\frac{y-y_D}{\tau_I}}, & \text{for } y \geq y_B \end{cases}$
DF13	Exponential bump	$EROI(y) = \begin{cases} EROI(y_0), & \text{for } y < y_D \\ EROI(y_0) + e^{-\frac{y-y_D}{\tau_{II}}}, & \text{for } y_D \leq y < y_B \\ EROI(y_0) - e^{-\frac{y-y_D}{\tau_{II}}}, & \text{for } y \geq y_B \end{cases}$

TABLE 2.11: Summary of EROI dynamic functions (DF), with $EROI(y)_0$ being the initial EROI value at the year 1950. They apply as long as $EROI(y)$ is greater or equal to 1, which is the minimum value EROI can hypothetically reach.

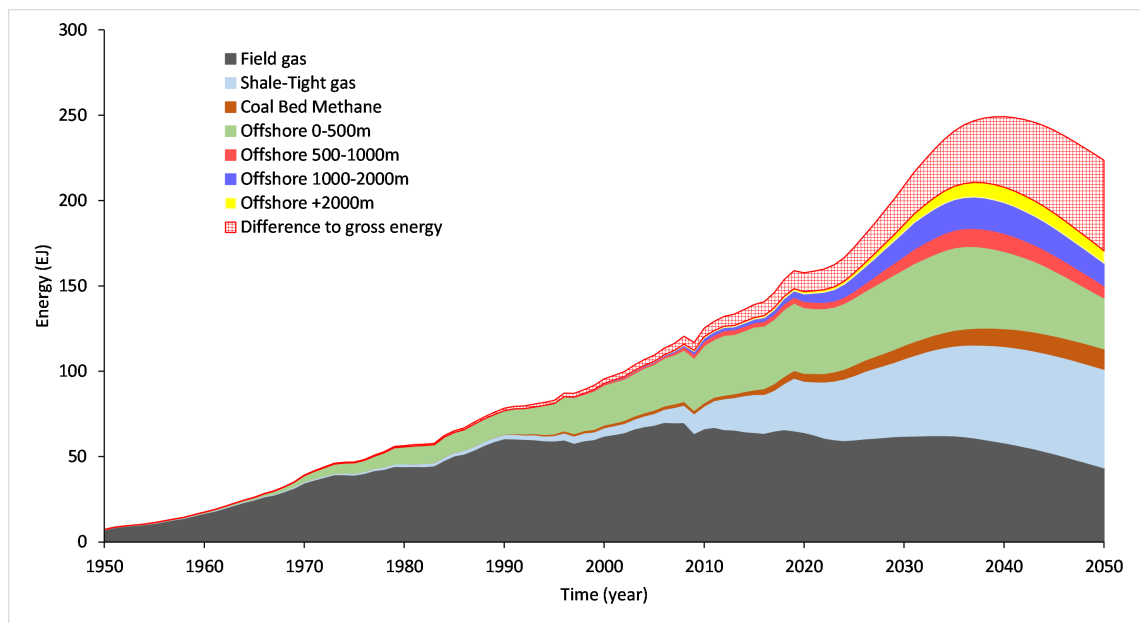


FIGURE 2.7: Average gas net-energy production from 1950 to 2050, compared to the gross energy.

gas (23%) and shale-tight (17%); the rest does not exceed 5% per gas. However, unconventional gases (all gases except onshore field gas and offshore shallow gas) grow in proportion over time to reach about 35% of the total gross energy produced between 2000 and 2050. Figure 2.7 presents the average net-energy production of gas from 1950 to 2050.

The weighted-average EROI experiences a steady decrease from its initial value of 141.5 to an apparent plateau of 16.8. This reduction is, in large part, due to the decrease in conventional gases' EROI, which begins to be inferior to: shale-tight gas EROI in 1992, offshore 500–1000 m in 2000, offshore 1000–2000 m in 2008, offshore +2000 m in 2016 and coal bed methane in 2022. Let us note that the drop-off of the conventional gases towards 2012 is linked to the reconciliation of the yearly EROI calculation with the historical and prospective exploitation resource ratios, a parameter used in the functional form definition (we recommend the reader consults the work of Court and Fizaine to clarify the theorized functional forms of EROI). Figure 2.8 illustrates the evolution of the EROI of all gas types, and the weighted average from 1950 to 2050.

The energy required for the production of gases grows from 1.3 EJ in 1990 to 11 EJ in 2020 and 53 EJ in 2050, showing an exponential increase until the curve starts to flatten from 2040. This respectively represents 1.7%, 6.3% and 23.7% of the gross energy production, as illustrated in Figure 2.9. In other terms, an amount equivalent to nearly a quarter of the energy production of gases will be necessary in 2050 in order to keep producing. Nevertheless, the precise breakdown by energy sources (electricity, gas itself, etc.) remains to be treated in future research.

2.2.3.2. SCENARIO-BASED SENSITIVITY ANALYSIS

EROI Estimates As one could expect, reduced EROI estimates induce an earlier peak, but the trend is rather weak (less than two years of difference between the high and low estimates). A more notable variation appears for the net-energy peak magnitude, with a 37 EJ gap between high and low EROIs estimates, which represents 17% of the net-energy peak for the medium estimate hypothesis. The decrease/increase ratio is the output the most sensible for the estimate, with a difference of 0.4 between the high and low estimates, which represents 44% of the

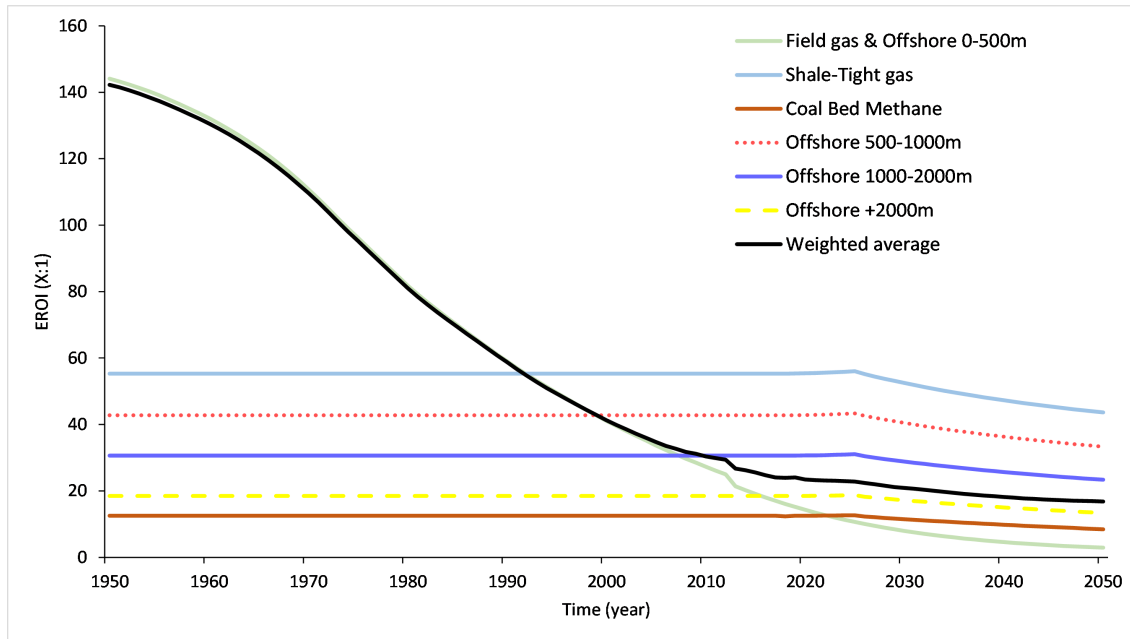


FIGURE 2.8: Evolution of the EROI of all gas types, and the weighted average from 1950 to 2050.

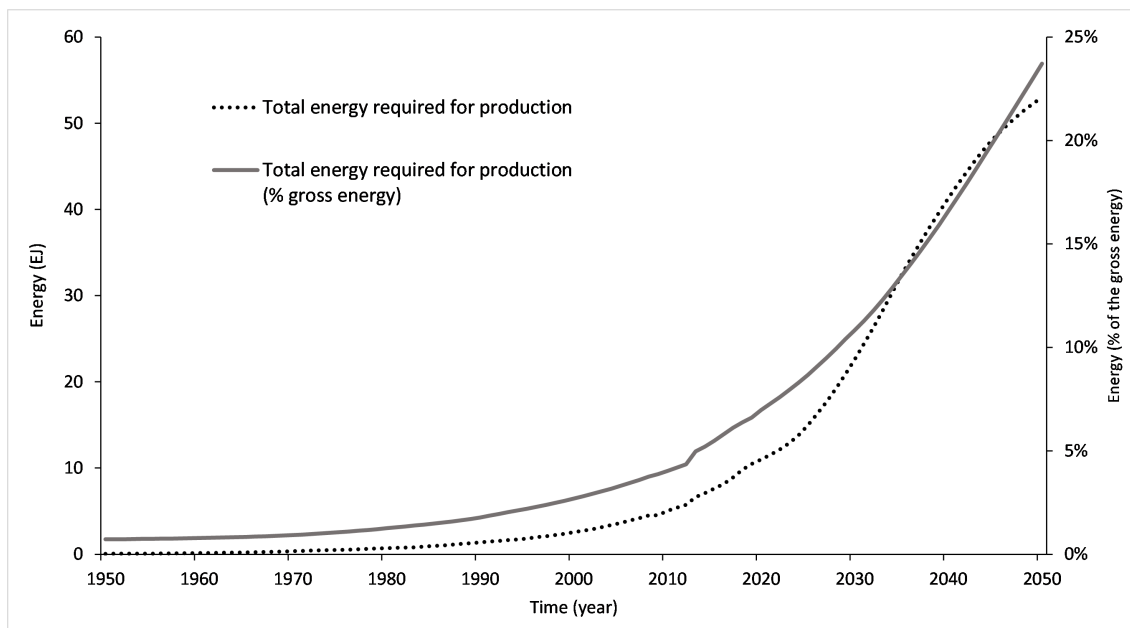


FIGURE 2.9: Evolution of energy required to produce gases from 1950 to 2050.

Output Assessed	High	Medium	Low
Peak year	2038	2037	2036
Peak magnitude	226.4	214.7	189.5
Decrease/increase ratio	0.8	0.9	1.2

TABLE 2.12: Dependence of the results on the EROI estimate hypotheses (high, medium, low).

Output Assessed	Constant	Constant, Decrease	Constant, Bump
Peak year	2037	2037	2037
Peak magnitude	211.8	210.0	211.5
Decrease/increase ratio	0.9	1.0	0.9

TABLE 2.13: Dependence of the results on the decline year hypotheses.

rate for the medium estimate. Table 2.12 summarizes the dependence of the outputs on EROI estimate hypotheses.

Dynamic Functions All the dynamic functions hypotheses present similar features in term of outputs. Taking dynamic functions into account lowers the peak magnitude but does not impact the peak year. However, it has a relative effect on the decrease/increase rates ratio. More precisely, the constant, increase and decrease function (named “constant, bump”) shows little to no difference when compared with other functions. However, these results would benefit from being re-examined with a greater diversity of decline functions, and should be put into perspective with regard to the important contribution of onshore field and offshore shallow gases that have yearly values. Table 2.13 summarizes the dependence of the outputs on the different dynamic functions’ hypotheses.

2.2.3.3. ROBUSTNESS OF THE RESULTS

In order to analyze the robustness of the results, we constructed a 3-level robustness scale. “0” indicates that the evaluation of the net-energy does not give a significant qualitative and quantitative variation compared to the gross energy (when the difference between gross and net-energy output values is less than half of the average standard deviation of net-energy), “+” indicates a qualitative significance (when the difference is of the order of the standard deviation) and “++” a qualitative and quantitative significance (when the difference is more than twice the standard deviation).

From this scale, it appears that net-energy is clearly robust for the peak year, the peak magnitude and the post-peak energy decrease rate, on both the qualitative and quantitative fronts. It is also qualitatively significant for the pre-peak increase rate and the decrease/increase ratio. Overall, these results testify that, in all likelihood, relative trends are independent of our choice of gross energy data. The results of this robustness evaluation are summarized in Table 2.14.

2.2.4. DISCUSSION

2.2.4.1. IMPLICATIONS FOR THE LOW-CARBON ENERGY TRANSITION

This study uses GlobalShift’s all-gases projection and a panel of standard EROI scenarios to characterize the dynamic evolution of the primary stage net-energy of gas along the transition from conventional to unconventional resources.

Output Assessed	Gross Energy	Net-Energy	$\frac{x_{gross} - x_{net,avg}}{\sigma_{net}}$	Scale
Peak year	2040	2037	3.6	++
Peak magnitude	249	211	2.5	++
Pre-peak increase	4.3	3.4	1.8	+
Post-peak decrease	2.6	3.1	2.5	++
Decrease/increase ratio	0.6	0.9	1.8	+

TABLE 2.14: Comparison between gross and net-energy outputs to estimate the robustness of the results.

We estimate the current energy required to produce gas to be in the order of 11 EJ for 2020, which is equivalent to 6.7% of the gross energy production of gas. We also show that if the weighted-average standard EROI of gas production is set to reach an apparent plateau of 16.7, the energy required to produce gas keeps increasing to reach 53 EJ in 2050, which would represent 23.7% of the gross energy produced by gas at that time. Finally, we point out that our model features are robust on the qualitative side, and, for some, on both on the qualitative and quantitative fronts. This means that the relative trends from our results are, in all likelihood, independent of the choice of gross energy data.

Retrieving the energy necessary for the oil liquid production from Delannoy et al. (2021b), we estimate the energy necessary for both fossil fuel production to equal 37.4 EJ in 2020. This is equivalent to the aggregated primary energy consumption of France, Germany, United Kingdom and Italy (BP, 2020). Moreover, the total amount of energy required for the production of oil and gas can be expected to grow exponentially. Increased energy consumption in the energy production sector can be likened to “energy cannibalism”, i.e., a reduction in the energy available for society’s other needs (Pearce, 2008) which itself bears energy security and environmental degradation risks. If we specifically highlight the danger of turning to coal (directly or indirectly) to power the oil and gas industry, the possible use of renewables is not without consequences too, as the production of energy, from whatever source, impacts the environment. Low and diminishing energy returns are, therefore, not only a threat to energy security, but also to the environment itself. We are concerned that both risks might be underestimated and urge energy transition models to adopt a net-energy perspective.

2.2.4.2. ON THE NEED OF NET-ENERGY STUDIES

That said, we feel that the published net energy literature is not sufficiently developed. For instance, interrogations remain on the EROI of renewable and fossil energy sources and their evolution over time (de Castro and Capellán-Pérez, 2020; Rana et al., 2020; Wang et al., 2021). As discussed by Carbajales-Dale (2019), there is significant confusion about the difference between energy return on investment and power return on investment, and not just regarding how to calculate each, but also what they imply. There also appears to be a missing link between economic, financial and net energy indicators, and how energy return can or cannot constrain future development in the long run (King and Hall, 2011; King et al., 2015a,b; King, 2015). We, therefore, believe that the debate would strongly benefit from more precise assessments of static and dynamic net energy ratios, including EROI and PROI, for a wide array of energy sources. We thus call for a new wave of net energy studies, possibly in line with exergy economics.

2.2.4.3. LIMITATIONS AND FUTURE WORK

Our study suffers from three main limitations. First of all, our analysis relies on the use of external gross energy data bought from GlobalShift, which, as for every future scenario, will, in all likelihood, not depict the reality. However, we have pointed out that because the results obtained here should be qualitatively correct, and, in all likelihood, semi-quantitatively correct in net vs. gross relative difference. Furthermore, one should note that the objective of this article is to estimate the impact of the net-energy perspective against the gross energy, rather than guess a peak date and magnitude. Secondly, our EROI scenarios are based on desk-research of the published resources, which comprises several uncertainties. We have attempted to compensate for them by developing a set of scenarios, which are characterized in a sensitivity analysis. Third, we only focused on standard EROI and did not pay attention to the societal EROI, which could be a more meaningful indicator (Brockway et al., 2019). However, restraining ourselves to standard EROI has made the EROIs of different gases more easily comparable (the basis of comparison being clearer and closer to physical extraction and other processes, and, therefore, less subject to interpretation).

Improvements to the present study could be carried out in several ways. First, a more precise assessment of how gas-producing countries would react to strong climate-change restrictions in GlobalShift's model would prove useful to support a faster transition to low-carbon energy sources. Second, the use of more precise EROI estimates or dynamic functions parameters would allow the study to gain in accuracy. Another improvement for EROI would be the use of societal EROI; in this way, net-energy variations along the transition from conventional to unconventional gases would be assessed for the entire value chain, but at the cost of increased uncertainty.

2.2.5. CONCLUSIONS

The industrial society can be likened to a thermodynamic system that profoundly relies on abundant and cheap energy intakes such as oil or gas to thrive (Smil, 2017). However, the rapid growth in use of non-renewable fossil fuels has undermined their future availability, and a shift from conventional sources to unconventional ones has started.

Such a shift has had considerable effects on the net-energy supply of gas. For instance, we find that the total energy needed for the gas production continually increases, from a proportion equivalent to 6.3% of the gross energy produced from gas at present, to 23.7% in 2050. We thus foresee an important use of energy to produce gas in the future, a phenomenon relating to "energy cannibalism" (Pearce, 2008), which bears energy security and environmental degradation risks. Low and diminishing energy returns are, therefore, not only a threat to energy security but also to the environment itself. Although our approach is subject to various uncertainties, the gaps between net and gross energy are statistically significant, to uphold the fact that our results are qualitatively and, to some extent, quantitatively robust. In other terms, this means that the relative trends from our results are, in all likelihood, independent of the choice of gross energy data.

Our findings highlight the necessity to see the energy transition from a net-energy perspective, not only for energy security concerns but also for the multiplication of environmental damages that a low-energy-yield energy production is likely to drive. We thus call for the energy transition debate to adopt a net-energy analysis, and for a new wave of net energy ratios studies, including EROI and PROI, to consider wise energy consumption and its environmental impacts.

2.3. MATERIALS NEEDS FOR INFRASTRUCTURES

Le Boulzec, H., Delannoy, L., Andrieu, B., Verzier, F., Vidal, O., and Mathy, S. Dynamic modeling of global fossil fuel infrastructure and materials needs: Overcoming a lack of available data. *Applied Energy*, 326:119871, 2022. doi:10.1016/j.apenergy.2022.119871

ABSTRACT

The low-carbon energy transition requires a widespread change in global energy infrastructures which in turn calls for important inputs of energy and materials. While the transport and electricity sectors have been thoroughly analyzed in this regard, that of the hydrocarbon industry has not received the same attention, maybe in part due to the difficulty of access to the necessary data. To fill this gap, we assemble public-domain data from a wide variety of sources to present a stock-flow dynamic model of the fossil fuels supply chain. It is conducted from 1950 to 2050 and along scenarios from the International Energy Agency. We estimate the concrete, steel, aluminum and copper requirements for each segment, as well as the embedded energy and CO₂ emissions through a dynamic material flow analysis (MFA) model. We find that (i) the material intensities of oil, gas and coal supply chains (in Mt/EJ) have stagnated for more than 30 years; (ii) gas is the main driver of current and future material consumption; and (iii) recycled steel from decommissioned fossil fuels infrastructures could meet the cumulative need of future low-carbon technologies and reduce its energy and environmental toll. Furthermore, we highlight that regional decommissioning strategies significantly affect the potential of material recycling and reuse. In this context, ambitious decommissioning strategies could drive a symbolic move to build future renewable technologies from past fossil fuel structures.

2.3.1. INTRODUCTION

Human society and nature interactions have experienced a radical change over the 20th century, driven by the rapid industrialization of Western economies and that of several emerging countries in more recent years (Krausmann et al., 2009; Fischer-Kowalski, 2011; Haberl et al., 2020). Economic expansion is largely attributable to the availability and affordability of fossil resources, whose high energy return on investment (EROI) have triggered productivity gains (Hall et al., 2014; Jackson, 2019). The abusive use of energy has however unleashed unprecedented climate and ecological damages, jeopardizing the planet's life supporting functions (IPCC, 2021).

As a tentative response, 196 countries gathered during the 2015 United Nations Climate Change Conference of Paris and agreed to hold the increase in the global average temperature to well below 2°C above pre-industrial levels. Such a target requires deep transformations of our society including, but not limited to, a shift away from fossil fuels to low-carbon energies, which

calls for important quantities of energy and materials (Bihouix, 2010; Vidal et al., 2013; Vidal, 2018; Ali et al., 2017; Bleicher, 2020; Fizaine, 2021). While the transport and electricity sectors have been thoroughly analyzed, the hydrocarbons have not received the same attention, to the best of the authors' knowledge²³. This may in part be due to the fact that infrastructure data for the fossil fuel industries are relatively difficult to access, and are often commercially sensitive. This makes the analysis of this sector particularly complicated for the scientific community not affiliated with fossil fuel producers or operators. To fill this gap, we present a stock-flow dynamic modeling of the infrastructures as a part of the fossil fuels supply chain, from 1950 to 2050 and along scenarios from the International Energy Agency (IEA). We estimate the concrete, steel, aluminum and copper requirements for each segment, as well as the embedded energy and CO₂ emissions through a dynamic material flow analysis (MFA). Finally, the potential of recycling steel from decommissioned fossil fuel infrastructures to build power technologies is further discussed.

This paper is structured as follows. Section 'Literature review' examines the existing literature. Section 'Methods and data' describes the methodology and data used. Section 'Results' presents the results, section 'Discussion' discusses them, section 'Robustness and limitations' details the robustness and limitations of the study and section 'Conclusion' concludes.

2.3.2. LITERATURE REVIEW

2.3.2.1. AN EVOLVING FIELD

Modeling the stocks and flows of metals or minerals that make the infrastructures has been a research topic for more than twenty years. Early publications focus on static global or regional MFA of the base materials used over the 20th century—such as copper and steel. The Stocks and Flows Project (STAF) launched in 2000 by the Center for Industrial Ecology is one example (Graedel et al., 2002; Spatari et al., 2002; Kapur et al., 2003; Vexler et al., 2004). These studies allow for top-down analysis, relying on material databases such as the International Copper Study Group (International Copper Study Group, 2021) and the World Bureau of Metal Statistics (World Bureau of Metal Statistics, 2021)²⁴. The authors aim at providing insights in the material cycles within human society, and quantifying the losses-dissipation, landfills—and the potential of secondary use. Materials analysis has progressively evolved towards dynamic studies, and bottom-up approaches²⁵ enable a better understanding of the technological drivers of raw materials demand over time. A significant number of these publications deal with the building sector because of waste generation and secondary resources aspects (Müller, 2006; Hashimoto et al., 2009; Arora et al., 2019), stock drivers (Wiedenhofer et al., 2015), the effect of lifetime (Hu et al., 2010) or materials demand in transition scenarios (Deetman et al., 2020; Marinova et al., 2020). More recently, several authors also analyze the material facet of the energy sector with growing consideration on the consequences of the ongoing energy transition.

2.3.2.2. THE ENERGY TRANSITION CHALLENGE

The transition requires vast amounts of minerals and metals (Vidal, 2018; Watari et al., 2019; Tokimatsu et al., 2018) due to a significantly higher material intensities of renewables (Kleijn et al., 2011; Elshkaki and Graedel, 2013; Vidal et al., 2013) and new technologies (IEA, 2020a). Vidal et al. (2013) state that "a shift to renewable energy will replace one non-renewable resource

²³The relevant literature is reviewed in Section 'Literature review'.

²⁴A top-down study is defined as a modeling relying on input output tables which assesses stocks from a flow analysis.

²⁵Bottom-up modeling focuses on describing parts of the system in details and then conducting a part-whole modeling.

(fossil fuels) with another (metals and minerals)”, while Li et al. (2020) point out the trend toward a “more metal-intensive energy future” as renewable energy are increasingly being developed. Recent dynamic MFA or simple flow analysis²⁶ focus on quantifying the prospective demand in non-energetic materials for a low-carbon energy system in various institutional scenarios (e.g. IEA-450, IEA Bluemap, NDRC scenarios), non-governmental scenarios (e.g. Greenpeace, WWF-Ecofys) or academic scenarios (e.g. SSP). Researchers show that the most environmentally ambitious scenarios display the highest material constraints (Elshkaki and Shen, 2019; Giurco et al., 2019), and identify two areas of concern: criticality, which is defined as the levels of importance in use and availability of a material (National Research Council, 2008), as well as environmental and energy impacts.

Among low-carbon technologies, the most significant material constraint could stem from solar PV and wind turbines along with power storage (Månberger and Stenqvist, 2018; Giurco et al., 2019) and the transmission and distribution networks (Deetman et al., 2021). A higher level of pressure for rare-earth elements (REE) than for base metals is emphasized, with potential constraint in REE for each PV solar technology (Elshkaki and Graedel, 2013; Elshkaki and Shen, 2019; Davidsson and Höök, 2017), region-specific supply risk (Nassar et al., 2016; Teubler et al., 2018; Shammugam et al., 2019; Beylot et al., 2019; Ren et al., 2021) which require future increase in numerous metal supplies (Habib and Wenzel, 2014; Kavlak et al., 2015) with potential limitations in reserves which could hamper future projects (Grandell et al., 2016). The downscaling of a global issue to a political scale also paves the way to the criticality literature, estimating potential supply risks for various situations (Knoeri et al., 2013; Moss et al., 2013; Goe and Gaustad, 2014; Roelich et al., 2014; Jin et al., 2016; Valero et al., 2018; Lee et al., 2020). Future constraint on raw materials also comes from the energy and environmental impact of their production. While the criticality research field focuses on technological materials, impact analyses are mainly conducted on base materials though the link between energy and materials.

2.3.2.3. RECYCLING AND THE ENERGY-RAW MATERIALS NEXUS

The energy-material nexus remains insufficiently addressed in energy transition scenarios, and several authors call for a better understanding of its impact (Elshkaki and Shen, 2019; Giurco et al., 2019) and for a better understanding of the assessment of the emission costs and gains of the energy transition (Li et al., 2020). Elshkaki and Shen (2019) further estimates that the global energy demand of material production for photovoltaic solar technologies could represent up to 12% of solar power generation in the IEA-450 scenario by 2050, and its CO₂ emissions could reach up to 2.2% of the global emissions. Several policy tools are incorporated in the publications, in order to discuss the upcoming challenges. First, recycling could diversify supply sources to reduce pressure on primary materials (Giurco et al., 2019; Watari et al., 2018) for geopolitical purposes (Habib and Wenzel, 2014), and environmental concerns as dilution of metals in deposits rises (Vidal et al., 2017; Vidal, 2021). However, the short-term objective of energy transition is equivalent to lifetimes of technologies, thus limiting the potential of recycling before 2050 (Vidal, 2018; Moreau et al., 2019; Ren et al., 2021). Second, studies emphasize that material supply pressure could be mitigated by reducing the material content in power generation technologies (Davidsson and Höök, 2017; Elshkaki and Shen, 2019).

²⁶Further modeling on the topic has been conducted through Life-Cycle Analyses. For example, Kleijn et al. (2011) examine the metals demand and CO₂ emissions of low-carbon energies for the power sector, in regard to four different scenarios, while de Koning et al. (2018) estimate the required extraction of 11 metals until 2050 under technology-specific low-carbon scenarios, for the electricity and road transportation systems and Hertwich et al. (2014) take on the issue by approaching the needs in steel, cement, copper and aluminum for power generation technologies in the IEA BLUE Map and Baseline scenarios.

2.3.2.4. TOWARD MORE SYSTEMATIC ANALYSIS

The upcoming material challenge is also addressed in integrated assessment models (IAMs), as a necessary step to produce "biophysically more consistent descriptions of society's future metabolism" (Pauliuk et al., 2017). IAMs allow to quantify the material requirements in scenarios of low-carbon transitions from a system perspective. For instance, Hache et al. (2019, 2020) and Seck et al. (2020) use a modified version of the TIMES model (TIAM-IFPEN) to study the critical materials for the transportation sector electrification, the impact of the future power generation on cement demand and the copper availability up to 2050. Sverdrup and Olafsdottir (2020); Olafsdottir and Sverdrup (2020) and Olafsdottir and Sverdrup (Olafsdottir and Sverdrup, 2021) focus on nickel, helium, copper, zinc and lead using the WORLD7 model. Relying on the MEDEAS integrated assessment model, Capellán-Pérez et al. (2019) assess the material investments necessary for a transition to renewable energies, in a Green Growth narrative, concluding it to be unrealistic.

The literature on the metals and minerals supply pressure stemming from the energy transition has been recently booming. However, despite the large share of fossil fuels in the global primary energy consumption, researchers have to date and to the best of the authors' knowledge not explored in detail the material requirements of the industry on a global scale and in a long-term perspective²⁷. This study attempts to tackle this question and fill the relative literature gap that exists today. To do so, the following methodology is carried out.

2.3.3. METHODS AND DATA

2.3.3.1. THE *DyMEMDS* MODEL

The *DyMEMDS* (Dynamic Modelling of Energy and Matter Demand and Supply) model is developed to estimate the needs in primary and recycled materials, as well as the energy and CO₂ emissions resulting from the extraction of these materials, along global or national energy scenarios²⁸. The entire energy chain is covered from primary energy to final consumption with forty technologies of energy production, storage, transport, transformation along three sectors of energy use: transport, construction and industry; and covers both the global and country-levels (Vidal, 2021). A multi-sector analysis of material stocks and flows is prepared for further work. Only the fossil fuels supply chain module is described in this section²⁹.

Historical infrastructures data and energy scenarios are used to model the hydrocarbon supply chain. When no data are found, we use Gompertz functions of Gross Domestic Product (GDP) and population or correlations with the energy supply. Technological material intensities, recycling rates, normal lifetime distributions and end-of-life recycling rate (EOL-RR) are used to estimate retrospective and prospective flows and stocks of materials. Indirect impacts of the materials demand are evaluated relying on state-of-the-art works on embodied energy and CO₂ emissions of materials. A local sensitivity analysis is finally conducted to assess the effects of the mean lifetime and materials intensities uncertainties. Figure 2.10 presents the methodology lying behind the *DyMEMDS* model.

The most important box, 'raw materials stocks and flows', can be extended for further clarification. The *primary production flow* in tons/year feeds an *in-use stock* in tons of materials immobilized in the infrastructure. At the end of the lifetime of the infrastructure considered, the *in-use stock* is reduced by the flow of materials to be recycled. Normal lifetime distributions

²⁷Only Wang et al. (2015) proposed an estimation of the steel weight of the drilled wells and the transportation pipelines in China.

²⁸For a detailed presentation of the *DyMEMDS* model, see the Appendix of Le Boulzec et al. (2023).

²⁹A detailed description of the inputs is provided in the Supplementary Information.

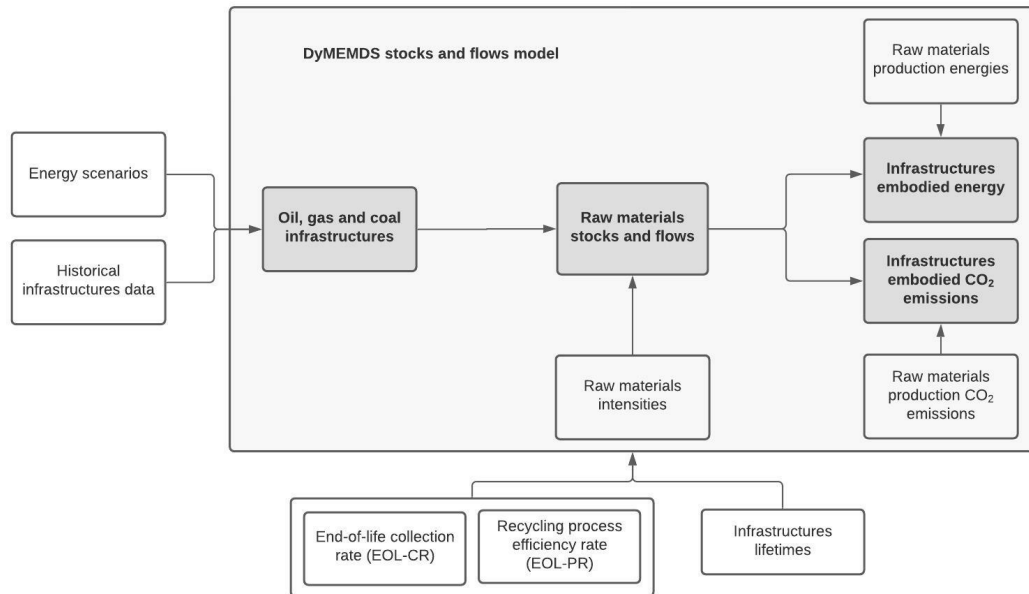


FIGURE 2.10: Simplified methodology lying behind the *DyMEMDS* model, a global model with country-level disaggregation representing infrastructures as well as their materials needs and impact from 1900 to 2050.

are considered in this study. The *losses flow during the recycling process* thus feeds the *cumulative losses stock*, while the *end-of-life recycling flow* builds a *recycled stock*. The latter then allows for secondary production of a *recycled materials flow*, which is ultimately reused in the *in-use stock*. New infrastructures thus mobilize primary and secondary production. In the specific case of a reduction of the infrastructure stock, there is a dismantling before the end of the life span. An *unused flow* is then created, ultimately feeding an *unused stock*, which then follows a recycling path. This stock could eventually produce a *reused flow* for other infrastructures. The infrastructures embodied energy and CO₂ emissions are finally estimated through assumptions about the material production energies and CO₂ emissions. Figure 2.11 details the key loop used in the *DyMEMDS* model to estimate the stocks and flows of materials during the construction and maintenance of the infrastructure.

Infrastructures The infrastructures considered in this study are separated into three main segments according to the historical distinction made in the petroleum industry: upstream, mid-stream and downstream activities. It totals 11 technologies used in supply activities from exploration to distribution. The fossil fuels supply chain encompasses a larger number of infrastructures some are excluded due to a lack of data (oil tanks, national coal transport and processing), large disparities in the data obtained (drilling rigs)³⁰, or difficulties to model future distribution in technologies related to decentralized demand (petrol stations and compressed natural gas services). Figure 2.12 displays the infrastructures typology used in *DyMEMDS*.

Dynamic evolution of infrastructures A stock-driven approach is conducted in order to model the dynamic evolution of fossil fuels associated infrastructures. The evolution of technology stocks is assumed to be correlated with the fossil fuels production (eq 2.10)³¹. Infrastructures

³⁰Significant disparities were observed in both material intensities and rigs census. It is explained by both the recent and rapid development of floating structures and the wide range of structure sizes.

³¹Some researchers rely on logistic or Gompertz functions, see for instance the work of Gutiérrez et al. (2009) for vehicle stocks and Huang et al. (2013) for buildings stocks. The link between hydrocarbon technologies and energy prices, as well as political decisions (e.g. OPEC's

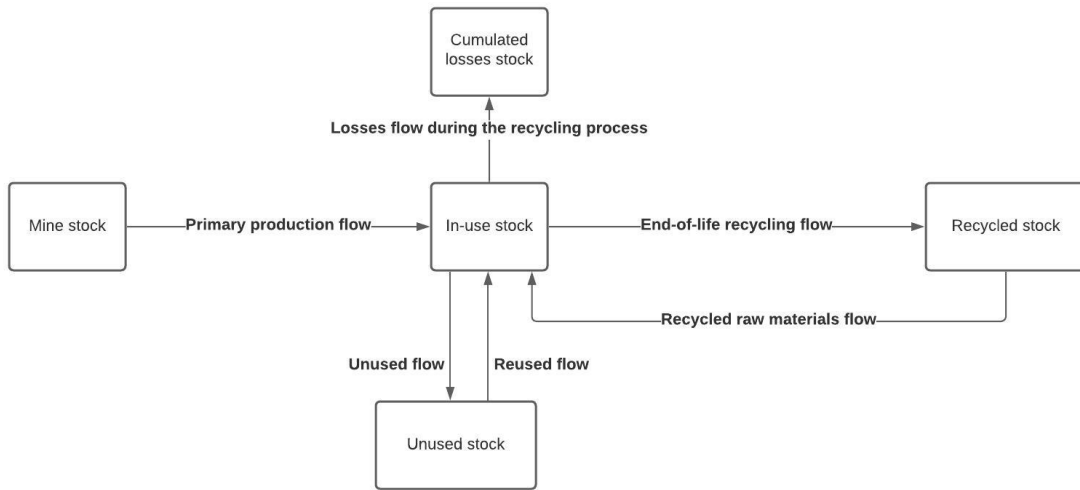


FIGURE 2.11: Key loop used in the *DyMEMDS* model to estimate the stocks and flows of materials during the construction and maintenance of the infrastructure.

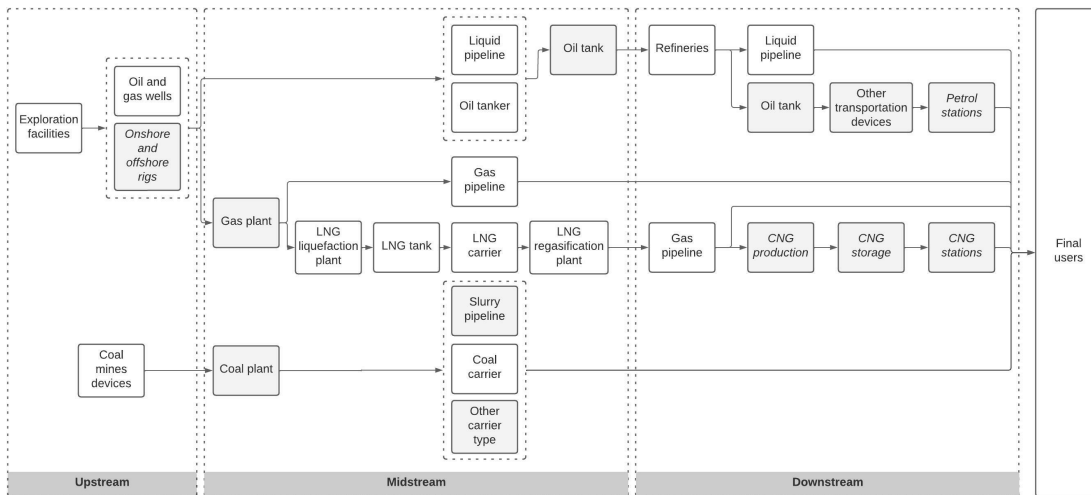


FIGURE 2.12: Oil, gas and coal infrastructures from production to final users supply. The infrastructures in grey and italic are not considered in this study.

	1950	2010	2030	2050
Concrete	0	0	0	0
Steel	0.6	0.7	0.74	0.84
Aluminum	0.39	0.45	0.48	0.54
Copper	0.34	0.4	0.42	0.48

TABLE 2.15: End-of-life recycling rates of the considered materials.

are then attributed to a fossil fuel, either fully (eg. oil tankers only carry petroleum products) or in a proportionate manner (eg. wells produce both oil and gas). In this case, the evolution of each infrastructure stock is correlated to its related share of fossil products in the supply chain using historical and prospective shares of oil, gas and coal traded from BP (BP, 2021) and the IEA³² (IEA and KEEL, 2019).

Substantial annual variations are observed in hydrocarbon production, but only wells experience significant upwards and downwards annual changes. An adapted function of each fossil fuel supply was established to prevent these variations. It is defined as a third-order exponential moving average³³ (eq 2.11), which enables both to smooth out the short-term impact of price variations on production and to overweight the more recent values.

$$S_{t,i} = \alpha_i \cdot \text{EMA}_{3,P_i}(t) \quad (2.10)$$

$$\text{EMA}_{3,P_i}(t) = P_i(t) \cdot 0.5 + \text{EMA}_{3,P_i}(t-1) \cdot 0.5 \quad (2.11)$$

With $S_{t,i}$ the stock of infrastructure i in the year t , α_i the correlation coefficient for the infrastructure i and $\text{EMA}_{3,P_i}(t)$ the third-order exponential moving average in year t of the hydrocarbon supply P_i related to the infrastructure i .

Material recycling This study focuses on four bulk materials, namely aluminum, concrete, copper and steel, which represent a significant share of material consumption (USGS, 2021a), energy demand and environmental impacts of material production (Bataille, 2019). No material substitution is assumed for the base materials, but some studies present contrasted views, e.g. Sverdrup et al. (2014); Sverdrup and Olafsdottir (2019). A dynamic end-of-life recycling rate (EOL-RR) is assumed for each material, encompassing both the recycling process efficiency rate (EOL-PR) and the old scrap collection rate (EOL-CR), as defined by Glöser et al. (2013) and Graedel et al. (2011). A global and multi-sectoral averaged EOL-CR is assumed in this study. Table 2.15 summarizes the considered rates.

2.3.3.2. MATERIALS, ENERGY AND CO₂ INTENSITIES

The material requirements for the hydrocarbon production infrastructures are obtained from Monfort-Climent et al. (2021). The dataset extensively relies on the Ecoinvent database³⁴, which provides with useful data for a large panel of infrastructures. Remaining intensities are obtained from both academic publications and private firms reports. The material intensity

influence on prices) hamper the application of this methodology here.

³²A high share of traded oil is noticed, while coal and natural gas are mostly consumed locally.

³³A moving average is defined as an average of a predefined number of past values in a dataset, which are weighted equally in its simple form. In its exponential form, the weight of the values decreases exponentially, which enables to outweigh the more recent data.

³⁴The Ecoinvent database contains life-cycle inventory data for a wide range of technologies, with a thorough documentation on their hypothesis and validity (e.g. geographical and temporal).

data used in this study come mostly from sources dating from the 1960s to the 2000s. The correlation between infrastructure stock and hydrocarbon production justifies the temporal validity of these data for the study, since nearly 60% of historical oil production and 57% of historical gas production took place between 1960 and 2000 (Court, 2016). The embodied energies of primary and secondary materials are dynamic between 1900 and 2100, and their scope extends from cradle to gate. Primary metals embodied energies depend on both the ore grade of the mined material and the technological improvement of production technologies (Norgate et al., 2007; Birat et al., 2013; Gutowski et al., 2013). Data from Vidal (2021) and Vidal et al. (2021) are considered for copper, aluminum, and steel (assuming all steel alloys represent steel). The production energy of concrete is estimated from a multi-regional approach to cement production and clinker energy intensities. Energy of metal recycling is assumed to be consumed during secondary production as a fraction of the energy of primary production. An annual technological progress in production processes of 1% is estimated between 1900 and 2100, as well as a floor value equal that of the thermodynamic limit of the recycling processes. The minimum energy of recycling equals the melting energy of each metal plus the energy of collection and sorting. CO₂ intensities of materials production are also considered in the model: they are dynamic and vary according to the CO₂ intensity of the energy consumed over time. We consider a decreasing intensity since 1900, and assume that 83g of CO₂ are emitted by MJ of consumed energy in 2015. This value is supposed constant from 2015 onward.

2.3.3.3. SCENARIOS

Two scenarios from the International Energy Agency (IEA) are selected: the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 (NZE) (IEA, 2020a, 2021b).

- The STEPS considers government measures already in place or officially announced and envisions a quick return to pre-COVID-19 consumption levels. By 2050, the electricity mix is 55% renewable, coal consumption falls by 15% from 2020, oil consumption rises by 15% and gas consumption rises sharply by 50%. The effects of climate change are limited to an average global warming of 2.7°C in 2100 compared to pre-industrial levels (Fig. 2.13).
- The NZE scenario offers a more ambitious approach. Considered by the IEA as a deepening of the former Sustainable Development Scenario (SDS) (IEA, 2020b), it assumes the achievement of a carbon neutrality of the energy sector by 2050, which allows to limit the average global warming to 1.5°C. Renewable energies play a predominant role, with solar and wind power accounting for nearly 70% of electricity production in 2050. Moreover, energy demand falls by 7% between 2020 and 2050, with a decline in coal consumption of 90%, 75% for oil and 55% for gas over the same period (Fig. 2.13). When some information is missing, data from the Sustainable Policies (SP) scenarios are used instead (IEA and KEEI, 2019).

2.3.3.4. SENSITIVITY ANALYSIS

A local sensitivity analysis was conducted to assess the impact of the input parameters uncertainties on outputs. Previous studies showed the significant share of lifetime uncertainty impacts in sensitivity analysis (Hu et al., 2010; Pauliuk et al., 2013), and further pointed out that the standard deviation and shape of lifetime distributions had little effects on the results compared to the mean value (Wiedenhofer et al., 2019; Glöser et al., 2013; Müller et al., 2011).

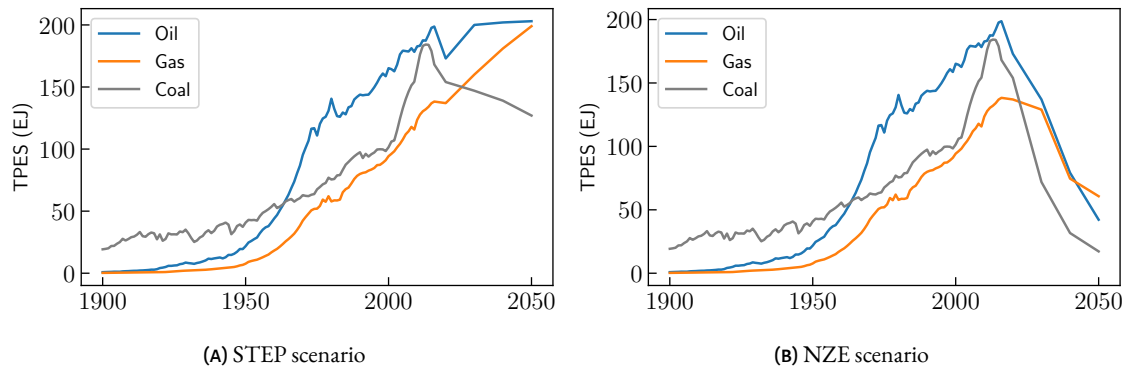


FIGURE 2.13: Historical and prospective global primary energy supply from fossil fuels in the STEPS and NZE scenarios.

The sensitivity analysis therefore focuses on the mean lifetime value in the normal distribution, for which variations of $\pm 20\%$ were computed.

2.3.4. RESULTS

2.3.4.1. INFRASTRUCTURES

Gas The gas infrastructures experience a significant increase in the STEPS and a drop after a peak in 2030 in the NZE scenario. The largest increase in infrastructure occurs for gas in the STEPS. The world fleet of LNG carriers reaches more than 1200 units in 2050 in the STEPS, the storage capacity exceeds 136 million cubic meters and the total capacity of liquefaction and regasification plants doubles to more than 3700 billion cubic meters between 2020 and 2050. Conversely, the carbon neutral NZE scenario involves 40% decrease in total LNG supply chain capacity between 2020 and 2050. The number of LNG carriers drops to 376, after peaking at 788 vessels in 2030. The global pipeline network displays a similar trend, raising to 15 million kilometers in 2050 in the STEPS, and dropping to less than 5 million kilometers in the NZE scenario (Fig. 2.14). The modeled values of the infrastructures stocks are available in the Supplementary Information.

Oil Two trends of the infrastructure of the oil supply chain can be identified. After a slight increase between 2020 and 2030, the stock stabilizes in 2030 in the STEPS, while a slowdown is observed in the NZE scenario between 2020 and 2025 and followed by a substantial reduction. This unveils a significant constraint on the infrastructures mobilized in the oil supply stages. Pipelines, tankers and refineries experience a drop in their stock by nearly 75% between 2020 and 2050. The number of pipelines decreases to 242,000 km, and the tanker fleet to only 150 Million Dead Weight Tons (MDWT)³⁵. In the STEPS, the growth of the traded oil shares combined with the rise of the oil consumption induces a faster development of transport infrastructures than storage or refineries. The stock of petroleum products pipelines reaches 1.08 million kilometers in 2050, and the fleet of tankers 670 MDWT, while the global refining capacity increases to nearly 108 million barrels per day. Wells development depends the cumulative consumption. The number of wells thus slightly raises from 1.35 million to 1.4 million in 2050 in the STEPS and experiences a substantial decrease to 300,000 in the NZE scenario (Fig. 2.14).

³⁵The DWT is a unit of the total carriage capacity of a vessel, including all types of goods and passengers.

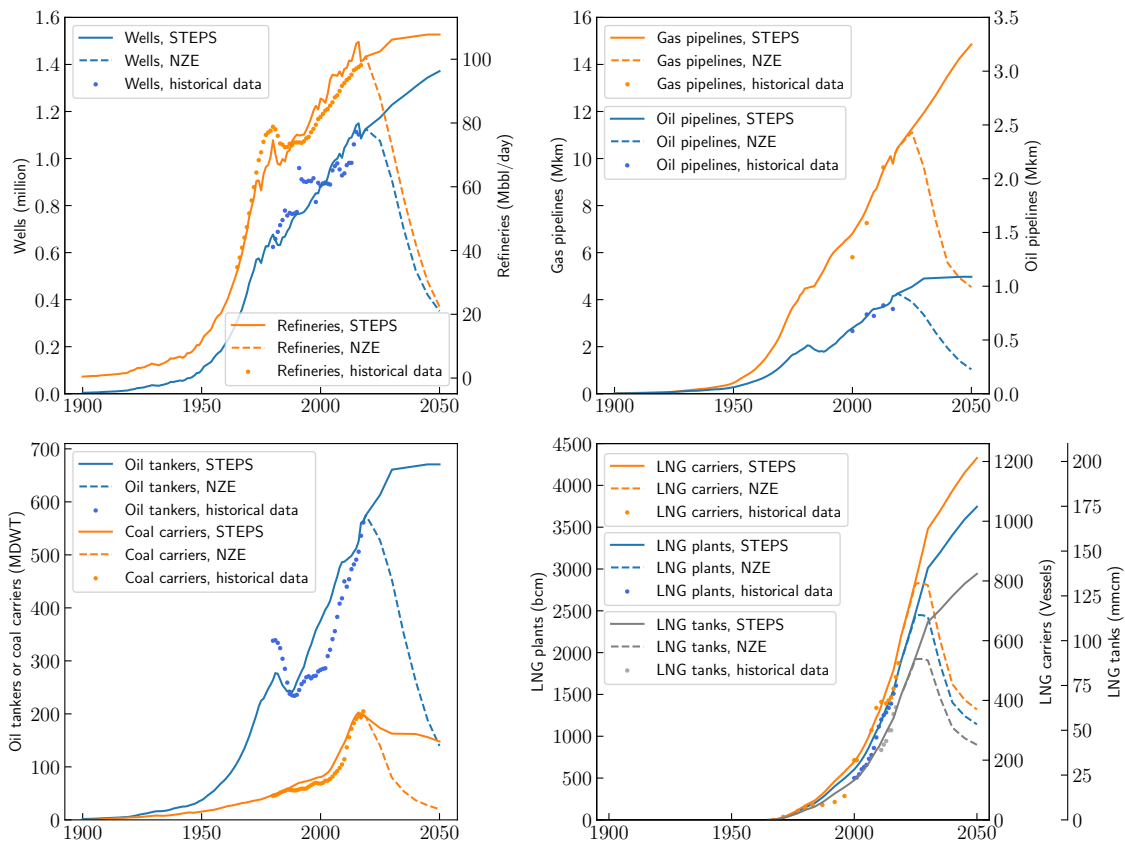


FIGURE 2.14: Historical and prospective stocks of key infrastructures in the STEPS and NZE scenarios, global scale.

Coal The two global scenarios consider a drop in coal consumption between 2020 and 2050, albeit of varying magnitude. The bulk carrier fleet thus collapses over the period and finally reaches 150 MDWT and 21 MDWT in 2050, respectively, in the STEPS and NZE scenarios (Fig. 2.14).

2.3.4.2. MATERIALS

Steel is the main source of materials requirements for fossil fuels. It represented nearly 70% of the sector materials demand between 1950 and 2020, and the remaining 30% is mainly concrete. In contrast, aluminum and copper consumption represent 0.04% and 0.06%, respectively. However, these proportions conceal major disparities in absolute annual consumption, depending on the evolution of the oil, gas and coal markets. A first peak in consumption can be observed in 1973, following the increase in hydrocarbon consumption since the early 1940s. The annual demand for concrete raised from 2.8 Mt/yr to 42 Mt/yr and steel consumption grown from 4.4 Mt/yr to 64 Mt/yr between 1940 and 1973. The succession of two oil peaks in 1973 and 1979 then reduced the demand for materials to almost zero for steel, concrete and copper, while the dependency of aluminum demand to oil products infrastructures drove its value to zero. The knowledge of historical material demand allows to estimate historical materials intensities for the global fossils supply chain. Their values between 1950 and 2016 are displayed in Fig. 2.15. We observe a stabilization of their level since the 1970s, despite a significant drop in the sector’s aluminum intensities in the 1990s.

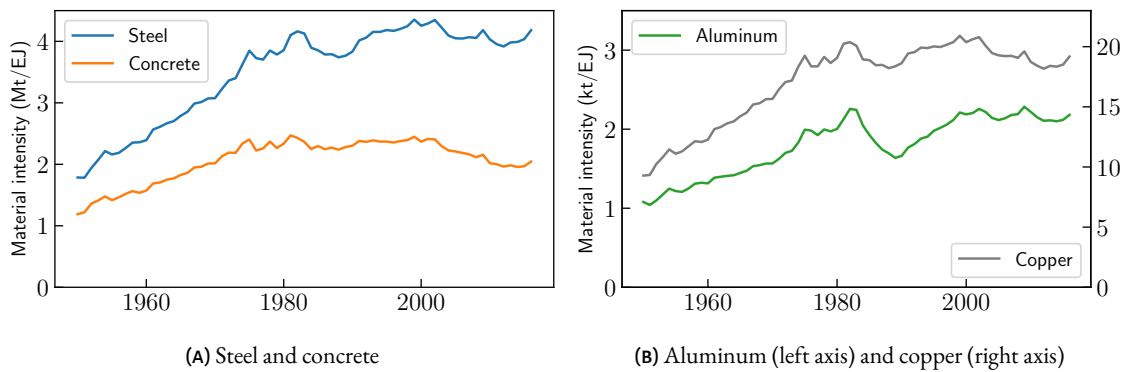


FIGURE 2.15: Historical material intensities in the fossils supply sector from 1950 to 2016.

2.3.4.3. MATERIAL CONSUMPTION IN THE SCENARIOS

The historical distribution pattern of the cumulative consumption among the four structural materials remains similar in the scenarios. Steel accounts for 70% of the cumulative sectoral material demand between 2020 and 2050 for the STEPS and over 77% in the NZE scenario. The share of concrete in the total consumption experiences a decrease in the scenarios considered and aluminum and copper shares remain low. The increase of the hydrocarbons demand until 2025 induces higher peak material requirements than those observed historically. The steel, aluminum and copper demands respectively reach 96 Mt, 80 kt and 0.44 Mt in 2025. In the STEPS, the cumulative flow of steel needed between 2020 and 2050 is 2.4 Gt and that of concrete exceeds 1 Gt. This represents 1.4 years of total global production at 2020 levels for steel, and a small amount compared to an estimated total global production of 20 to 24 Gt in 2020 for concrete (USGS, 2021a,b). The NZE scenario requirements reach 0.34 Gt for steel and 0.1 Gt for concrete. An identical trend is observed for copper and aluminum. The cumulative demand for copper reaches 11 Mt in the STEPS, compared to a total global production of 20 Mt in 2020, and cumulative demand drops to only 1.5 Mt in the NZE scenario. The total aluminum requirements amount to 0.86 Mt for the STEPS and 51 kt for the NZE, which respectively represents 1.3% and 0.08% of 2020 total global production. The combination of this lower consumption and the identical historical stock allows the NZE scenario to rely more heavily on recycled materials. The proportion of recycled metals reaches more than 80% in the NZE scenario, and 29% to 42% in the STEPS scenario. The stock of concrete reaches more than 1.2 billion tons in 2050, while a substantial drop to 0.35 billion tons is observed in NZE scenario. This trend is similar for the three structural metals, and steel stock amounts to 2.9 billion tons in the STEPS and 0.82 billion tons in the NZE scenario in 2050 (Fig. 2.16). The peaks and drops observed in the stock evolution in 2017 are explained by the differences between the historical and prospective data.

Material consumption per fossil fuels and segments The oil and gas infrastructures represent most of the raw materials, which is explained by the complexity and decentralization of the supply infrastructures. The aluminum is entirely consumed by the oil product pipelines for all scenarios—due to underlying data—and the midstream segment therefore dominates aluminum consumption. Conversely, the split between oil and gas remains more equal for concrete, steel and copper, although there is a clear trend towards an increase in the share of gas in materials demand over time. The share of gas in concrete consumption evolves from 30% to nearly 60% between 1950 and 2050 and from 45% to nearly 70% over the same period for steel. The distribution between the segments also shows important differences. The upstream segment

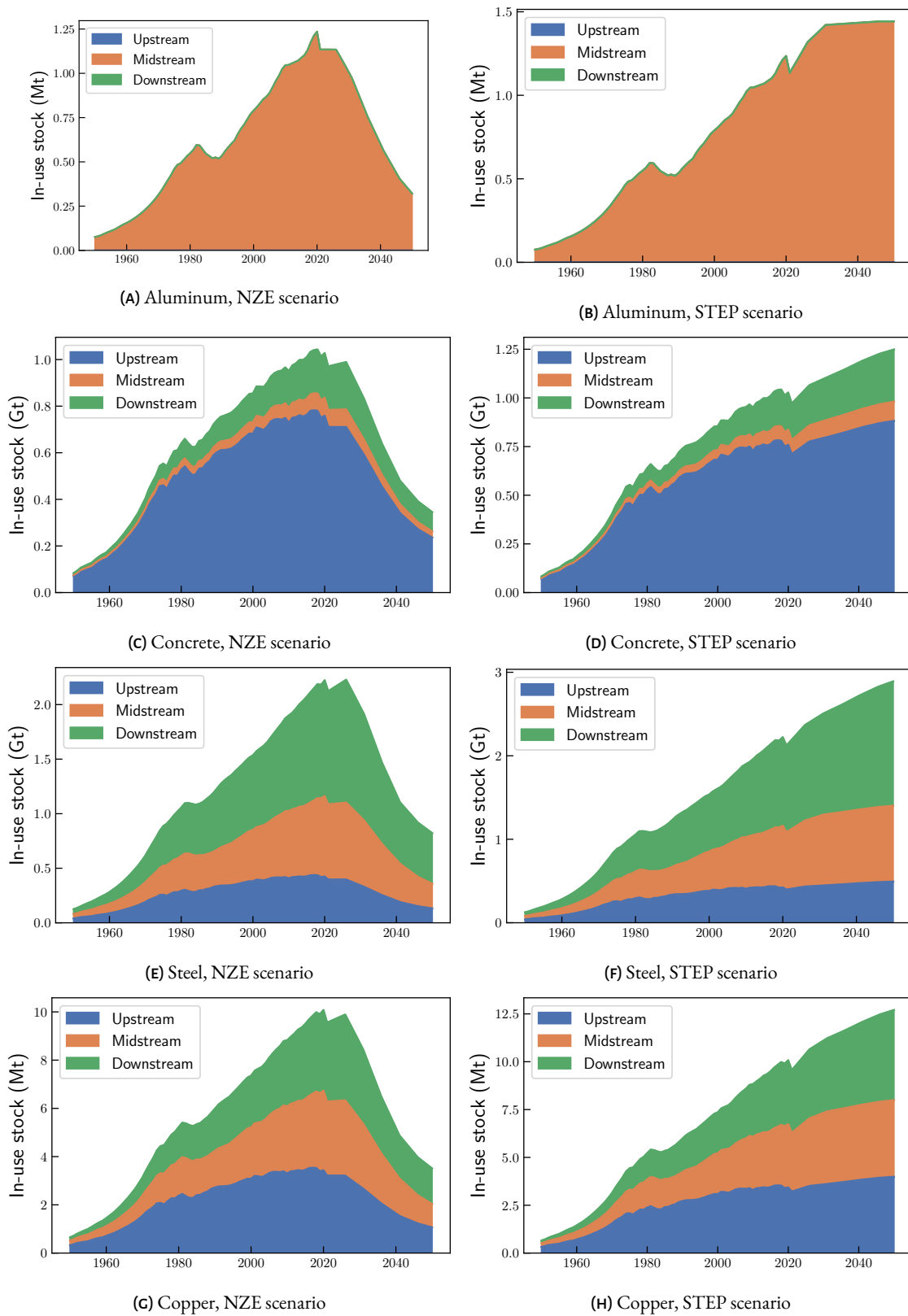


FIGURE 2.16: Historical and prospective stocks of structural materials in the NZE (left column) and STEPS (right column) scenarios.

represents most of the concrete demand between 1950 and 2050—in the production of wells—while a more equal distribution is observed for steel and copper.

Material consumption per infrastructures The bulk materials demands show high level of domination of some infrastructures. Wells represented about 80% of concrete consumption until 1970 and their share declined with the progressive development of gas pipelines, which share reaches about 25% in 2050 in the STEPS. A slight increase of the oil pipeline share was noticed, finally reaching 5% in 2050. The gas network also carries most of the sectoral steel demand. Its share experienced a rise from 45% of the consumption between 1950 and 1970 to almost 60% in 2050 in the STEPS. The wells have an opposite profile and the oil pipelines represent 20% of steel demand over the period. Copper is mostly consumed in steel alloys in the hydrocarbon supply chains. It therefore displays a distribution profile similar to steel. Finally, nearly all aluminum is consumed in oil pipelines—due to the underlying data.

Opportunity and uncertainties in the future amount of recycled materials The share of recycled materials in the hydrocarbon supply chain increased over time. It evolved from 3% in 1950 to nearly 20% in 2020, with disparities depending on the metals considered. A future stabilization or drop in the fossil fuels demand could further induce a substantial rise of the recycled share of metals inflow in 2050, as pointed out in the STEPS and NZE scenarios. The combination of this trend with a lower production energy of recycled metals results in an overall decline of the embodied energy and CO₂ emissions in the oil, gas and coal infrastructures. A high recycling content of material depends on the EOL-RR of the hydrocarbon supply industry, which could be hampered by the evolution of the EOL-CR of the fossil fuels supply sector. The future of the unused infrastructures is a growing research field (e.g. OGUK (OGUK, 2020) in the United Kingdom and Kaiser (Kaiser, 2018) in the Gulf of Mexico), and regional political decommissioning strategies will have significant impacts on the EOL-CR. Simulation of several decommissioning strategies by declines of 20% and 50% of the EOL-CR on the obsolete stock of steel are displayed in Figure 2.17. An estimated 0.8 billion tons of steel alloys are estimated to be accumulated in landfills or leave in-situ by 2050 in the STEPS. A decrease by half of the EOL-CR could lead to a substantial rise of this amount to almost 2 Gt by 2050. Similar results are observed in the NZE scenario, which is explained by the time-delay impact of the lifespan on end-of-life flows. The decommissioning scenarios will therefore have significant effects on the possibilities of recycling.

2.3.4.4. ASSOCIATED ENERGY AND CO₂ EMISSIONS

The energy consumed to produce the materials increased significantly between 1950 and 2019. A domination of steel is observed in the historical and future results. It raised from 0.5 EJ to more than 1 EJ between 1950 and 2019, which represents about 0.15% of the world's primary energy demand in 2019. The energy requirements experience a slight drop to 0.96 EJ in 2050 in the STEPS and to only 0.08 EJ in the NZE scenario in 2050 (Fig. 2.18). This represents 0.1% of global final energy consumption in 2050 in the STEPS scenario and 0.02% in the NZE. A substantial rise is observed in the CO₂ emissions of sectoral materials production between 1950 and 2019. It evolves from 50 MtCO₂ to more than 130 MtCO₂, i.e. 0.4% of global emissions in 2019. They first peaked at more than 200 MtCO₂ in 1973, before decreasing sharply in the 1980s. The trajectories observed in the scenarios allow for a slow decrease to 86 MtCO₂ in 2050 in the STEPS scenario and a significant drop to 25 MtCO₂ in the NZE scenario (composed only of recycling-related emissions, Fig. 2.18).

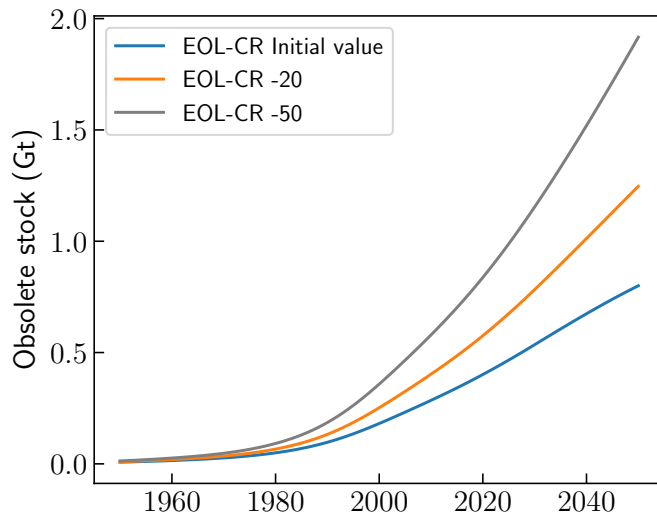


FIGURE 2.17: Obsolete steel stock in the hydrocarbon supply chain from 1950 to 2050 in the STEPS.

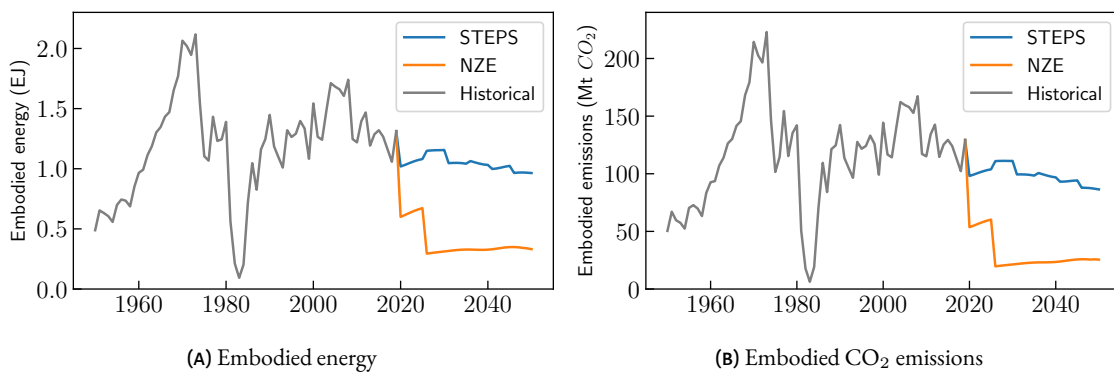


FIGURE 2.18: Embodied energy and CO₂ emissions of materials supply in the STEPS and NZE scenario.

2.3.4.5. SENSITIVITY ANALYSIS

The local sensitivity analysis focuses on the mean lifetime value, for which variations of $\pm 20\%$ were computed. The results show that the materials inflows vary between -11% and $+14\%$, and the outflows changes range from -14% to $+19\%$. Higher impacts are observed in the outflows than on the inflows, as well as in the STEPS than in the NZE scenario.

2.3.5. DISCUSSION

2.3.5.1. DRIVERS OF DEMAND AND MATERIALS INTENSITIES IN THE FOSSILS SUPPLY SECTOR

The bulk materials computed in this study display different drivers. It was found that the midstream and downstream segments are the main drivers of steel, copper and aluminum demand. Conversely, the upstream segment constitutes the main consumer of concrete, ahead of the midstream activities. Those global findings can be extrapolated to national oil, gas, and coal industries. Indeed, a segmentation of countries depending on their profile (producer and/or consumer, oil, gas and/or coal) allows to estimate their materials demand pattern. A mainly consumer country is assumed to have a developed upstream segment on its domestic territory and thus a more significant share of concrete in the material demand than the global share depicted in this study. However, detailed sector data are required to accurately assess national materials demands. Sector materials intensities for the global fossils supply chain were estimated in this study (Fig. 2.15), and further intensities by segments were assessed (Figures S9 to S12 in the Supplementary Information). It allows for a first order evaluation of the materials consumed per EJ of fossils produced and can be useful in future top-down materials modeling studies.

2.3.5.2. WHAT POTENTIAL FOR FOSSIL FUELS STRUCTURES TO PROVIDE MATERIALS FOR THE ENERGY TRANSITION?

The estimated amount of materials consumed in the hydrocarbon supply chain remains low compared to the global demand—with about 5% of the steel consumption, 1.7% of the copper and smaller share for aluminum and concrete—and to others sectors. A comparison of material intensities, annual demand, cumulative demand and in-use stock with previous studies is provided in Table 2.16 for both the power infrastructures and the fossil fuels supply chain. The renewable and fossil primary energy supply in scenarios considered in the studies are summarized in Table 2.17. The current steel demand and in-use stock estimated in this study are higher than in the power infrastructures computed by Deetman et al. (2021), while concrete, copper and aluminum needs remain well below. A similar trend is observed for the in-use stocks, and an estimation of the base materials need for the fossil fuels infrastructures in SSP2 BL and SSP2 450 are provided in Table 2.16 for comparison basis with the results for renewable energies, grid and storage in Deetman et al. (2021). Conversely to copper, aluminum and concrete, the steel in-use stock in the fossil fuels supply chain remains twofold the amount in the renewables and power infrastructures in 2050.

Only the recycling of steel from end-of-life or decommissioned fossil fuels structures could potentially provide a significant contribution to the construction of low-carbon infrastructures. However, it will depend on both future fossil fuel and renewable supply. Relying on data scenarios and sectoral material intensities (Table 2.16), an estimation of the available recycled steel is provided in Table 2.17 and hereafter compared with the cumulative demand for the renewable technologies. An EOL-RR of 0.8 was assumed, and the actual available amounts will ultimately depend on the evolution of the collection rate. We observe that the increase of fossil fuels demand in the STEPS, SSP2 BL and 450 hinders any secondary steel use in the construc-

References	Steel (<i>iron</i>)	Concrete	Copper	Aluminum	Years	Technologies	Scenarios
			Sectoral material intensities (Mt/EJ)				
Deetman et al. (2021)	5.9	54	0.4	1.5	2015	PG+G+S	Historical
This study	4	2	0.02	0.002	2015	HU+HM+HD	Historical
This study	3.8	2.5	0.023	0.006	2015	Oil	Historical
This study	9.7	3.8	0.038	0	2015	Gas	Historical
			Demand (Mt/yr)				
Deetman et al. (2021)	29	184	2.1	7	2015	PG+G+S	Historical
This study	79	30	0.4	0.04	2015	HU+HM+HD	Historical
Deetman et al. (2021)	58	108	4.2	14	2050	PG+G+S	SSP2 BL
Deetman et al. (2021)	75	227	4.9	16	2050	PG+G+S	SSP2 450
Vidal (2018)	50	200	1.7	5.5	2060	R	Bluemap
Vidal (2018)	600	1600	5.5	23	2060	R	GO
This study	2.3	0.2	0.01	0.005	2050	HU+HM+HD	NZE
This study	86	34	0.37	0.05	2050	HU+HM+HD	STEPS
			Cumulative demand (Mt)				
Vidal et al. (2017)	1,000	N/A	40	160	2000-2050	R	Bluemap
Vidal et al. (2017)	12,000	N/A	200	300	2000-2050	R	GO
Månberger and Stenqvist (2018)	N/A	N/A	40-170	N/A	2010-2050	R+T	B2D
Moreau et al. (2019)	840	N/A	57	94	2010-2050	R+S	WWF
Moreau et al. (2019)	1,500	N/A	32	46	2010-2050	R+S	2D
Moreau et al. (2019)	900	N/A	78	130	2010-2050	R+S	IRENA REMAP
This study	1,000	390	4.6	0.6	2010-2050	HU+HM+HD	NZE
This study	3,200	1,300	14	1.9	2010-2050	HU+HM+HD	STEPS
			In-use stock (Mt)				
Deetman et al. (2021)	521	4,772	38	132	2015	PG+G+S	Historical
This study	2,000	1,000	9.3	1.1	2015	HU+HM+HD	Historical
Deetman et al. (2021)	1,456	9,199	98	365	2050	PG+G+S	SSP2 BL
This study	2,880	1,390	12.6	0.77	2050	HU+HM+HD	SSP2 BL
Deetman et al. (2021)	1,413	8,386	91	319	2050	PG+G+S	SSP2 450
This study	2,700	1,340	12	0.86	2050	HU+HM+HD	SSP2 450
Vidal (2018)	5,000	1,200	40	120	2060	R	Bluemap
Vidal (2018)	32,000	13,200	140	480	2060	R	GO
This study	820	350	3.5	0.3	2050	HU+HM+HD	NZE
This study	2,900	1,250	12.7	1.4	2050	HU+HM+HD	STEPS

TABLE 2.16: Summary of the materials intensities, demand, cumulative demand and in-use stock consumed in the power generation, storage and grid infrastructures and comparison with the hydrocarbon supply chain. PG = power generation, R = renewables, G = power grid, S = power storage, T = electric transportation, HU = hydrocarbons upstream, HM = hydrocarbons midstream, HD = hydrocarbons downstream, GO = scenario by García-Olivares et al. (2012). Value do not sum due to rounding.

tion of low-carbon infrastructures. Conversely, moderate reduction of fossil consumption in the Bluemap, 2D and B2D scenarios could allow to partially supply the cumulative steel need of the power technologies³⁶. Finally, significant amounts of steel could be recycled in the WWF-Ecofys, NZE and GO scenarios, which would potentially meet the cumulative steel demand of the renewable and power storage infrastructures in the WWF-Ecofys scenario. It would only represent about 17% of the need in the GO scenario, which considers a 100% renewable energy mix. Through intensive recycling of decommissioned infrastructures, the accumulated steel stock in the fossil fuels supply chain could therefore represent an achievable means to reduce the energy and environmental toll of material use for the energy transition.

2.3.5.3. THE NEED TO CONDUCT AMBITIOUS DECOMMISSIONING STRATEGIES

The significant potential of recycling materials-and especially steel-in end-of-life fossil fuels structures was identified previous sections. We estimated that the current in-use stock of steel

³⁶Careful attention must be paid to the technological scope of each study.

Scenario	Year	Renewable supply (EJ)	Fossil supply (EJ)	Total TPES (EJ)	Estimated available recycled steel (Mt)	Reference
Historical	2015	23	370	474	N/A	IEA (2021c)
SSP2 BL	2050	84	694	842	0	Riahi et al. (2017)
SSP2 450	2050	98	590	771	0	Riahi et al. (2017)
Bluemap	2050	125	297	674	510	IEA (2010b)
WWF-Ecofys	2050	144	13	262	1,500	Singer et al. (2011)
2D	2050	152	269	633	470	IEA (2017)
B2D	2050	172	192	581	830	IEA (2017)
STEP	2050	193	490	742	0	IEA (2021c)
IRENA REMAP	2050	222	166	494	N/A	IRENA (2018)
NZE	2050	258	110	550	1,000	IEA (2021b)
GO	2050	389	0	389	2,000	García-Olivares et al. (2012)

TABLE 2.17: Primary renewable, fossil and total energy supply in 2050 in energy transition scenarios. Bioenergy is not accounted for in the renewable supply. The available recycled steel is estimated from the steel in-use stock in 2015 and the scenarios fossil supply in 2050, assuming a 0.8 EOL-RR. GO = scenario by García-Olivares et al. (2012).

could provide large amount of secondary materials to build the future renewable technologies, but that the future EOL-RR could substantially impact recycled materials availability. Two main elements could affect the EOL-RR. First, most of the copper of the fossil fuels supply chain is consumed in steel alloys (e.g. stainless steel, 7% nickel steel and 36% nickel steel in LNG infrastructures), for which down-cycling³⁷ is frequently observed. Hatayama et al. (2010) and Ciacci et al. (2017) outlined the losses of copper in alloys recycling and changes in functionality of complex recycled steel alloys. Second, partial or total phasing-out of fossil fuels will require decommissioning policies. Many strategies can be adopted depending on the technology (e.g. removal, partial removal, left in place, reefing or left in place and repurposed) and will impact the EOL-RR. The removal process of the infrastructures could generate substantial energy consumption and environmental impacts (Tan et al., 2021), which-if recycled-could be compared to the savings from avoiding the extraction of primary materials at a global scale in future studies.

Decommissioning remains decisive to avoid both indirect environmental impacts (e.g. preventing primary material production) and direct environmental impacts³⁸ (e.g. GHG emissions of abandoned wells (Boothroyd et al., 2016; Kang et al., 2016; Davies and Hastings, 2022)³⁹). Ambitious decommissioning policies could allow to enhance material recycling and reuse⁴⁰. However, some processes will require material demand (e.g. cement plugs of oil and gas wells), a part of the estimated in-use stock will inevitably be left in place (e.g. the materials embedded in the wellbore (Vrålstad et al., 2019)) and prohibitive collection price could hamper material recovery⁴¹. The EOL-CR will ultimately be impacted by the primary material prices and the local decommissioning policies. At a global scale, decommissioning remains at its early stage, and while some countries pave the way for ambitious policies (Kaiser, 2018; OGUK, 2021), other display nascent strategies (Melbourne-Thomas et al., 2021). However, the climate emergency

³⁷Down-cycling is defined as the recycling resulting in a lower quality of materials, and therefore a loss of functionalities.

³⁸The materials and environmental opportunities of decommissioning have been emphasized (Ekins et al., 2006; Sommer et al., 2019).

³⁹Significant methane emissions have also been identified during the operational phase (Lauvaux et al., 2021). The study shows that large methane emissions during maintenance or failures of oil and gas equipments could represent between 8% and 12% of the sector global methane emissions.

⁴⁰Davies and Hastings (Davies and Hastings, 2022) estimated that a 16,000 tons steel jacket left in place and repurposed could retain 55,040 tCO₂eq in GHG emissions.

⁴¹Raimi et al. (2021) estimated median prices for wells plugging and surface reclamation to \$76,000 in the US, with significant disparities.

urges to take rapid action to reduce the environmental toll of human activities, and ambitious decommissioning strategies could provide an additional way to increase materials recycling and reuse.

2.3.6. ROBUSTNESS AND LIMITATIONS

2.3.6.1. ROBUSTNESS CRITERIA AND LOCAL SENSITIVITY ANALYSIS

The dynamic modeling of the hydrocarbon production and supply infrastructure stock proposed in this study represents a simple global approach to the sector, focusing on the main infrastructures. This model needs to be robust and transparent, and several robustness criteria have been identified. First, the stock modeling results are satisfactory for nine of the eleven infrastructure types modeled from energy production. A first category of modeled infrastructure stocks displays averaged errors of less than 10% (wells, gas and oil product pipelines, LNG liquefaction and regasification plants, LNG storage facilities and refineries) and a higher value are observed for coal carriers (11%), oil tankers (12%) and LNG carriers (16%). Second, the global approach developed in this study allows to assess the evolution of hydrocarbon supply chain from a minimal panel of characteristics of the hydrocarbon production and supply sector. This approach, although minimal, does allow for the analysis of the evolution of infrastructure stocks according to assumptions such as the progression of LNG or non-conventional hydrocarbons.

The sensitivity analysis conducted in this study shows moderate effects of lifetime changes. However, as previously described by Dong et al. (2019) and Yin and Chen (2013), the time delay induced by the lifetime carries growing effects over time. A better knowledge of technological and regional values of lifetime over time is needed to prevent substantial variations in prospective dynamic modeling. It can also be noticed linear impacts of the material intensities on stocks and flows of the model. Global homogeneous data were assumed in this analysis, and a better understanding of the regional dynamics could increase the accuracy of the results. Finally, local sensitivity analysis only describes variations in a given point in space. This methodology therefore carries limitations (Saltelli, 2008), and further studies should develop global sensitivity analysis on more parameters and their possible interactions (Buchner et al., 2015).

2.3.6.2. METHODOLOGY-RELATED LIMITATIONS

The hydrocarbon production and supply sector are computed independently of the other sectors, and the materials recycled are consumed in the same sector. This approach does not represent the actual recycling industry, and only a multi-sector study considering recycling as a sector would estimate accurate flows of recycled metals between the consumer sectors. In addition, the materials consumed for well closure is not considered (Vrålstad et al., 2019), as well as the numerous decommissioning strategies. The choice of a physical approach to the flows and stocks of materials also carries limitations on the effectiveness of the model in terms of operational reality of the sector. For example, an increase in concrete demand is observed in the late 2040s in the NZE scenario, despite a context of significant slowdown in hydrocarbons production. It is explained by end-of-life renewal of some infrastructures. Assumptions of life extension, well closure for profitability considerations and other sectoral and financial realities could be considered in further studies.

2.3.6.3. DATA-RELATED LIMITATIONS

Most of current infrastructures data on the fossil fuels supply chain are difficult to access. To overcome this problem, the sector's players call on the services of economic intelligence companies (IHS Markit, Rystad Energy, Wood Mackenzie, etc.) which collect confidential information (obtained in an undisclosed manner) and provide data, tools and analyses in return of a high price. Conversely, this study relies on free and online available dataset describing the evolution of the global fossil fuels supply chain over time. The dataset displayed in the Supplementary Information aims at providing global data for future studies. Further free regional data on fossil fuel infrastructures were gathered in other studies, for instance Byrnes (Byrnes, 2020). In the present study, the data require extensive sources research, remain scarce and suffer from a lack of sources comparison and from numerous gaps, which hamper any extrapolation over time. For instance, access to reliable data over time and consistent over the geographical perimeter remains a limitation to this study. The selected data were qualified according to their geographical scope, technological scope and year of the study. The data collected do not allow a complete understanding of the complexity of the hydrocarbon production sector, due to the great variety of systems used from exploration to distribution⁴². Detailed data on all these technologies and their associated material intensities are not yet available, and sub-segment scale data were therefore considered⁴³. Thus, the results displayed in the study are likely an underestimate of the actual material demand. In addition, most of the data are based on European or North American devices, which could create high uncertainties in the results. This is explained by the difference in both the global hydrocarbons production and consumption patterns⁴⁴.

Furthermore, our analysis relies on oil production scenarios which can be thrown into question. Indeed, the International Energy Agency tends to assume parameters which proved to result in too optimistic projections in the past (Jakobsson et al., 2009; Wachtmeister et al., 2018). It consequently neglects the possibility to suffer from a production crunch in the coming years (Hacquard et al., 2019) or to experience a peak in the production of all oil liquids in the mid 2030s now envisioned by an important number of actors (Tupaz, 2020). While the issue of credible long-term oil scenarios is critical at times of the resurgence of the 'peak oil' debate (Delannoy et al., 2021b), it seems not to be taken into account by the IEA. We acknowledge the fact that projecting oil demand and supply is an intricate and complex task. Yet, we feel that the projections we used carry great uncertainty, and that they should be treated with a grain of salt.

2.3.7. CONCLUSIONS

This study models the evolution of the world's fossil fuel infrastructures and estimates dynamic embedded materials, energy, and CO₂ emissions from 1950 to 2050. To do so, it firstly collects and centralizes free data from a large number of sources and thus avoids using expensive datasets from energy intelligence firms (McKenzie, IHS Markit, Rystad Energy, etc.). Without claiming to provide the same quality and disaggregation of data, our comprehensive dataset can be used by other researchers to understand the role of hydrocarbon infrastructures in the energy transition. Secondly, it develops and applies a dynamic material flow analysis (MFA).

We find that (i) the material intensities of oil, gas and coal have stagnated for more than 30 years; (ii) gas is the main driver of current and future material consumption and (iii) recycled

⁴²A detailed list of equipment used in the offshore production of hydrocarbons is provided by Rosneft.

⁴³For example in the exploration sub-segment, see Supplementary Information.

⁴⁴Oil and gas drilling technologies are different from country to country, with conventional hydrocarbons requiring fewer wells drilled than unconventional hydrocarbons for an equivalent level of production. There is therefore a lack of correlation between the amount of oil produced and the number of wells drilled at the regional level, with OPEC, for example, accounting for nearly 32% of global oil production and 15% of natural gas production between 1980 and 2019 for only 2.8% of wells completed over the same period (GlobalShift, 2020; OPEC, 2019).

steel from decommissioned fossil fuels infrastructures could meet the cumulative need of future low-carbon technologies and reduce its energy and environmental toll.

We furthermore highlight that the regional decommissioning strategies will significantly affect the potential of material recycling and reuse. In this context, ambitious decommissioning strategies could drive a symbolic move to build future renewable technologies from past fossil fuel structures.

APPENDIX

GLOBAL HISTORICAL DATA OF THE HYDROCARBONS SUPPLY INFRASTRUCTURES

Upstream The upstream segment is common for oil and gas, and is composed of exploration and production devices for which recent data is available. This segment includes exploration infrastructures including devices used in seismic, magnetic and gravity methods-wells and on-shore and offshore drilling rigs. At the global level, the Organization of the Petroleum Exporting Countries (OPEC) provided a census of the number of wells between 1980 and 2016 with more than 1.1 million wells in 2016 and 5,123 well pads in 2013 (OPEC, 2018). The organization also listed drilling platforms between 1982 and 2013, without distinguishing between onshore and offshore structures. However, those drilling devices are not considered in the study, because of the high level of uncertainty on the data collected. Indeed, the census of rigs remains difficult at the global level, notably due to the lack of detail in the perimeter considered in the majority of sources, and the diversity of offshore infrastructures. Baker Hughes provided a monthly report on onshore and offshore rotary rig counts worldwide, with a value of 758 rigs in June 2021⁴⁵. A value of more than 6,000 offshore oil and gas platforms are announced globally by Bull and Love (2019) and Schroeder and Love (2004), compared to 3,000 fixed offshore platforms by the IEA (2018) and more than 12,000 offshore devices by Ars and Rios (2017). However, IEA (2018) stated that the recent increase in offshore production has been partly provided by floating facilities, the number of which more than doubled between 2000 and 2016, making any accurate assessment of offshore production devices difficult. Adding to this difficulty of identification is a trend toward larger platforms, greatly complicating modeling from fossil fuel generation. IEA (2018) stated that the size of platforms increases over time, allowing production to be maintained while decreasing their number. Conversely, no census of the equipment used in exploration methods has been obtained, but a study listing the quantities of raw materials consumed has been produced by the American Petroleum Institute (Steiniger, 1962). Finally, the coal mines have been separated into two underground and opencast categories. It is estimated that 40% of coal production comes from surface mines and 60% from underground mines (World Coal Institute, 2009), with various extraction equipment.

Midstream In contrast to upstream, the activities of the midstream segment are different for oil and gas, especially for processing. While oil does not require processing, several steps are required before eventual gas transportation and then distribution. Schori (2012) further stated that the extent of processing depends on the quality of the gas produced. The processed gas and oil are then transported to consumption centers. Four methods of transportation exist: road, rail, sea, and pipeline. Only the last two are modeled here. Only 20% of gas is traded on international markets and not consumed regionally. Similarly, in 2015, 61% of the transportation of petroleum products was by sea lanes (EIA, 2017). For natural gas, pipeline transportation and marine transportation in liquefied form were therefore considered in this study. It includes

⁴⁵Baker Hughes proposes a monthly inventory of the global active rigs.

the liquefaction of natural gas, its transport in the form of liquefied natural gas (LNG) in LNG tankers, and its regasification. The market share of LNG has strongly increased over the recent decades, with global liquefaction capacity growing from 165 bcm in 2000 to more than 467 bcm in 2017, while regasification capacity has evolved from 334 bcm to more than 1,138 bcm in the same period (ENI, 2018). Similarly, the evolution of the number of LNG carriers since the late 1960s - the years of construction of the first ships - follows a strong growth, linked to the rapid development of LNG globally. IGU (2018) detailed a growth to about 200 ships in 2000, eventually progressing to 525 units in 2018. The liquefaction of gas allows storage. Over the past decades, LNG global storage capacity have increased from 39 mmcm to 62.8 mmcm between 2011 and 2018⁴⁶ (IGU, 2018). Gas pipelines represent the second main way of transportation of natural gas. The network of natural gas transmission and distribution pipelines has grown considerably over the last two decades. Its length was estimated at more than 844,000 kilometers in 2000, finally evolving to 3.04 million kilometers in 2017 (CIA, 2019). However, these data do not agree with the estimates of CEER (2018), announcing more than 1.9 million kilometers for the European network, compared to only 224,000 km for CIA (2019). We can also identify a strong difference for the French case, with 195,000 km of gas pipeline network announced by the French Ministry of Ecological Transition (2022), against about 15,000 km for CIA (2019), as well as for Canada, with more than 450,000 km of gas pipelines NRCAN (2020) against 110,000 km for CIA (2019), and finally the United States, with 1.9 million kilometers announced by CIA (2019), lower than the 2.3 million kilometers identified by PHMSA (2022). These differences stem from the scope of the studies considered. Pipelines can be separated into three broad categories: transmission pipelines, carrying hydrocarbons over long distances from production centers, distribution pipelines, serving end-users over short distances, and gathering pipelines, used between the field and the transmission system (Moureau and Brace, 1993). However, the latter network remains a minority, accounting for only 0.7% of the U.S. gas network in 2018 (PHMSA, 2022). Using data for the European, US, and Canadian gas networks, we estimated a distribution pipeline share of 85% of the pipeline network. The rate was applied to the data on the gas transmission pipeline network provided by CIA (2019), allowing us to obtain the historical evolution of the global network between 2000 and 2017. In this study, the transportation network evolved from 840,000 km to more than 1.36 million km between 2000 and 2018.

For petroleum products, the midstream segment includes both tankers, transport and distribution pipelines, and storage infrastructure. Globally, tanker transport grew strongly between 1980 and 2018, from 388 million Dead Weight Tons (MDWT) to 561 MDWT, for about 12,000 units (UNCTAD, 2018; GIIGNL, 2019). Tanker transport can be considered "dynamic" storage, but is not considered as such here to avoid double counting. Geological storage was also excluded, due to lack of raw material data. Finally, only man-made "static" storage tanks have been considered here. These are estimated at 8 billion barrels, more than half of which are in OECD countries, including both commercial and strategic stocks (Oil Sands Magazine, 2016; IEA, 2018; OPEC, 2018). Finally, in contrast to the natural gas pipeline network, the petroleum product pipeline network has seen little growth between 2000 and 2018, with the length increasing from 584,000 km to 788,000 km (CIA, 2019). The data considered do not suffer from the same drawback, as the global network is predominantly a transportation network, not a distribution network, unlike the gas network. For coal, the midstream segment remains simpler. After extraction, coal can be processed before being transported, in order to meet customers' requirements. This is accomplished by crushing it, separating it by size, and

⁴⁶The storage capacity is measured in).

then purifying it of mineral matter (Miller, 2017).

Downstream The final segment of the hydrocarbon supply chain is the downstream, which gathers refining and distribution activities. Refining capacity has increased significantly between 1965 and 2017, from 34.8 to more than 98 million barrels per day with more than 600 refineries worldwide (BP, 2021; OGJ, 2009, 2014). In the absence of data on the share of transmission and distribution networks, the entire petroleum product network was considered a transmission network. The gas network is 86% a distribution network, and its length has increased from 4.4 to over 10 million kilometers between 2000 and 2018 (CEER, 2018; CIA, 2019; NRCAN, 2020; PHMSA, 2022).

RECENT EVOLUTION OF THE OIL, GAS AND COAL SECTORAL PRODUCTION STRUCTURE

Several developments in the oil and gas sector have been taken into account in this study. As mentioned above, an increase in the share of gas transported in the form of Liquefied Natural Gas (LNG) has been considered, as well as the share of unconventional oil and gas. Unconventional production has been separated into two main categories with different characteristics: oil sands and shale oil on the one hand, shale gas and tight gas on the other. Since oil sands exploitation does not require drilling, only the second category was considered. In order to model the impact of the increase in production of unconventional hydrocarbons, three factors were considered: a decrease in the lifespan of the wells, a decrease in their depth, and an increase in their number.

For the same level of production, more unconventional wells are needed, which is explained from the production profile of unconventional drilling, measured by the production decline rate. It is defined as the annual rate of reduction in oil or gas production from an oil field, and is calculated for each well and at the aggregate level. It differs according to the age of the well, but also between conventional and unconventional hydrocarbons, for which its value is higher (Kleinberg et al., 2018). The average value of the production reduction rate is about 2% to 8% for conventional hydrocarbons (IEA and KEEL, 2019; Michaux, 2019; Höök et al., 2009). The rate fluctuates depending on the size of the oil field, its geographical location and its physical situation—offshore or onshore (Höök et al., 2009; IEA, 2013). The values observed for fields producing unconventional hydrocarbons are considerably higher. In the Bakken field, located in the United States, this rate reached nearly 60% in the first year of production, and then 25% in the second year (IHS, 2013), while the Barnett field experienced a rate of 39% after 2 years, eventually reaching 95% over 10 years (Stevens, 2010), and the Eagle Ford field experienced a reduction of 74%, 47%, and 19%, respectively for the first, second, and third year of production (Wachtmeister et al., 2017). This hyperbolic pattern of production reduction therefore explains the need to increase drilling in order to maintain a high level of production. The density of wells per square kilometer, however, varies considerably by reservoir, by hydrocarbon type, and by data source. Komduur (2010) announced a density of 12 wells per km² in the Barnett oil field in the United States, compared to 2 wells per km² according to the EIA (2013). At the national level, the EIA (2013) provided the density of wells in the large unconventional American fields, ranging from 0.4 to 6 wells per km² with an average value of 2.8 wells per km², which is still higher than the largest conventional fields in the world for which the values vary between 0.07 and 8.9 wells per km². Because of this large disparity, no difference in well density was retained in this study.

In addition to a change in well density, a decrease in well life is observed. Indeed, the production reduction rates allow us to estimate a lifetime of unconventional hydrocarbon wells

between 8 and 12 years, compared to 30 to 40 years for conventional hydrocarbon production (Stevens, 2010). Finally, the increase in the share of unconventional hydrocarbons and deep-water drilling changes the average depth of drilling. The horizontal drilling technique increases the total length of the wells, composed of a vertical part and then a horizontal part. The first part of the drilling consists of the vertical part of the well, in the same way as conventional hydrocarbons. Newell et al. (2016) announced an average vertical depth between 1,200 and 3,900 meters, while Zendehboudi and Bahadori (2017) between 1,000 and 3,000 meters. This value reaches an average of 1828 meters in the Marcellus Basin (Fractracker, 2022). Once the reservoir depth is reached, horizontal drilling begins. On the Marcellus Basin, located in the United States, the average length of this second portion was 1150 meters between 2006 and 2016, and an increase in the length of the horizontal portion of drilling over time (Doak et al., 2019). The average horizontal drilling distance in the Marcellus Basin increased from 690 meters in 2003 to 1,200 meters in 2013, and to 3,000 meters in 2018. Nationally, this distance has evolved from 1547 meters in 2012 to 2,221 meters in 2018 (Hugues, 2019), for a total drilling length of approximately 4,000 meters in unconventional wells in the United States. This evolution can be seen in the distribution profile of drilling in Canada and the United States, with a sharp increase in the proportion of drilling to a depth of around 2,000 meters, and the appearance of drilling to a depth of over 5,000 meters. The average depth of drilling in the United States has increased from 1,100 meters in 1950 to more than 1,700 meters in 2008. Finally, the characteristics retained are an average drilling length of 1,500 meters and a life span of 40 years for conventional deposits and 4,000 meters and 12 years for non-conventional deposits.

EMBODIED ENERGY AND CO₂ EMISSIONS

The embodied energies of primary and secondary materials considered in this study are dynamic between 1900 and 2100, and their scope extends from cradle to gate. Primary metals embodied energies depend on both the ore grade of the mined material and the technological improvement of production technologies (Norgate et al., 2007; Birat et al., 2013; Gutowski et al., 2013; Vidal et al., 2021). Data from Vidal et al. (2021) are considered for copper, aluminum, and steel. The values considered for steel are used for all steel alloys in this study. Cement and concrete production is decentralized, so material intensities depend on the efficiency of regional production facilities. Numerous cement and concrete material intensities are proposed in the literature, both globally (Van den Heede and De Belie, 2012; Birat et al., 2013) and by region (Marinković et al., 2017; Goggins et al., 2010; Praseeda et al., 2015)⁴⁷. Because of this decentralization, a multi-regional approach is adopted to estimate a global cement material intensity. In this study, we have assumed an identical intensity for clinker and cement, theoretically composed of 95% cement (Taylor et al., 2006). In order to simplify the calculations, only the main producing areas have been considered. China, India, Europe, the United States and Japan represent nearly 70% of the world cement production between 1956 and 2016 (USGS, 2021a), so regional energy intensities were determined for these regions using historical data and a logistic approach. For this purpose, a theoretical energy intensity limit for cement was set at 1.76 MJ/kg (Worrell et al., 2001; Taylor et al., 2006) and a maximum intensity of 20 MJ/kg. This value remains uncertain but has little impact on the study since 96.7% of cement produced since 1900 was manufactured after 1950, and nearly 90% after 1970 (USGS, 2021c). Regional energy intensities are then weighted by regional cement production, yielding a global cement/-

⁴⁷Many other studies provide regional cement and concrete intensities. A non exhaustive list of them include : Alcorn and Wood (1998); Hammond and Jones (2008); Baird (1997); Kofoworola and Gheewala (2009); Dias and Pooliyadda (2004); Scheuer et al. (2003); Debnath et al. (1995); Wan Omar et al. (2014); Dixit (2017); Worrell et al. (1994, 2000); Praseeda et al. (2015); Li et al. (2015); Gervasio et al. (2018); Lu et al. (2009); Mack (2015); Taylor et al. (2006)

clinker intensity. Historical data for regional shares of global production are obtained between 1956 and 2016 (USGS, 2021c). The observed 1956 distribution is assumed constant since 1950, and the 2016 distribution is assumed constant through 2100. Cement/clinker energy intensity thus varies annually between 1900 and 2100 2.19 according to the combined change in regional energy intensities and regional market shares in world production.

Recycling reduces the energy required for the production of materials, due to the lower number of stages in the production of secondary metals than in primary metals. Indeed, primary production involves steps such as mining and mineral processing (for copper, nickel, zinc, lead...) or crushing and screening for steel (Norgate et al., 2007; Chen et al., 2019b), which are not mobilized during secondary production. Secondary production primarily involves scrap smelting and refining, as well as several steps of collection, recovery sorting and shredding (Norgate, 2013). Schäfer and Schmidt (2019) and Johnson et al. (2007) pointed out that the origin of the metals collected influences the energy required for their recycling, and report embodied energy of secondary copper sometimes of the same order of magnitude as that of primary copper. The scope of secondary metals production thus includes processes from collection to refining. In this study, the embodied energy of secondary metals is assessed from a literature review of the energy typically consumed in secondary processes, either in absolute terms or in terms of the energy consumption of primary processes. However, this proportion of primary production consumption varies considerably over time as the ore grade changes (Norgate and Jahanshahi, 2006). The proportion estimated in this study is therefore valid only for the current period. This makes it possible to estimate a world average consumption of secondary metals, varying then according to an annual rate of technological improvement of 1% between 1900 and 2100. Only steel, aluminum and copper are considered in the secondary production. Nearly 70% of steel is currently produced by the Blast Furnace/Basic Oxygen Furnace (BF/BOF) process and 30% via Electric Arc Furnace (EAF), with large regional disparities (Yellishetty et al., 2010). EAF route steel represents most of the secondary steel production, explaining this heterogeneity. This route allows secondary steel to consume between 1.3 and 6 GJ/t currently (Harvey, 2021), 2.6 MJ/kg according to Norgate (2013), 4.5 MJ/kg in Europe according to Birat et al. (2013) and decreasing from 8.8 MJ/kg in 2010 for the United Kingdom (Hammond and Jones, 2008) and 7 MJ/kg at the end of the 1990s for the most energy efficient processes (de Beer et al., 1998). Secondary steel thus consumes between 8 and 37% of the primary production energy depending on the source. A current value of 20% is chosen, in agreement with the most recent sources, i.e. 3.5 MJ/kg for the metallurgical processes. After adding the energy needed for collection, recovery, sorting and shredding, the final value of embodied energy of 3.9 MJ/kg is finally considered⁴⁸.

Aluminum has a more drastic decrease of the energy consumption necessary for its production thanks to recycling⁴⁹. It reaches between 5 MJ/kg and 8.9 MJ/kg (Kear et al., 2000; Quinkertz et al., 2001; Schifo and Radia, 2004; Green, 2007; Birat et al., 2013; Norgate, 2013; Milford et al., 2011), which represents a proportion of the primary production energy mostly between 5% and 10%, and reaching up to 13%. A current proportion of 7% was selected based on a weighting according to the age of the sources, allowing to estimate an average embodied energy value of secondary aluminum of 5.1 MJ/kg for metallurgy, and a final value of 5.6 MJ/kg. Secondary copper production is achieved depending on the origin of the copper scrap, either through the pyrometallurgical process or the hydrometallurgical process, especially for printed circuit boards (Xu et al., 2016). No works studying the embodied energy of secondary copper

⁴⁸This value depends on the distance traveled for between the collection site and the recycling site (Norgate, 2013). A distance of 150 km was considered in this study. The strong impact of transport on recycling was also considered by Barba-Gutiérrez et al. (2008)

⁴⁹Salonitis et al. (2019) provided a breakdown of energy consumption by primary production stage.

at the global level have been found. At the Chinese level, Chen et al. (2019b) proposed a quantification of each stage of primary and secondary production, and arrive at a proportion of 21% of secondary copper embodied energy to primary. A similar proportion is estimated by Gaines (1980), with 20% on the US perimeter. Presenting differences according to the ore concentration rate, Norgate and Jahanshahi (2006) reported a share of smelting and refining of only 9% for copper mined with a concentration of 0.5%, reaching 40% for 3% Cu. A world average value of 15% is finally retained, i.e. 11.6 MJ/kg for the metallurgical process, and 12.8 MJ/kg for the final embodied energy value of secondary copper.

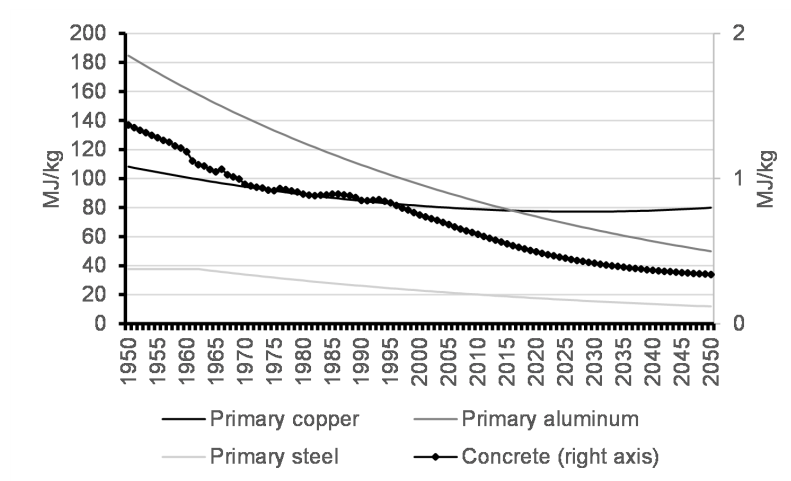


FIGURE 2.19: Embodied energy of the primary materials production.

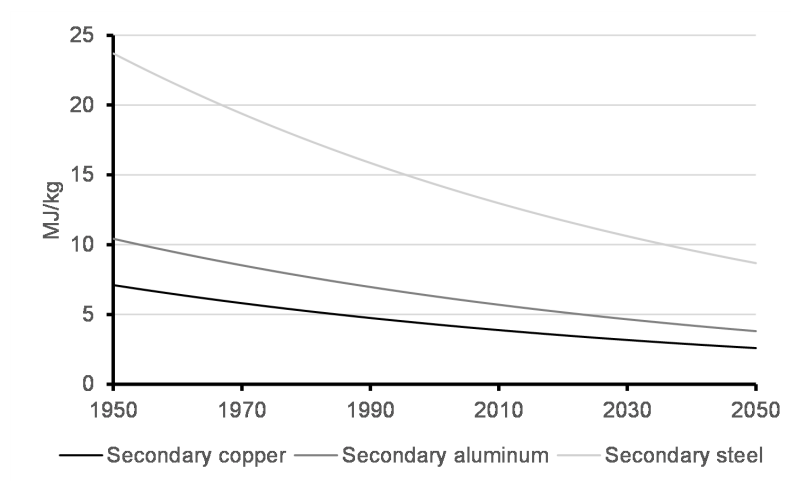


FIGURE 2.20: Embodied energy of the secondary materials production.

MATERIALS, ENERGY AND CO₂: FURTHER RESULTS

BULK MATERIALS PRIMARY AND SECONDARY FLOWS IN THE STEP AND NZE SCENARIOS

The bulk materials primary and secondary flows are presented in this section for the two considered scenarios.

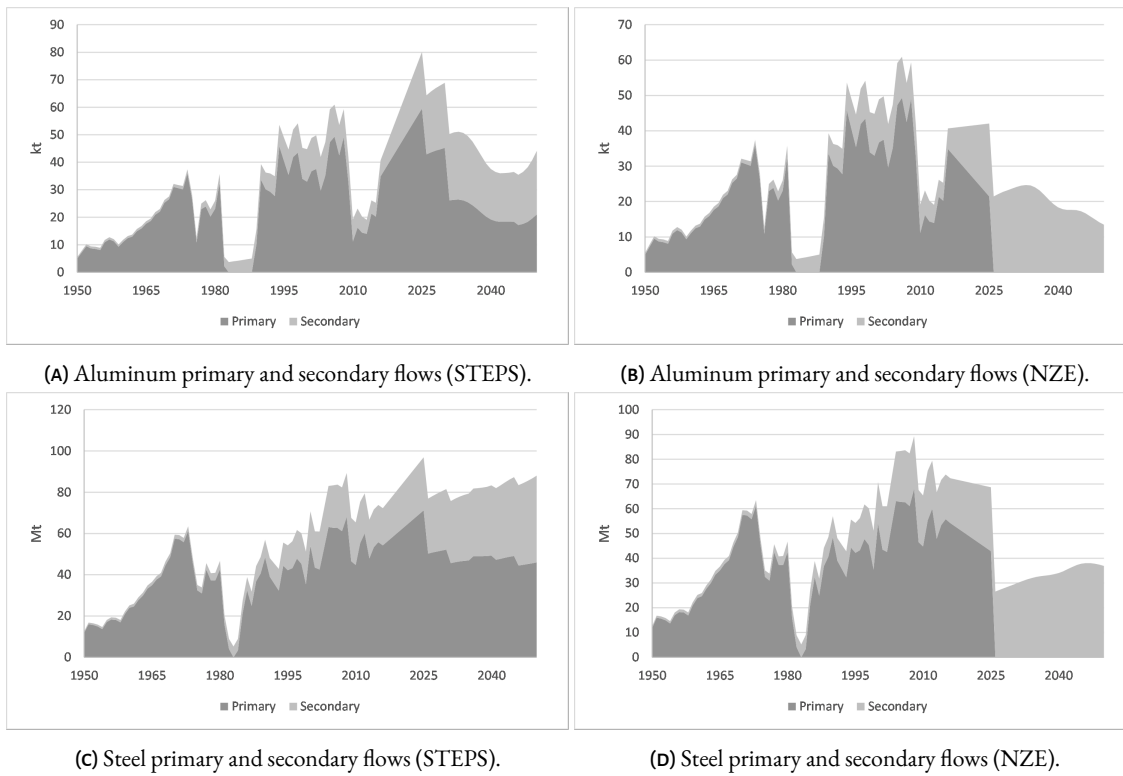


FIGURE 2.21: Aluminum and steel primary and secondary flows in the fossil fuels supply sector for the NZE and STEPS scenarios.

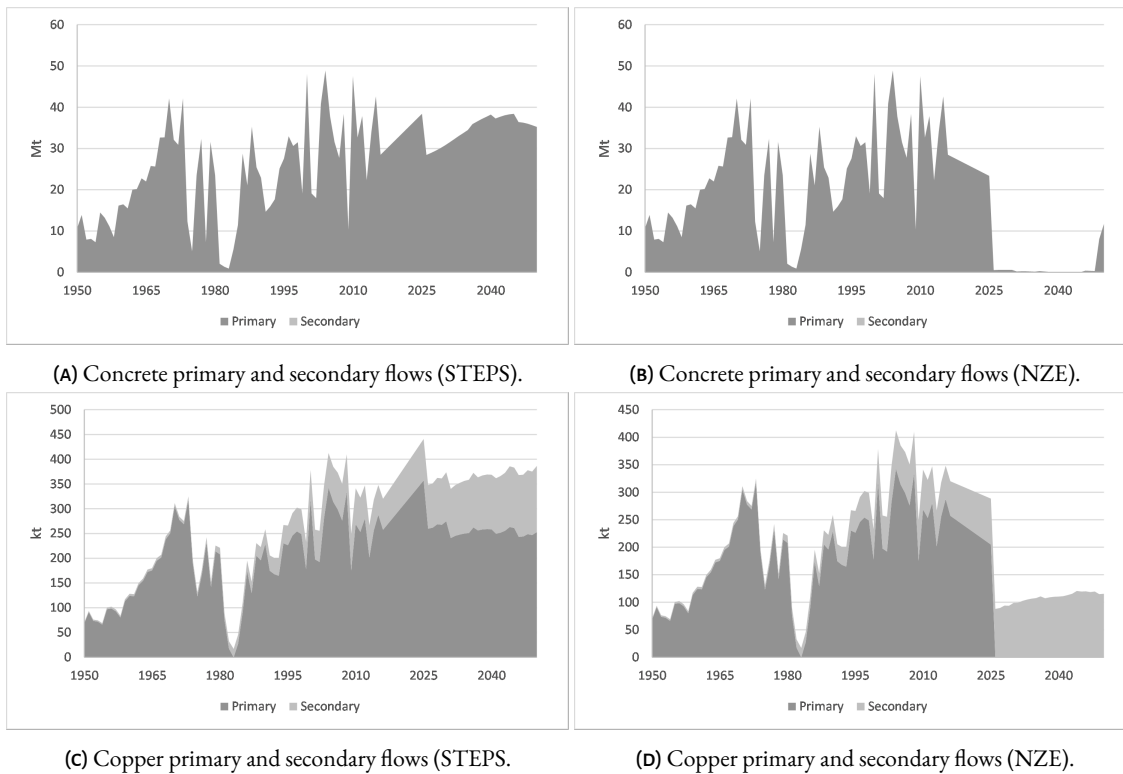


FIGURE 2.22: Concrete and copper primary and secondary flows in the fossil fuels supply sector for the NZE and STEPS scenarios.

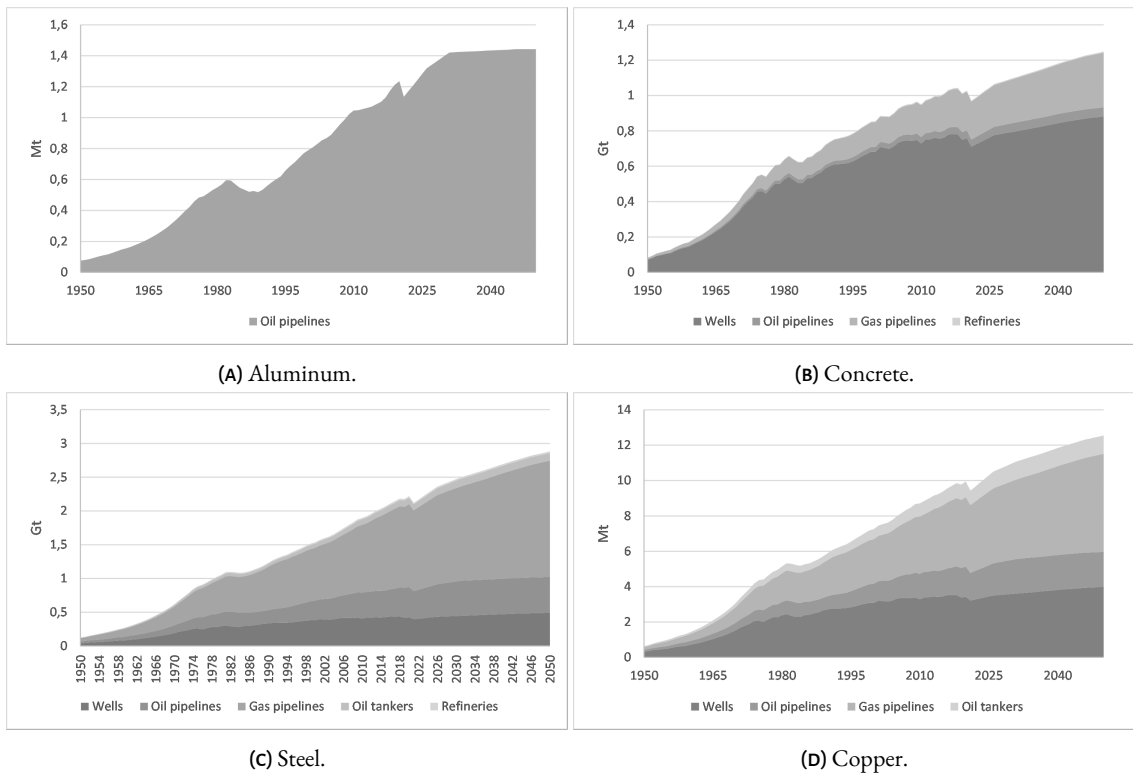


FIGURE 2.23: Structural materials stocks by main consuming infrastructures in the STEPS scenario.

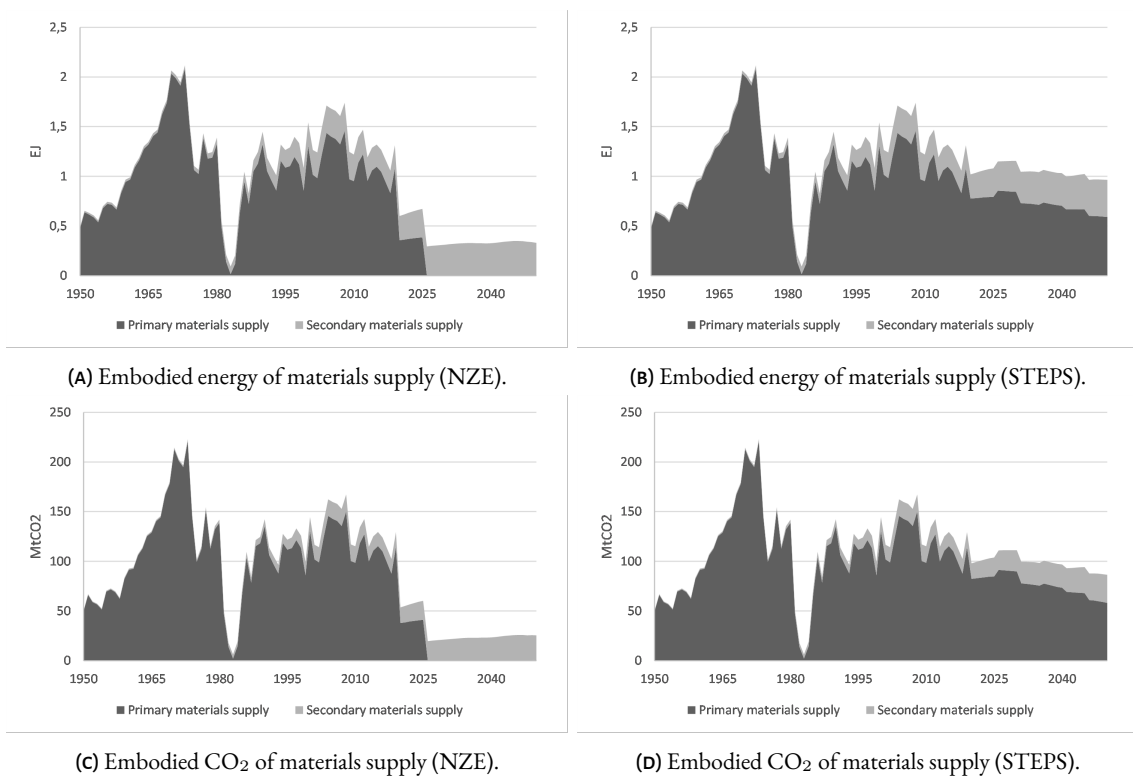


FIGURE 2.24: Embodied energy and CO₂ of materials supply by segments in the STEP and NZE scenarios.

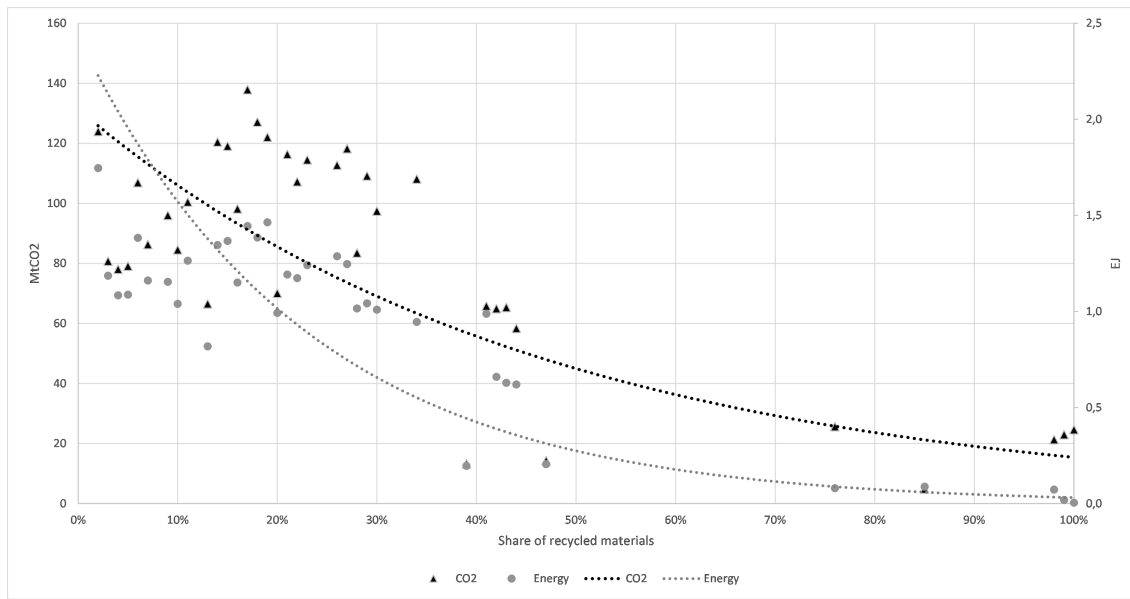


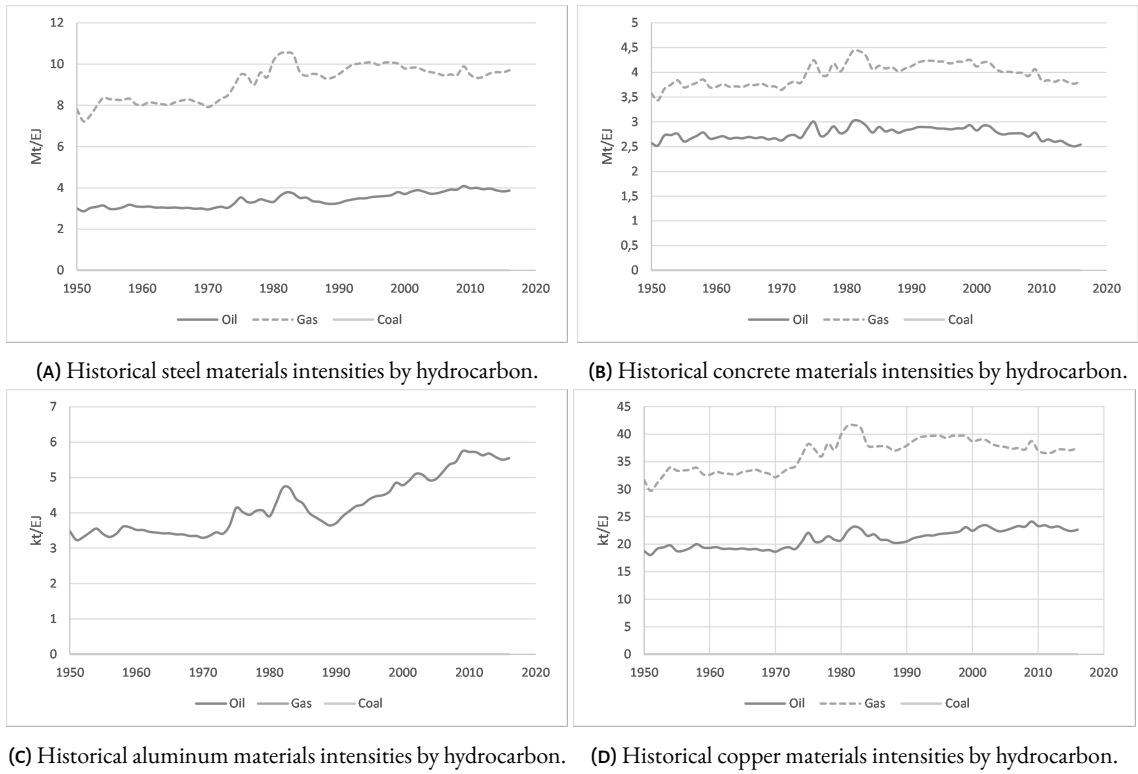
FIGURE 2.25: Evolution of embodied CO₂ emissions and embodied energy consumption depending on the share of recycled materials in the demand.

HISTORICAL SECTORAL MATERIALS INTENSITIES IN THE FOSSILS SUPPLY SECTOR

References	Steel (iron)	Concrete	Copper	Aluminum	Years	Technologies	Scenarios
Sectoral material intensities (Mt/EJ)							
Deetman et al. (2021)	5.9	54	0.4	1.5	2015	PG+G+S	Historical
Deetman et al. (2021)	3.9	50	0.3	0	2015	PG	Historical
Deetman et al. (2021)	2	4	0.1	1.5	2015	G	Historical
This study	4	2	0.02	0.002	2015	HU+HM+HD	Historical
This study	0.8	1.5	0.007	0	2015	HU	Historical
This study	1.3	0.1	0.006	0.002	2015	HM	Historical
This study	1.9	0.4	0.006	0	2015	HD	Historical

TABLE 2.18: Summary of the materials intensities in the power generation, storage and grid infrastructures and comparison with the hydrocarbons supply chain. PG = power generation, R = renewables, G = power grid, S = power storage, T = electric transportation, HU = hydrocarbons upstream, HM = hydrocarbons midstream, HD = hydrocarbons downstream. Value do not sum due to rounding.

HISTORICAL SECTORAL MATERIALS INTENSITIES BY HYDROCARBONS IN THE FOSSILS SUPPLY SECTOR



HISTORICAL SECTORAL MATERIALS INTENSITIES BY SEGMENT IN THE FOSSILS SUPPLY SECTOR

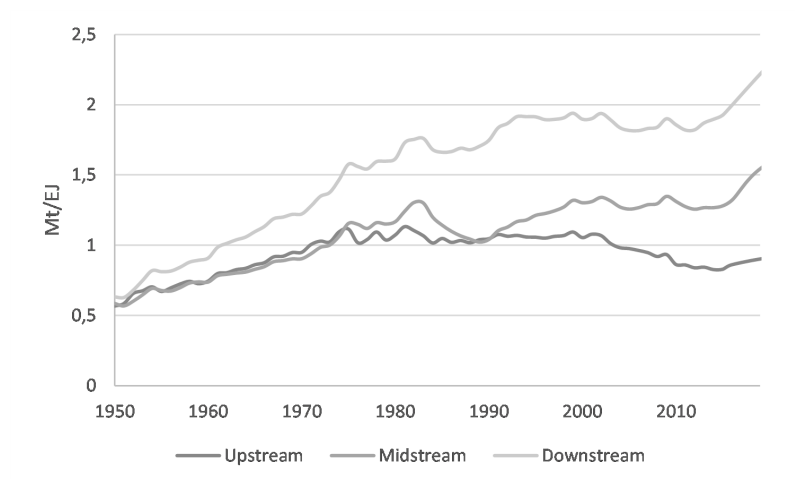


FIGURE 2.27: Historical steel materials intensities by segment.

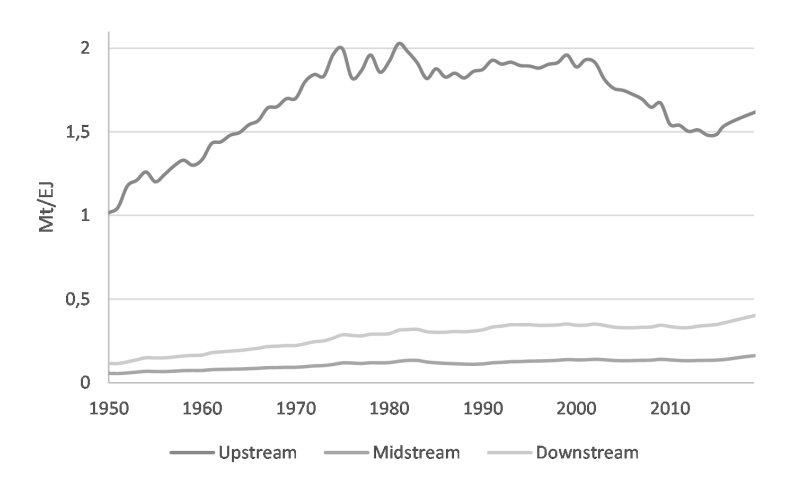


FIGURE 2.28: Historical concrete materials intensities by segment.

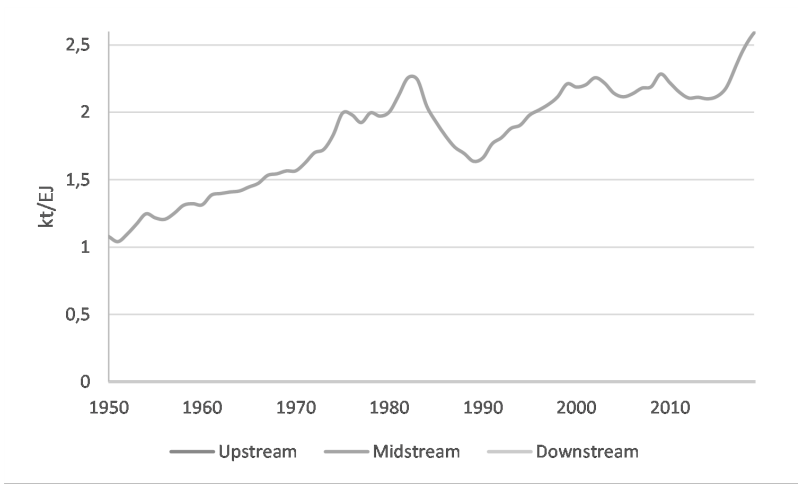


FIGURE 2.29: Historical aluminum materials intensities by segment.

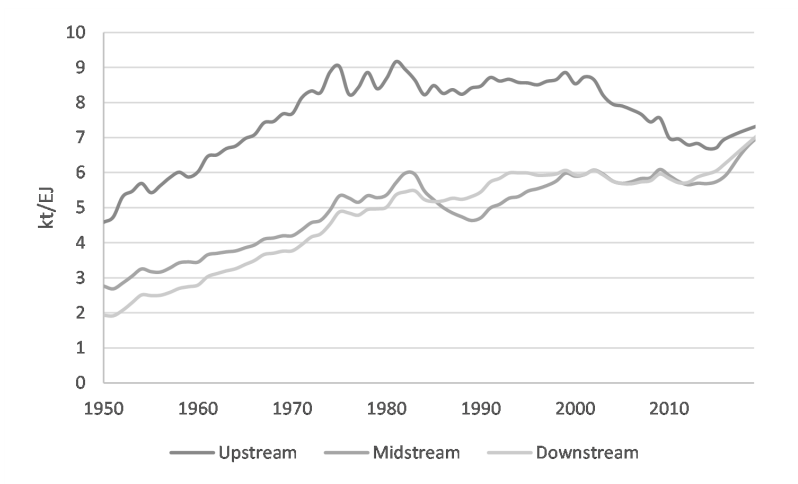


FIGURE 2.30: Historical copper materials intensities by segment.

CHAPTER 3

ANCHORING MACROECONOMIC MODELS IN REALITY

The problem of the modern economy is not a failure of a knowledge of economics; it's a failure of a knowledge of history.

John Kenneth Galbraith

This chapter presents two studies that advance the integration of energy constraints in macroeconomics models:

- The first article presents the TEMPLE model, an ecological, stock-flow consistent macroeconomic framework designed to assess the economic consequences of a global energy transition scenario compatible with the 1.5°C objective of the Paris Agreement. Its novelty resides in the incorporation of detailed bottom-up estimates for the high capital intensity of renewable energies and the decreasing energy return on investment (EROI) of fossil fuels.
- The second article is an opinion piece federating a significant fraction of the net energy community, and contending that most mitigation pathways and Integrated Assessment Models overlook net energy aspects. Not only this article provides for the first time a common account of the state of the art of the NEA community, but also highlights agenda-setting insights for every researcher working on the global and societal challenges of providing energy and protecting our environment.

3.1. THE ECONOMIC CONSEQUENCES OF A TRANSITION

Jacques, P., Delannoy, L., Andrieu, B., Yilmaz, D., Jeanmart, H., and Godin, A. Assessing the economic consequences of an energy transition through a biophysical stock-flow consistent model. *Ecological Economics*, 209:107832, 2023. doi:10.1016/j.ecolecon.2023.107832

ABSTRACT

The biophysical foundations of socio-economic systems are underrepresented in the vast majority of macroeconomic models. This lack is particularly troublesome when considering the links between energy, matter and the economy in the context of the energy transition. As a remedy, we present here a biophysical stock-flow consistent macroeconomic model calibrated at the global scale, that combines detailed bottom-up estimates for the high capital intensity of renewable energies and the decreasing energy return on investment (EROI) of fossil fuels. We find that the completion of a global energy transition scenario compatible with the 1.5°C objective of the Paris Agreement leads to a decrease of the system's EROI and to high investment share, employment and inflation trends, characteristic of a "war economy". Our results further indicate that a slower growth rate eases the transition, and call for further work on post-growth scenarios studies.

3.1.1. INTRODUCTION

Abundant cheap energy has been the main driver of economic development in modern societies (Ayres and Warr, 2009; Smil, 2017; Hall and Klitgaard, 2018). Its extensive use has, on the other hand, caused unprecedented climatic and ecological damage, jeopardizing the planet's life support functions (IPCC, 2021). In order to halt global degradations, humanity must adopt sustainable consumption habits and shift away from fossil fuels to inherently intermittent, less concentrated, and capital-intensive renewable energy sources. Ecological stock-flow consistent macroeconomic models are a promising way to study the energy transition in a combined ecological, economic and energy perspective (Carnevali et al., 2019). However, and as discussed in the next section, current models are only partially able to assess robust transition pathways as they lack an accurate representation of the interactions between the energy production sector with its inherent biophysical constraints, the real economy, and the financial sphere.

To fill this gap, we present an ecological, biophysical stock-flow consistent macroeconomic model calibrated at the global scale, that combines detailed projections for the evolution of the energy intensity of the productive sub-sectors and dynamic estimates of the Energy Return On Investment (EROI) for fossil fuels and renewable energy technologies. We then analyze the biophysical and macroeconomic dynamics of an energy transition scenario compatible with the 1.5°C objective of the Paris Agreement. We finally explore how these dynamics are sensitive to changes in the growth rate of the economy.

This paper is structured as follows. Section 'Literature review' examines the existing litera-

ture. Section 'Materials and methods' presents the materials, data and methods used. Section 'Results and discussion' details the results obtained from the simulation of a complete global energy transition and compares them to a similar scenario, but where the global economy exhibits a slower growth rate. Section 'Robustness, limitations and further work' evaluates the robustness of the results, underlines the limitations of the model and suggests perspectives for future research. Section 'Conclusion' concludes.

3.1.2. LITERATURE REVIEW

3.1.2.1. THE EMERGENCE OF ECOLOGICAL MACROECONOMICS

The intensifying articulation of ecological, economic and social degradation has highlighted, in the wake of the Global Financial Crisis (GFC), several weaknesses in the standard macroeconomic edifice (Keen, 2011; King, 2012; Stiglitz, 2018). To inform on how these crises are interconnected and describe fair pathways to sustainability, a novel field of research has arisen: ecological macroeconomics (EM) (Rezai et al., 2013; Jackson, 2017).

EM holds its roots in the view that societies are dissipative thermodynamic systems collecting high-quality energy and materials before releasing them into the environment in a degraded form. It has brought together theories from several disciplines and schools of economic thought, among which are Keynesian and post-Keynesian economics (Kronenberg, 2010; Fontana and Sawyer, 2016; Cahen-Fourot and Lavoie, 2016). Its interdisciplinary approach partly explains why it is not defined in a consensual manner. Still, a basis for a common understanding is emerging within the themes treated (natural resources dependency, post-growth, environmental damages, etc.), the assumptions made (endogenous money creation, rejection of the idea of rational, profit or utility maximizing firms and consumers, etc.) and the policies it advocates for (increased regulation of finance, support for large "green" investments, etc.) (Victor and Jackson, 2020).

The models making up the field are eclectic (Hardt and O'Neill, 2017; Saes and Romeiro, 2019). Yet, as noted by Svartzman et al. (2019), "a clear focus on post-Keynesian stock-flow consistent (SFC) models can be identified", giving birth to ecological SFC macroeconomic models, or simply Eco-SFC (Carnevali et al., 2019). SFC macromodels are characterized by two main features: a distinct accounting framework and behavioral equations. The accounting framework relies on a set of matrices that reproduce the balance sheets and transactions of each of the sectors that constitute the economy. Behavioral equations model the transactions which are not directly determined by the accounting structure of the economy. The main interest of SFC models is that they ensure the overall consistency of the modeled economy: the outflows of one sector are always the inflows of another sector, and similarly the liabilities of one sector are always the assets of another sector. Moreover, SFC models allow finance, the real economy and the interactions between the two to be represented in a single picture, see Godley and Lavoie (2012) for an extensive description of the approach and Caverzasi and Godin (2015); Nikiforos and Zezza (2018) for recent literature reviews.

3.1.2.2. BIOPHYSICAL CONSTRAINTS TO ECONOMIC GROWTH

Socio-economic systems rely upon two essential biophysical processes: the collection of raw energy and materials (the source function) and the release of waste into the environment (the sink function) (Hall et al., 1986). The expansion of societies can therefore be limited both by input and output flows.

Energy The collection of energy from the environment is constrained by its availability and accessibility. The first constraint is represented by the limited volume of fossil fuels likely to be extracted by mankind due to geological, economic and technological factors – called Ultimately Recoverable Resource (URR)¹. This first constraint is also represented by the maximum harvesting potential of renewables due to physical and geographical aspects of the planet (Zhou et al., 2015; Hoes et al., 2017; Dupont et al., 2018, 2020). The second constraint, closely interrelated with the first one, is the declining accessibility of resources because of the increase in the energy required for their extraction and processing. We here relate to the concept of Energy Return On Investment (EROI), a ratio characterizing the energy obtained from a given process in relation to the energy inputs required to realize the process (Hall, 2017). An EROI greater than unity means that the system under study is a net producer of energy whereas a system with an EROI lower than unity requires more energy than it produces. Since its inception fifty years ago, the concept has mainly been applied to oil and gas at their point of extraction (“standard” EROI, denoted as $EROI_{ST}$). As energy systems become more and more electrified and interconnected however, a growing interest has arisen in the evaluation of EROI at the point of use (“final” EROI, denoted as $EROI_{FIN}$), especially for renewables (Murphy and Hall, 2011a; Raugei, 2019). The literature agrees that the exploitation of fossil fuels requires more and more energy to drill, dig, extract, refine, etc. Admittedly, mankind tends to use first the resources that are the easiest to exploit (Delannoy et al., 2021b,a). It follows that the aggregate standard and final EROI of fossil fuels are declining, the latter at a smaller pace (Brockway et al., 2019). The final EROI of renewable energy for electric end-use is often higher than that of fossil fuels, but depends to a large extent on geographical parameters (Murphy et al., 2022). For thermal end-use, some renewable energies may have a higher EROI than fossil fuels, but the latter still remains competitive.

Materials Minerals are finite resources too. They differ from energy resources though, in the sense that – among other things – they are inherently recyclable and do not deplete after initial production² (Prior et al., 2012). There are still availability risks for mineral types with low remaining reserves, poor geographical distribution, limited adequate substitutes³ or subject to economic, social or environmental constraints (Meinert et al., 2016). The accessibility of these minerals is limited too by the energy intensity associated with their extraction, which is on the verge of rising for a number of metals, driven by thermodynamic limits and ore grade decline (Le Boulzec et al., 2022; Vidal et al., 2021). Such increases in energy extraction costs might potentially impact the EROI of different technologies which rely on these metals (Fizaine and Court, 2015).

Waste Economic activity implies the release of various types of waste impacting our environment and driving non-linear feedbacks on the economy (Lenton et al., 2008). The most well-known feedback is climate change, induced by the emission of greenhouse gases (GHG) and leading to an increase in the mean global temperature, extreme weather events, sea level rise, etc. However, there exist plenty of other feedbacks, as illustrated by the concept of planetary boundaries (Steffen et al., 2015). For instance, biodiversity is experiencing a major loss commonly referred to as the sixth mass extinction (Ceballos et al., 2015). The economic value pro-

¹Coal and gas seem rather plentiful (with local concerns of undersupply) but there are reasons to believe that oil production might peak in a near future (Hacquard et al., 2019; Tupaz, 2020).

²Note that the recycling of metals requires a significant energy cost, which negatively affects the EROI of energy systems built using those recycled metals. Yet, the dispersive use of initially concentrated materials significantly reduces their recycling potential.

³These minerals include for instance copper, zinc, lead, gold and phosphorus (Northey et al., 2014; Wellmer and Scholz, 2016; Calvo et al., 2017; Sverdrup and Olafsdottir, 2019).

Model	Authors	Biophysical constraints							Model of the economy					
		Energy		EROI	Materials		Waste			Eq. mechanism Demand-driven	Sectors included			
Av. NRE	Av. RE	Av.	EI		Biodiv.	Poll.	GHG	CD	Gov.		CB	RoW	Multi-sect.	
n/a	Barth and Richters (2019)	×	×	✓	×	×	×	✓	×	✓	✓	×	×	×
n/a	Berg et al. (2015)	×	×	✓	×	×	×	✓	✓	×	✓	×	×	×
GEMMES	Bovari et al. (2018a)	×	×	×	×	×	×	✓	✓	×	×	×	×	×
GEMMES	Bovari et al. (2018b)	×	×	×	×	×	×	✓	✓	×	×	×	×	×
GEMMES	Bovari et al. (2020)	×	×	×	×	×	×	✓	✓	×	×	×	×	×
n/a	Carnevali et al. (2021)	✓	✓	×	✓	×	×	✓	✓	✓	✓	✓	✓	✓
DEFINE	Dafermos et al. (2017)	✓	×	×	✓	×	×	✓	✓	✓	✓	×	×	×
DEFINE	Dafermos et al. (2018)	✓	×	×	✓	×	×	✓	✓	✓	✓	×	×	×
EUROGREEN	D'Alessandro et al. (2020)	×	×	×	×	×	×	×	×	×	✓	✓	✓	✓
n/a	Deleidi et al. (2019)	✓	✓	×	✓	×	×	✓	✓	✓	✓	✓	✓	✓
n/a	Gonzalez-Redin et al. (2018)	×	✓	×	×	×	×	×	×	×	×	✓	×	×
EIRIN	Gourdel et al. (2022)	×	×	×	×	×	×	×	×	×	×	✓	×	×
n/a	Jackson (2020)	×	×	✓	×	×	×	×	×	×	✓	×	×	✓
LowGrow	Jackson and Victor (2020)	×	×	✓	×	×	×	×	✓	×	✓	✓	✓	✓
Transim	Jackson and Jackson (2021)	×	×	✓	×	×	×	×	×	×	✓	×	×	✓
HARMONEY	King (2020)	✓	×	✓	×	×	×	×	×	×	✓	×	×	✓
HARMONEY	King (2021)	✓	×	✓	×	×	×	×	×	×	✓	×	×	✓
n/a	Naqvi (2015)	✓	×	✓	×	×	×	×	×	×	✓	✓	×	×
n/a	Naqvi and Stockhammer (2018)	×	×	×	×	×	×	×	✓	×	✓	×	×	×
SFCIO-IAM	Sers (2021)	×	×	✓	×	×	×	×	✓	×	✓	×	×	✓
TEMPLE	This paper	×	✓	✓	×	×	×	×	×	✓	✓	✓	×	✓

TABLE 3.1: Major ecological SFC models. A check in a column means that the model is taking into consideration the biophysical constraint to growth or is including the sector in its stock-flow consistent description of the economy. "Av. NRE" = Availability of Non-Renewable Energy. "Av. RE" = Availability of Renewable Energy. "Av." = Availability [of materials]. "EI" = Energy Intensity. "Biodiv." = Biodiversity loss. "Poll." = Pollutants directly affecting human health (e.g. fine particles). GHG = Greenhouse Gases emissions. "CD" = Climate Damage through feedback loop. "Gov." = Government. "CB" = Central Bank. "RoW" = Rest of the World (multi-regional model). "Multi-sect" = Multi-sectorial model.

vided by ecosystem services (food provisioning, water and air filtration, carbon storage, etc.) is not only at risk; the life-support properties granted by biodiversity are altogether jeopardized. Another example of feedback is the effect that pollutants and waste have on human health. We choose here to mention only those three aspects, which illustrate the polymorphic character of the environmental crisis in place.

Additional constraints It is argued that other limits to economic growth might arise, for instance for land or water (Manfroni et al., 2021b). Performing a review of these other biophysical constraints is beyond the scope of the present paper as we focus on the energy-matter-economy nexus.

3.1.2.3. BIOPHYSICAL-BASED ECOLOGICAL SFC MODELS

Several authors have paved the way for integrating biophysical constraints to growth into ecological SFC macroeconomic models. We here review their contributions and find a total of 20 major studies, listed and classified in Table 3.1.

A number of observations can be made from the table. First of all, most contributions are very recent (i.e. after 2015), which testifies to the youth of this field of research. This novelty partly explains why no model integrates all of the previously identified biophysical constraints to growth – from the most represented (GHG) to the most absent (energy intensity of minerals, biodiversity loss and to some extent, pollutants directly affecting human health e.g. fine particles). Second, we find that most models are demand-driven but diverge on the economic sectors included. For instance, the presence of a government or a central bank varies greatly among models. Lastly, a more in-depth investigation of these models informs us that significant work remains to be done to study the interrelated dynamics between the biophysical constraints affecting the transitioning energy system and the real and financial spheres of the economy. Indeed, the most advanced biophysical SFC models in that respect are either describing a single country (Jackson and Jackson, 2021), assume simplistic EROI curves (Naqvi, 2015), or

do not consider pivotal financial actors such as the central bank (Berg et al., 2015; Barth and Richters, 2019; Sers, 2021). Thus, we present in this paper a model (*TEMPLE*) aimed at studying thoroughly those dynamics at a global scale. This model includes a complete description of the world economy (even though disparities across regions are not represented) and includes biophysical constraints through detailed dynamic EROIs. Unlike all other models presented in Table 3.1, *TEMPLE* includes both the EROIs of renewable and non-renewable energies, as well as the availability constraint for renewable energy.

3.1.3. MATERIALS AND METHODS

3.1.4. THE *TEMPLE* MODEL

The *TEMPLE* model (Tilting Economic Momentum for Progress to Low-carbon Energies) represents a closed world economy. It combines the general structure from Dupont et al. (2021a) with a dynamic economic model similar to the one of Bovari et al. (2018a), but excluding the climate feedback loop developed in the latter article. Figure 3.1 gives an overview of the economic and financial flows between the different sectors in the model. As illustrated, the private sector is divided into energy firms and “other firms”. The former produces energy for the entire economy while the latter produces a homogeneous general-purpose good, named “final good”, for consumption and investment. Furthermore, a distinction is made between the workers (who receive their earning from their work) and capitalists (whose revenues depend on their capital investments). This distinction is of course a purely logical one, since one person can perceive both a salary and earnings from financial investments. *TEMPLE* also incorporates the banking sector, which grants loans and receives deposits, as well as the government, which intervenes (taxes, subsidies, regulations) on the different sectors of the economy and through its issuance and buy-back of public bonds. In the following subsections, we briefly describe the main features of the model. The Transaction Flow Matrix and balance sheet, which present in a more formal way the information conveyed by Figure 3.1, are given in Appendix. The equations of the model are detailed in Appendix.

Production and demand Production takes place in the energy and the final goods sub-sectors, in both cases according to a Leontief production function with three non-substitutable factors of production: energy⁴, labour and capital, which depreciates over time. The quantity of energy, capital stock and labour needed for a given production of energy or final goods is determined by the energy intensity, capital intensity and labour intensity of the related sub-sector. These intensities evolve through time, as will be made clear in Section 3.1.4.2. Production decision determines the utilization rate of capital, defined as the ratio between actual output and practical full capacity output. The latter is the maximum level of production that allows normal maintenance and renovation of machinery to take place without impeding production (Eichner, 1976; Steindl, 1952). Unlike the supply-driven version of the *TEMPLE* model, presented in Appendix, where the economy is always at full capacity, our demand-driven model allows the utilization rate to vary between zero and one. The energy demand is composed of energy needed to fuel the production of the energy and final goods sub-sectors, and energy consumed by workers and capitalists. On the other hand, final goods are required for investment into the capital stock of both productive sub-sectors and for the consumption of workers and capitalists. Moreover, the energy market is assumed to be at equilibrium at all times, unlike the market of

⁴As made clear by Keen et al. (2019), energy is indeed a fundamental factor of production.

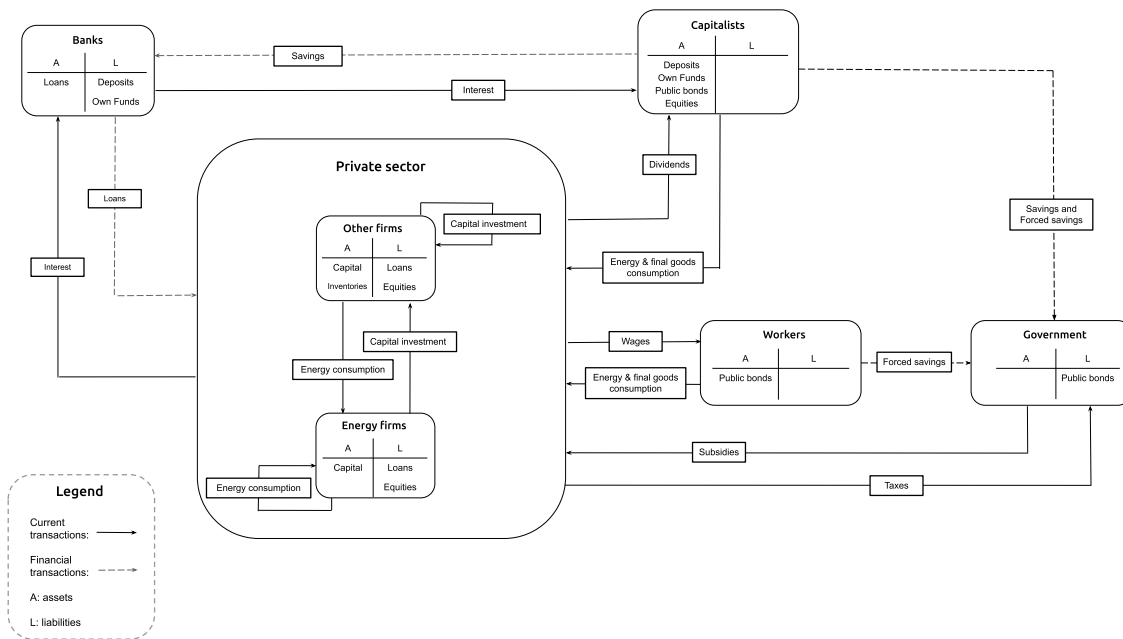


FIGURE 3.1: Overall structure of the TEMPLE model - economic and financial flows.

final goods which is cleared by inventories. Hence, inventory levels increase to absorb excessive production of final goods, and decrease when the demand for final goods is higher than supply.

Inflation We consider target mark-up pricing on unit costs (Lee, 1999), combined with inventory management. Inflation in the price of final goods has two components: one which is cost-push, depending on unitary cost of production, and a demand-pull component determined by disequilibrium in the market for final goods. We assume that in such case of a disequilibrium, prices and quantities adjust to eliminate it, with different speeds. The unitary costs of energy and final goods production have three components corresponding to the three factors of production. Since the demand for energy is assumed equal to production – hence removing any inventory management effect – the inflation in the energy price has only a cost-push component. Thus, the evolution of the unitary cost of energy production drives inflation in the energy price, together with a government tax or subsidy on energy products.

Profits, investment and debt The firms’ profits are determined by the price of the products they sell (energy or final goods), their unitary cost of production, the government taxes and subsidies and the interest that firms have to pay on their debt. Because of the mismatch between supply and demand in the final goods market, final goods firms also formulate expectations about their future profits, which differ from the actually realized profits. These expected profits (or the realized profits in the case of energy firms) determine the amount of dividends paid by firms to their shareholders. The retained part of the firms’ profits then serves to finance investment into new productive capital stock. The investment level of final goods firms is derived from their expected profits. On the other hand, the investment of energy firms into new capital is assumed to be independent of their profits and determined solely by their desire to fulfill at all times the energy demand targeting a specific utilization rate of capital⁵. The difference between the firms’ investment and their retained earnings is financed by issuing new debt⁶ (if it is positive)

⁵This reflects the fact that the energy sector is in reality a semi-public sector, aiming to meet the demand for energy at all times.

⁶We assume that all the external financing needs of firms (i.e. investments net of retained earnings) are met through debt and that banks are fully accommodating.

or on the contrary allows to reimburse this debt (when it is negative). The difference between capital stock and debt of energy and final goods firms is their private (non-traded) equity, which appears on the balance sheet in Appendix.

Workers, banks, capitalists and public sector The number of workers in employment in the global economy is determined by the production level of energy and final goods and by the labour intensity of these productions. The ratio of workers in employment to the world population (which evolves according to dynamics described in Section 3.1.4.2) determines the global employment rate⁷. Workers exchange their labour force for a wage, which is determined following a Goodwinian process depending on the global employment rate and the price of final goods. This allows to capture behaviour of the Phillips Curve as well as a certain degree of money illusion. We assume, following Kalecki (1935), that workers consume all their wages. Regarding the productivity of labour, its growth follows a linear Kaldor-Verdoorn dynamics (Kaldor, 1961, 1978; Verdoorn, 1949, 1980). Furthermore, banks receive deposits from capitalists and grant loans to firms to finance their investment into new capital stock. Banks revenues comes out of interests on loans. The interest rate is set as a mark-up on the policy rate. The latter is set by the central bank according to a purely inflation targeting Taylor (1993) rule. Banks transfer part of their earnings to their owners (the capitalists) and use the rest to maintain a sufficient level of own funds, in order to comply with prudential requirements. Thus, capitalists have two sources of revenues: the dividends coming from banks and the dividends paid by energy and final goods firms. We assume that capitalists consume a constant share of these revenues and save the rest. Finally, the public sector is modeled only through its taxes on energy products and its subsidies to the energy firms. We therefore abstract from most of the public sector's actions in reality (i.e. we do not consider public expenditure or most of the fiscal revenues). The taxes and subsidies, which vary depending on the progress of the energy transition, lead to public bonds' emissions or repayment. These bonds are bought or sold by the capitalists and households as a form of savings. Since we do not focus on the sustainability of public finances in this paper, we assume that these bonds do not bear any interest.

All the equations which correspond to the model's features described above can be summarized, after performing the computations described in Appendix, into a reduced form model. This reduced form model comprises 12 differential equations and is presented in Appendix.

Calibration We choose to calibrate the *TEMPLE* model on an initial steady-state for the world economy, based on data for the year 2019. The data comes mainly from the Penn World Table 10.0, the IEA data tables and Dupont et al. (2021a). As a result of the calibration process, all energy quantities become expressed in joule or exajoule per year and all (deflated) final goods quantities become expressed in US\$2017. The detailed calibration procedure and data sources are presented in Appendix.

3.1.4.1. MODELLING KEY DRIVERS OF THE ENERGY TRANSITION

Our goal is to study the short and medium-term impacts on the world economy of a rapid transition towards a 100% renewable energy system. To this end, we first calibrate the model to a steady state where time-dependent parameters are constant and all real and nominal variables are growing at constant rates. We then impose a path for the evolution of energy intensity and population growth, which gives us a quasi-steady state baseline scenario. Two other sce-

⁷Note that we choose to define the global employment rate as a fraction of the total population, and not as a fraction of the active population. This explains why the employment rates given in Section 3.1.6 appear to be so low.

narios are built on top of it, as described in Section 3.1.4.2. The strength of these scenarios lies in the detailed, dynamic evolution of several characteristics of the energy-economy system. These fundamental characteristics are the final EROI of wind and solar energies, the decreasing final EROI of fossil fuels and the evolving energy intensity of the global economy. By modeling these characteristics with dynamic functions, we improve on previous energy-economy models in which such parameters were constant or linearly decreasing (Sers and Victor, 2018; Capellán-Pérez et al., 2020; Jackson and Jackson, 2021). In addition, our model and scenarios are enhanced by using the population projection from Vollset et al. (2020). The sources and main hypotheses of these dynamic functions and projection are described in the following subsections.

Renewables EROI We use the global final EROI curves generated for wind and solar energies by Dupont et al. (2018, 2020)⁸. The curves describe how the mean EROI of renewable energy production facilities (onshore wind turbines, offshore wind turbines or solar panels) evolves as new facilities are added to scale up renewable production worldwide. These curves were built using a grid-cell approach: a mesh of 115k cells was applied on the Earth's surface and a series of databases were crossed in order to obtain for each cell the mean solar irradiation, the mean wind speed at an altitude of 100 m, the current land use, etc. Based on these data, the maximum wind and solar energy production potential was computed for each cell, as well as the energy inputs required for building, maintaining, and decommissioning the wind turbines and solar panels. Then, a mean EROI was computed for each cell and each energy type with the formula:

$$\text{EROI} = \frac{E_{out}(1 - \eta_{op})}{E_{in,cap}} \quad (3.1)$$

where E_{out} is the total amount of electricity produced throughout the lifetime of the facility, η_{op} is the fraction of this production that is directly auto-consumed on-site and $E_{in,cap}$ is the direct and indirect energy inputs needed to extract, process and transport the materials, build the facility, maintain it and decommission it at the end of its lifetime. E_{out} and $E_{in,cap}$ are both expressed as final energy. Note that $E_{in,cap}$ only relates to the energy embodied in wind turbines and solar panels themselves. They do not include the energy costs related to the necessary reinforcement of the electricity grid or the building of new storage capacity when the share of intermittent renewable energy sources increases, which we include later (see Section 3.1.4.2). The EROI values computed for each geographical cell, together with the maximum renewable production potential of the cell, can finally be assembled to give rise to the EROI curves. The fundamental hypothesis underlying the construction of these curves is that wind turbines and solar panels will always be installed first at the sites which display the best energy returns, hence these EROI curves are monotonously decreasing functions. Besides, future technological improvements are not considered in the calculation of EROI (that is, the EROI curves do not evolve with time).

Fossil fuels EROI The final EROI of the fossil fuels production is estimated through a multi-step process. First, yearly estimates from 1995 to 2011 are obtained from Brockway et al. (2019)⁹ and put in perspective with the cumulative production of final energy from fossil fuels using BP (2020) values. Second, an exponential decay relation with a minimum threshold of 1 is sought, in line with the functional forms used in Court and Fizaine (2017) and Delannoy et al.

⁸The code used to generate these EROI curves is open-source and available at <https://github.com/EliseDup/WorldEROI>.

⁹This study is, to the best of the authors' knowledge, the only one computing end use EROI values at a global scale. Another study (Feng et al., 2018b) also estimates the point-of-use EROI of fossil fuels, but does so for China only.

(2021b,a). Based on these two points, a prospective function for fossil-fuel EROI can be computed, whose argument is the cumulative final energy production from fossil fuels. In order to verify that our EROI function is realistic, forecasts of fossil fuels production are retrieved from IEA (2020a) for coal (Net Zero scenario) and GlobalShift (2020) for oil and gas. This allows us to compute the prospective EROI against future cumulative production and make sure that our EROI function gives a plausible result. The obtained EROI function is a decreasing exponential, as detailed in Appendix.

Global energy intensity of the economy Over the last three decades, the energy intensity of GDP has been decreasing for almost all world regions (Ahmad and Zhang, 2020; Vita et al., 2021). Even though thermodynamic limits ultimately constrain energy efficiency, significant gains are still possible (Cullen et al., 2011). Quantifying these gains is a complex and intricate task, subject to multiple uncertainties (de Blas et al., 2019).

We here rely on EXIOBASE3 (Stadler et al., 2018), a global multi-regional input-output database (GMRIO) to calculate energy footprints of GDP for the period 2011-2017 and project their future evolution. EXIOBASE3 provides economic data in current euros and must be corrected for purchasing power parity (PPP), using sector-level PPPs in constant currencies from the International Comparison Panel (ICP) cycles 2011 and 2017 (World Bank, 2020a) and Eurostat to distinguish between the dynamics of goods and services (Andrieu et al., 2022b)¹⁰. Energy intensities for goods, services and energy are then calculated (and expressed in MJ / 2017 US\$) to account for the final energy required for producing consumption goods and delivering services for workers and capitalists. Yearly improvements of 0.96%, 0.84% and 2.3% per year were computed for goods, services and energy, respectively.

We assume in our model that these energy intensities continue to decrease exponentially during the period 2019-2060 at these same constant rates as in 2011-2017¹¹. As the share of services vs. goods in final consumption stayed constant from 2011 to 2017, we consider it to be constant until 2060 but still challenge this hypothesis with a sensitivity analysis in Section 3.1.7.2. A similar methodology is used to compute the energy intensity of the production of capital. The energy intensity of the capital stock of the final goods sector is supposed to be that of Gross Fixed Capital Formation (GFCF) from EXIOBASE, corrected for purchasing power parity using ICP data and capital-details from Penn World Tables (PWT) (University of Groningen, 2021). Finally, the energy intensity of the production of energy capital stock is supposed to be equal to that of the Machinery and Equipment sector of EXIOBASE, also corrected for purchasing power parity using ICP and PWT data. This distinction is important since the energy intensity of Machinery and Equipment for the year 2017 is 81% above that of GFCF. However, the yearly improvement of the energy intensity of Machinery and Equipment is almost three times higher than that of GFCF (1.7 vs. 0.59% per year). Figure 3.2 summarizes the computed values of the different energy intensities for the year 2019 and their projected evolution until 2060, which corresponds to the end time of our simulations (see Section 3.1.6). The corresponding values are given in Table 3.6 in Appendix.

World population As noted by Rozell (2017), population dynamics are a key feature for models of the ecological transition and should be represented as accurately as possible. In the *TEMPLE* model, the projection from the reference scenario of Vollset et al. (2020), adapted in Figure 3.3, is used. To our best knowledge, these authors present the most solid scenarios available today

¹⁰See the annex for the detailed article

¹¹The 2.3% rate of decrease in the direct energy consumption of households can be reasonably prolonged until 2060 thanks to the efficiency gains associated with the electrification of mobility and heating.

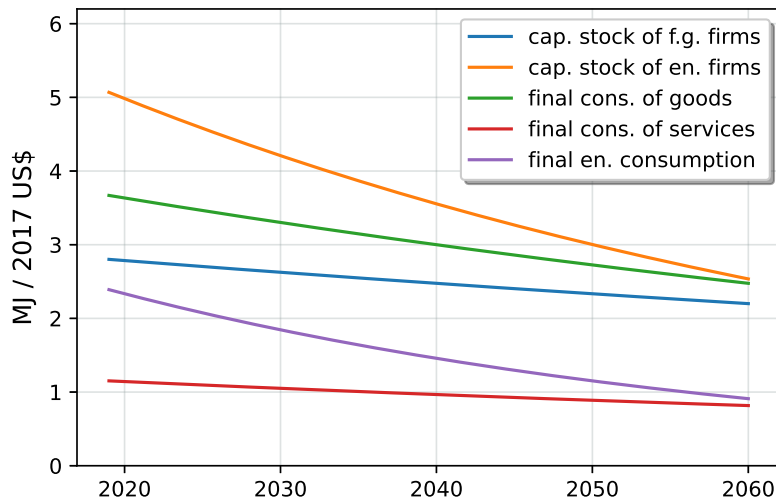


FIGURE 3.2: Energy intensities of final goods production and consumption. Computed values for the year 2019 and projected evolution until 2060.

for the evolution of the world population. According to their projection, the world population will “peak at 9.73 billion (95% UI 8.84–10.9) people in 2064 and then decline to 8.79 billion (6.83–11.8) in 2100”. Future population is modeled as a function of fertility and mortality rates, the former being driven by education level and access to contraception. To ensure more reliability, completed cohort fertility at age 50 is used rather than total fertility rate. Yet, the effects of climate change and pessimism about the future on fertility and mortality rates are neither studied, nor included in these scenarios.

3.1.4.2. SCENARIOS

We start from the steady-state economy obtained after calibration, which models the world economy at the end of the year 2019, before the COVID pandemic swept across the globe. The economic impacts of the pandemic are out of the scope of this paper and are ignored in our scenarios, just like the consequences of international conflicts. We then depart from the steady-state by adding the changes in energy intensities from Figure 3.2 and the population growth from Figure 3.3. The evolutions for energy intensities and population are thus imposed exogenously to the model. This altered steady-state model provides the baseline scenario, which will serve as the foundation on which to build the other scenarios. These other scenarios all include the energy transition. To model it, we proceed as in Dupont et al. (2021b) and define a new variable χ , the “degree of progress of the energy transition”, as the fraction of total final energy output which is produced by renewable energies. We assume that renewable energy sources are limited to wind and solar energy, since these two renewable sources are expected to clearly dominate all the others throughout the transition (IEA, 2020a; Moriarty and Honnery, 2020; EIA, 2020). According to the IEA statistics, wind and solar represented 3% of the total final energy supply in 2019 i.e. $\chi(2019) = 0.03$. We define a first scenario for the energy transition by exogenously imposing a sigmoid profile for the evolution of χ ¹². This sigmoid profile is represented in Figure 3.4 and corresponds to the scenario of a rapid energy transition scenario compatible with the Paris Agreement, which leads to an energy system based nearly entirely on

¹²Other profiles than a sigmoid are of course possible for the evolution of χ , as discussed in Section ‘Results and discussion’.

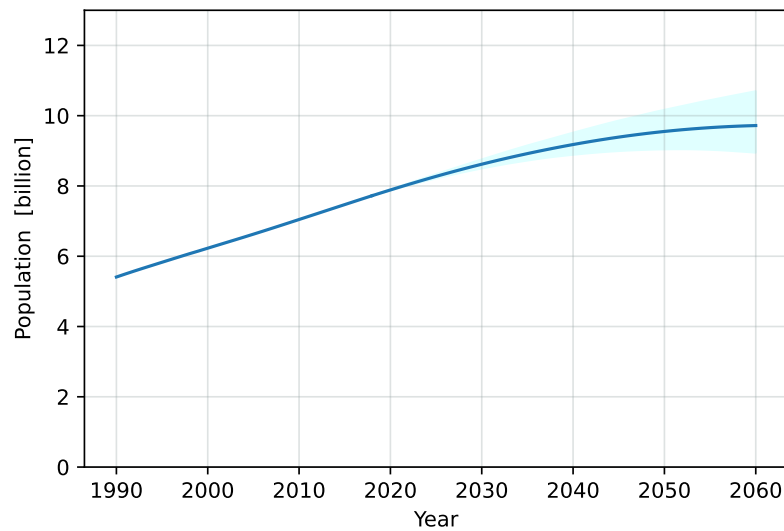


FIGURE 3.3: Global population projection in the reference scenario with 95% UI, adapted from Vollset et al. (2020).

renewables by 2050^{13,14}. Thus, the goal of our work is not to study the required measures to unlock the energy transition, but rather to assume that a rapid energy transition takes place and assess the economic consequences thereof.

In the *TEMPLE* model, the energy transition materializes through the evolution of the capital and energy intensities of the energy sub-sector. Indeed, these intensities are rewritten as the weighted averages of the intensities of non-renewable and renewable energy production, the weights being respectively $(1 - \chi)$ and χ . As in Dupont (2021), the energy intensity of renewable energy production is assumed to be the fraction of renewable electricity which is lost through grid losses. The capital intensity of renewable energy production is deduced from the EROI of renewable energy, as explained in Appendix. After performing this conversion, the final EROI curve for wind and solar energy production worldwide becomes a capital intensity curve. Then, in order to take into account the additional costs of the electricity grid and storage that will be generated by the penetration of renewable energies, a corrective factor is introduced to the capital intensity γ_{re} (which only included so far the capital required for building the wind turbines and solar panels). Relying on the systematic review of Heptonstall and Gross (2020), we extrapolate linear trends for the grid and balancing costs and aggregate both, taking 20% of the second to consider only the costs related to storage (and not other types of balancing costs, like demand-side actions). We thus find that the storage and grid costs will be 33% higher at the end of the transition compared to 2019, and that this will lead to an increase of 11% of the capital intensity of renewable energy production (in other words, the curve for capital intensity of renewable energy production must be multiplied by the factor $(1 + \frac{\chi}{9})$ in order to encompass the storage and grid costs). As for the energy and capital intensities of non-renewable energy production, they are assumed to evolve inversely proportionally to the fossil fuels' global EROI.

Thus, in *TEMPLE*, the impact of the energy transition on the economy is modeled through the evolution of the capital and energy intensities of energy production. The evolution of the

¹³To be precise, in our scenario the transition is only 100% completed in 2060

¹⁴Note that in this paper, we only study the energy transition from fossil fuels to renewable energies (limited to wind and solar). Nuclear power, which amounted to around 7% of the world total final energy supply in 2019, is neglected in our analysis as its massive deployment worldwide faces several critical issues (Markard et al., 2020). Yet, studying to what extent the transition could be eased by adding a portion of nuclear power to the decarbonated energy mix could be a valuable avenue for future research.

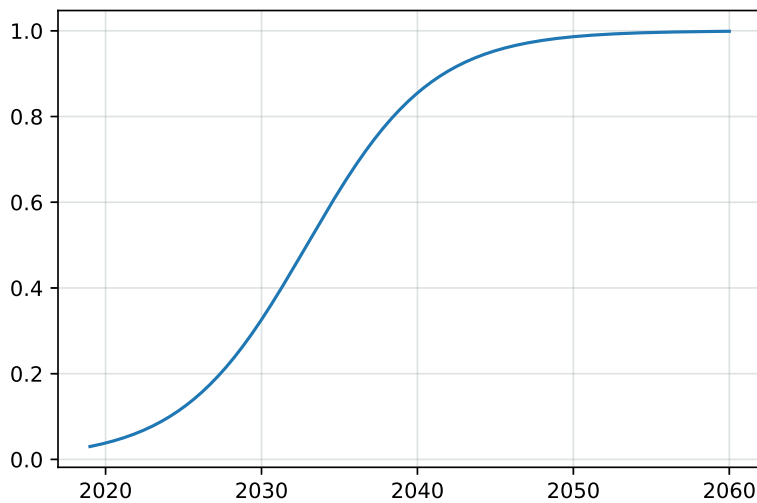


FIGURE 3.4: Degree of progress of the energy transition, i.e. χ , as a function of time in the second and third scenarios.

energy intensity of final goods production is also modeled in detail, as explained in Section 3.1.4.1. Regarding the capital intensity of final goods production, we assume that it stays constant throughout the transition. Indeed, this parameter has remained stable at world level for the last 30 years (Dupont et al., 2021b). We investigate three scenarios with TEMPLE:

1. The **baseline scenario** is the quasi-steady state economy, as described at the beginning of Section 3.1.4.1.
2. In the **energy transition scenario**, we exogenously impose an energy transition on the baseline, such that the energy system becomes almost 100% renewable-based by 2050. The decreasing EROI of fossil fuels is also included. We make some major assumptions for this scenario: (i) a ceiling of 10% is imposed by the government on the inflation of the energy price¹⁵. To avoid negative profits for energy firms because of this cap, we model subsidies provided to these firms by the government. We also assume that the government guarantees the debt of these firms, such that they benefit from an interest rate of 1% on their debt; (ii) as will be made clear in Section 3.1.6, the demand for final goods largely surpasses supply during the transition. We assume that any excess demand for final goods leads to constraints on the consumption of workers and capitalists. Any other allocation would imply either a lower capital accumulation in the final goods sector (and hence a lower economic growth, see next scenario and Figure 3.7)(a)) or a slower energy transition due to lower capital accumulation in the energy sector.
3. The **slower growth scenario** is identical to the previous one, except that a slower economic growth is imposed by exogenously reducing the propensity of final goods firms to invest (see Appendix for the equations' details).

3.1.5. RESULTS

Figure 3.5 presents the macroeconomic dynamics obtained in the energy transition scenario¹⁶. Figure 3.6 complements them by showing the biophysical dynamics of the energy system un-

¹⁵Other threshold values are of course possible for this cap.

¹⁶The model was run using R and the package `sysde`. All codes are available in the github repository <https://github.com/pierrejac1/TEMPLE>

der that same scenario. Finally, Figure 3.7 underlines the most relevant differences between the energy transition scenario and the two other scenarios. To avoid hazardous projections too far into the future, the results are shown only until the year 2060, once the energy transition is completed and a certain number of variables have converged. Note that the model does not converge to a steady-state after 2060, because the intensities of the factors of production (the capital intensity of energy production, mainly) exogenously evolve during the simulations. These ultimately limit economic growth, but discussing such limits is out of the scope of this paper, which focuses on the energy transition.

3.1.5.1. A LARGE IMBALANCE ON THE FINAL GOODS MARKET

When analysing the simulations, the first thing to notice is that due to the high capital intensity of renewable energy production (as outlined in the Appendix, the capital intensity of renewable energy production is one order of magnitude higher than for non-renewable energy production), the demand for final goods quickly exceeds supply. Indeed, as explained in Section 'Materials and methods', the demand for final goods has three components: investment into capital stock of energy firms, investment into capital stock of final goods firms and final consumption by workers and capitalists. The rapid energy transition causes supply constraints to bind. The capacity of final goods firms to increase their production capacity is hence reduced, which reinforces supply constraints. As a consequence, as shown in Figure 3.5(a), demand largely exceeds supply during the transition. The difference between demand and supply even reaches 27% of supply at the peak in 2040. Such mismatch, which arises already at the beginning of the transition in 2024, can only be handled thanks to a strong supervision of the economy by the government. We assume that the latter limits consumption of workers and capitalists through forced savings, in order to leave enough room for investment into renewable infrastructure¹⁷. The savings of workers and capitalists correspond to the buying of public bonds. Those new funds are used by the government to subsidize the energy sector, as described below. Besides, one can observe two kinks, in 2024 and 2041, on the curves presented in Figure 3.5. The first kink corresponds to inventories of final goods hitting a minimum value of zero: in fact, before constraining the consumption of workers and capitalists, the mismatch between demand and supply is first absorbed by depleting inventories. They become null in 2024 and keep this zero value until the end of the simulation. The mismatch also creates a pressure to increase the utilization rate of the capital stock of final goods firms. This utilization rate progressively increases until hitting the ceiling value of 1, which causes the kink in 2041.

3.1.5.2. TOWARDS A WAR ECONOMY ?

Figure 3.5(b) depicts the evolution of the GDP shares throughout the transition, that is, the fractions of GDP which correspond respectively to the wages of workers ("wage share"), the gross profits of the private companies and banks ("profit share") and the share of taxes and subsidies of the government. Those three shares sum up to 1, as detailed in Appendix. In addition, Figure 3.5 (b) depicts the investment into new capital ("investment share"), also equal to the fraction of GDP that is not consumed by workers and capitalists. We observe that the wage share increases from 69% in 2019 to 79% in 2060, while at the same time the profit share rises from 11% to 22%. In fact, the increase in the wage share is pulled by the increase in employment in the energy sector (see below), while the subsidies and debt guarantee provided by the govern-

¹⁷Thus, the TEMPLE model becomes supply-constrained as a result of the transition. This explains why the alternative, supply-driven version of the model gives similar simulation results, see Appendix.

ment ensure that energy firms keep positive profits. Concomitantly, high inflation decreases the real cost of labour in the final goods sector, hence allowing the profits of final goods firms to grow substantially. We also observe that the energy transition causes the investment share of the economy to drastically increase, from 26% in 2019 to 43% during the transition, because of the constraints imposed on consumption (i.e. forced savings). As put in perspective by Režný and Bureš, during WWII, “*at the peak of the war effort, the US economy was able to devote over 40% of its output solely to defence spending*” (Režný and Bureš, 2019). In other words, the energy transition scenario displayed here corresponds to a temporary transition of the global economy to a war economy.

3.1.5.3. A COUNTER-INTUITIVE RISE IN ENERGY INTENSITY

Regarding the evolution of the energy intensity of final goods production (which is a good proxy for the energy intensity of GDP), Figure 3.5(c) provides us with a rather unexpected result: contrary to what is often predicted, this energy intensity temporarily increases during the transition. In fact, even if all energy intensities of the sub-sectors of final goods production are assumed to decrease monotonously (see Figure 3.2), the transition implies a shift in production from less energy-intensive goods and services for consumption towards more energy-intensive capital for the energy sector infrastructure.

3.1.5.4. HIGH EMPLOYMENT, HIGH INFLATION

The evolution of employment during the transition, shown in Figure 3.5(d), is equally remarkable. The employment level in the energy sector displays a strong rise, from 0.8% of total population in 2019 up to 11% during and after the transition. As a consequence, the global employment rate of the world economy increases significantly. This increase is further reinforced by the economic dynamism brought about by the transition (high investment share) and by the declining growth rate of the world population (Figure 3.3).

Another key figure of our scenario is the evolution of inflation. The capital costs of renewable energy are much higher compared to fossil fuels. The energy firms try to pass these costs onto their clients and the inflation in energy prices soars as soon as the transition starts. As stated in Section 3.1.4.2 and as made clear in Figure 3.5(e), a 10% cap is imposed on the inflation in energy prices. Inflation in the price of final goods, in turn, increases as a result of the transition, up to a value of 11.4%. Such rise in the inflation in final goods price has three main drivers: (i) the mismatch between supply and demand which exerts an upward pressure on the prices (ii) the strong inflation in the price of energy (iii) the rising cost of labour resulting from the strong increase in the rate of employment.

3.1.5.5. AN ENERGY SECTOR STRONGLY SUPPORTED BY THE GOVERNMENT

As explained in our scenario definition, the public sector provides large subsidies to the energy firms to ensure their profitability despite the cap on the energy price. The subsidies given are of the order of magnitude of the forced savings shown in Figure 3.5(a). In addition, the debt of energy firms is guaranteed by the government, so that the interest rate on their debt never exceeds 1%. Figure 3.5(f) displays the dynamics of the debt ratios of energy firms and final goods firms throughout the transition. Despite the notable assistance from the government, their debt ratio (that is, the ratio between the aggregated debt of energy firms and the value of their capital stock) reaches a dangerously high value of 0.75 in 2034, before returning to its 2019 level.

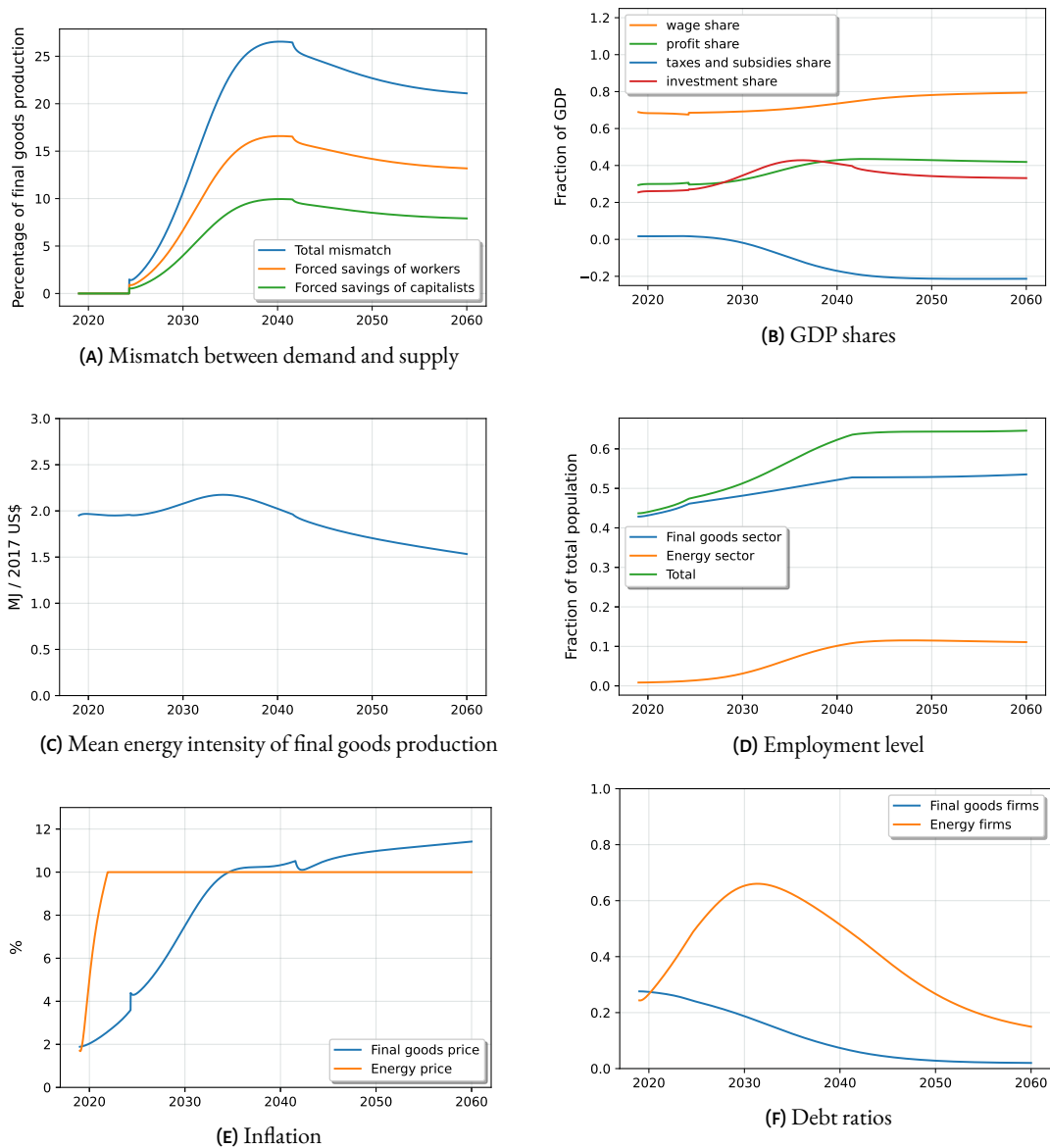


FIGURE 3.5: Simulated macroeconomic dynamics of the energy transition under the second scenario: "energy transition scenario".

This temporary increase serves to finance the huge investments required by the energy transition. The debt ratio of final goods firms, on the contrary, follows a steady decrease up until the year 2060. This deleveraging of final goods firms is driven by two dynamics: on the one hand inflationary pressures eroding the real value of debt and on the other hand, a transition to full capacity operation of the capital stock, increasing the profit rate and hence reducing external funding needs.

3.1.6. DISCUSSION

3.1.6.1. AN EROI PERSPECTIVE ON THE TRANSITION

Coming back to the biophysical constraints, Figure 3.6 displays the evolution of several characteristics of the energy system along the energy transition scenario. The first thing to no-

tice is that on the medium term, such transition is not constrained by the availability of energy. Indeed, Figure 3.6(a) shows that the total energy production from renewables in 2060 is around half of the global potential of 2150 EJ/year computed by Dupont et al. (2021b). The energy production from fossil fuels, on the other hand, decreases rapidly and falls to zero by mid-century. The total cumulative production from fossil fuels between 2019 and the end of the transition is of 7'230 EJ, which is one order of magnitude below the remaining URR of 60'000 EJ, as estimated using Maggio and Cacciola (2012); Mohr et al. (2015); Wang and Bentley (2020). As a stylized comparison with the maximum potential of renewables, we represent in Figure 3.6(a) a uniform distribution of this URR over the period 2020-2060, for a value of 1500 EJ/year.

As the transition proceeds, the energy production sector requires a growing and significant portion of the energy available to society, as made clear in Figure 3.6(b). Its share of the total energy production starts at 11%, peaks at 32% in 2037 before decreasing to 20%, as renewable energy systems require mainly upfront energy investments, when the system is being built. This evolution is to be put in perspective with the final EROI of technologies, Figure 3.6(c), and the EROI of the energy system¹⁸, Figure 3.6(d). Renewables display a higher point of use EROI than fossil fuels, while showing a marked decrease during the transition, as the best locations for wind and solar facilities become progressively saturated. On the contrary, the EROI of fossil fuels does not evolve substantially between 2019 and 2060 as their extraction declines abruptly in the assumed energy transition. When taking into account electrical losses in the grid (mainly) and investment in storage facilities (to a lesser extent), the EROI of the entire renewable energy sub-system is in fact smaller than its non-renewable counterpart. After a period of decline during the transition, the overall EROI of the energy system rebounds after 2040, in similar proportions as in Fabre (2019) or the S2-M and S5-R scenarios of Slameršak et al. (2022). Besides, the system's EROI and its evolution take practically the same values as in the "low green capital" baseline simulation of Jackson and Jackson (2021).

An important insight is that the main stumbling block of the transition does not lie in the required quantity of energy for building and operating the energy system, but rather in the form which these required energy inputs must take and how this interacts with the rest of the economy. The transition implies to shift from an energy sector relying chiefly on direct energy inputs (for operating the oil and gas fields, the refineries, etc.) to an energy sector whose energy inputs are overwhelmingly "embedded into the capital stock". This was already foreseen in previous works (Jacques, 2019; Dupont et al., 2021b) and explains why integrating biophysical with macroeconomic perspectives is essential when studying the transition. These insights face however several limitations, discussed in detail in Section 3.1.7.3.

3.1.6.2. WHAT IF THE ECONOMY GROWS MORE SLOWLY?

The previous subsections have described the results of the energy transition scenario. Figure 3.7 contrasts the main results of this scenario with the two other scenarios outlined in Section 3.1.4.2. The only difference between the energy transition scenario and the slower growth scenario is that the growth rate of the capital stock of final goods firms is lower in the latter case. As shown in Figure 3.7(a), the growth rate decreases from 3% in 2019 down to 2% in the slower growth scenario, instead of an increase to 4% in the energy transition scenario. This decrease is due to an exogenously imposed reduction of the final goods firms' propensity to invest. This reduction could have multiple reasons, for example climate damages (not explicitly modeled in

¹⁸To be precise, the fraction of total energy devoted to feeding the energy sector is exactly equal to the inverse of the system's PROI (Power Return On Investment). The difference between the system's EROI and PROI is outlined in Appendix.

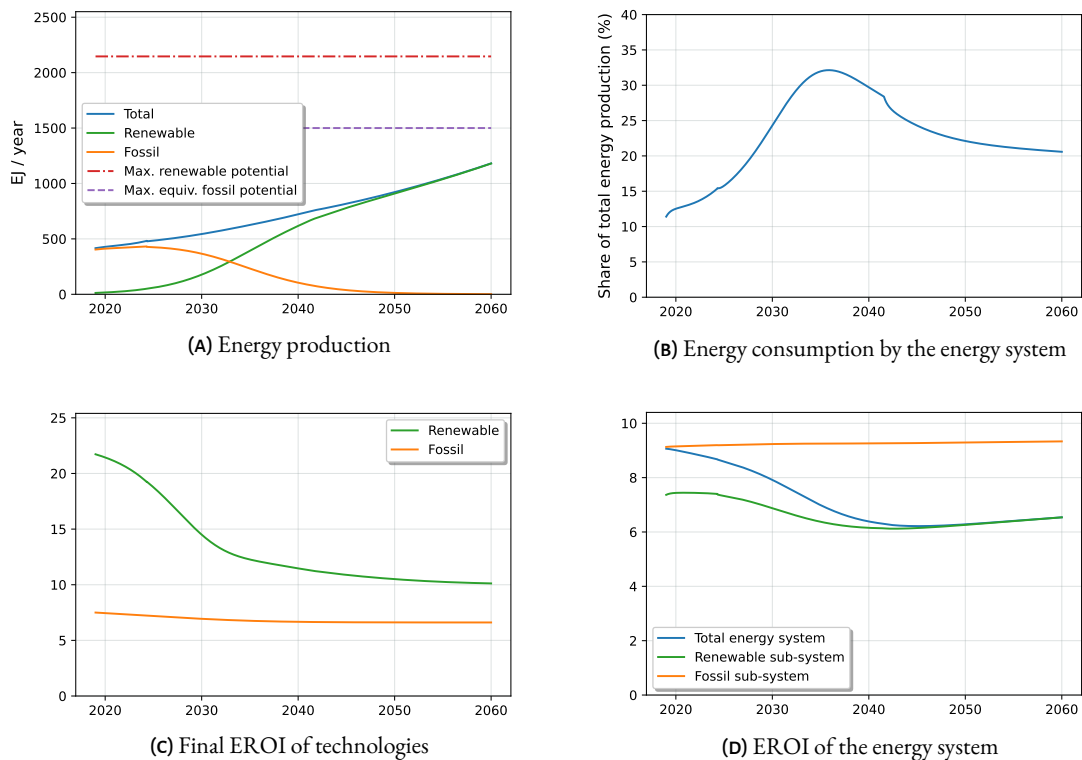


FIGURE 3.6: Simulated biophysical dynamics of the energy system under the energy transition scenario.

TEMPLE) or an aversion to the risks accompanying the transition. Whatever the reasons for this slower growth rate, we observe that it greatly facilitates the transition. Indeed, with a slower growth rate, the energy demand grows more slowly too and the EROI of renewable energies decreases less (unlike in Figure 3.6(c) for the energy transition scenario). We thus have a smaller level of inflation in energy prices. Combined with a slightly less dynamic economy, this implies a less tight demand for workers and hence less increase in wages. This results in a maximum inflation rate in final goods prices that is less than half of the maximum rate reached in the energy transition scenario with high growth (see Figure 3.7(b)). Similarly, Figure 3.7(c) shows that in the slower growth scenario, the transition can be completed with a peak in investment share at “only” 35%, compared to the value of 43% in the second scenario. Thus, we observe that contrary to what is often advocated, a slower economy realises much more easily its energy transition and allows to avoid a vicious cycle in which more economic growth would require more energy, which in turn would require a high economic growth for investing into the capital stock of the energy sector.

3.1.7. ROBUSTNESS, LIMITATIONS AND FURTHER WORK

3.1.7.1. COMPARISON OF RESULTS WITH OTHER MODELS

Findings of other authors generally confirm the main features of the transition outlined by our model. In their literature review, Rye and Jackson (2018) observe that in most EROI-based models, as a result of the transition, “*the energy sector outgrows the economy (aka. energy cannibalism)*”, resulting in a shortage of available investment for other sectors. Such crowding out effect is particularly present in the conclusions of Dale et al. (2012a); Dupont et al. (2021b);

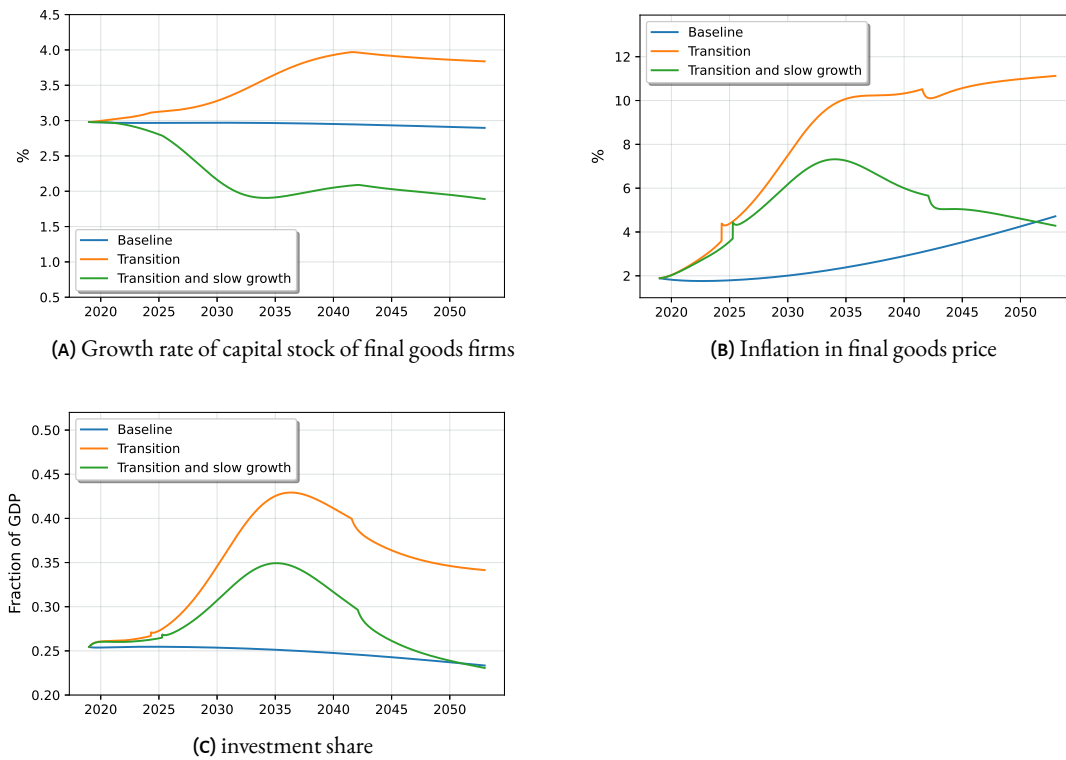


FIGURE 3.7: Major differences in the macroeconomic dynamics of the three scenarios modeled with TEMPLE

Režný and Bureš (2019) and Sers and Victor (2018). Thus, the rest of the economy can either reduce its growth rate, or try to maintain it by increasing the global investment share (Dupont, 2021). Like us, Režný and Bureš (2019) and Dupont et al. (2021b) state that the transition in a growing global economy can only be completed with an investment share reaching levels unseen since WWII. Moreover, Režný and Bureš (2019) come, as we do, to the conclusion that economic growth is not incompatible with a 100% renewable energy system. Nonetheless, economic growth, in the context of the transition, can come as a penalty rather than an asset (Sers and Victor, 2018; Sers, 2021).

Our finding that the transition implies a temporary rise in the global energy intensity of the economy, however, appears to be novel. We do not have knowledge of previous works highlighting a similar conclusion. This reflects the fact that the evolution of energy intensities has been too little investigated in detail up until today.

Furthermore, we can compare our model results to the works which are the closest to ours: the ones of Jackson and Jackson (2021) and Sers and Victor (2018). TEMPLE shares similar structure and assumptions with the TranSim model from Jackson and Jackson (2021). However, in both scenarios investigated with TranSim, the inflation resulting from the required investments into the energy sector are less important than in the energy transition scenario from TEMPLE. Besides, there is no crowding-out in TranSim. Such divergences in the models' results are due to three main divergent modeling assumption¹⁹: (i) in TranSim, real variables tend to grow at a rate of 1% per year, driven by the exogenous growth of labour productivity. It is also the case in TEMPLE, except that labour productivity grows faster and population also

¹⁹There are of course numerous differences in the structure and equations of TranSim, such as the use of three types of firms instead of two, variable markups for profits and vintage capital. Yet, these differences impact far less the models' results than the three divergent modeling assumptions described here.

grows, to give a growth rate of over 3%²⁰ in TEMPLE, the capital intensity of renewable energies evolves via a detailed function, while it stays constant in TranSim. This renewable capital intensity more than doubles through the course of the transition in TEMPLE; (iii) the choice of calibration for demand-pull and cost-push inflation adjustment speeds in TEMPLE (see the sensitivity analysis in next Section). Due to these three reasons, required investments in the energy sector are higher than in TransSim and lead to a crowding-out, with different inflationary dynamics than in TranSim. Such crowding-out effect also appears in the third energy transition scenario modeled in Sers and Victor (2018). This scenario includes EROI values and investment needs in the renewable infrastructure comparable to those of TEMPLE. Despite having a much less detailed description of the non-energy part of the economy than TEMPLE, the EETRAP model of Sers and Victor (2018) shares a similar structure. However, there is no households consumption to constrain in EETRAP so the mismatch between demand and supply of final goods can only be cleared by reducing the investment in non-energy capital stock. The transition thus considerably slows down economic growth in the third scenario of Sers and Victor (2018), which displays similar values of investment share as the slower growth scenario from TEMPLE²¹.

3.1.7.2. SENSITIVITY ANALYSIS

The sensitivity of our results in the second scenario are tested regarding key parameters of the model. First, we re-ran the simulations after modifying the capital intensity of renewable energies by +/- 30%. As outlined by the literature review of Murphy et al. (2022), there still exists a large uncertainty on the EROI of renewable energies, on which our computation of capital intensity is based. For example, when using some of the assumptions and data from Fthenakis and Leccisi (2021) to compute the EROI of PV panels worldwide with the method from Dupont et al. (2020), we obtain capital intensity values 30% lower for solar energy. Second, we re-ran the simulations after modifying the degrowth rates of the energy intensity of each final goods sub-sector by +/-50%. Indeed, high uncertainty exists on energy intensity data. As for the share of services in final consumption of workers and capitalists, considered to be equal to 55% (vs. 45% for the share of goods), we carry out a sensitivity analysis of +/- 10%. A higher difference from historical values seems very unlikely as this share stayed constant between 1995 and 2017. Third, a sensitivity analysis was conducted for population growth rate, using the bounds previously shown in Figure 3.3. Fourth, an alternative, hypothetical curve was tested for the imposed evolution of the degree of progress of the energy transition. Instead of following the sigmoid curve from Figure 3.4, this alternative specification follows a linear increase up to the value of 1 in 2050.

The results of these sensitivity analyses are plotted in the Appendix. We observe that the conclusions previously stated are robust regarding the different tested parameters. Indeed, the general dynamics of the transition stay the same. Only the exact peaking values (for example of the investment share or of inflation) are affected by the variation of the parameters.

Nevertheless, since TEMPLE is a system dynamics model, it is sensitive to the values of the adjustment speeds used in the differential equations. These values were obtained through calibration and hence changing them can significantly affect the model's results. For example, we can modify the adjustment speeds which determine the relative weights of demand-pull versus cost-push inflation, as shown in Figure 3.8. Since the main driver of inflation in the price of final

²⁰At the steady-state in 2019, those 3% are split between 1.9% of productivity growth and 1.1% of population growth.

²¹The third scenario modeled with EETRAP shows an investment in renewables that ramps up to a constant fraction of 10% of GDP. In the slower growth scenario of TEMPLE, the investment in renewables reflects the fact that most of the investment has to be made upfront. It peaks to a value of 17% of GDP in 2035, before decreasing to 7%.

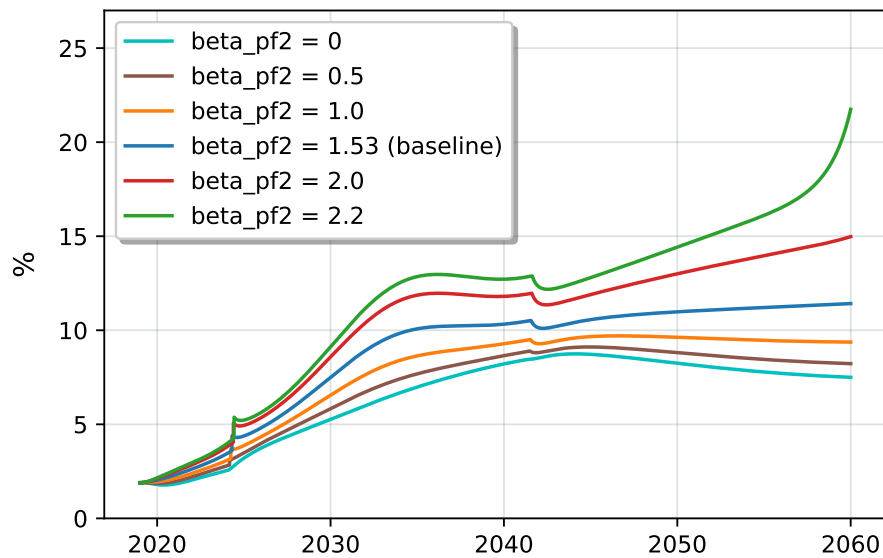


FIGURE 3.8: Impact on inflation of varying jointly the adjustment speeds for cost-push and demand-pull inflation in the final goods' price

goods is the mismatch between demand and supply, increasing the relative weight of demand-pull inflation amplifies the inflation caused by the transition, which can become so important for certain adjustment speeds' values that the economy collapses. On the other hand, reducing the relative weight of demand-pull inflation compared to cost-push inflation makes the model's results similar to those of the supply model, presented in the Appendix. Finally, increasing the adjustment speed of expected demand to actual demand in the final goods sector also adds inflationary pressure on the economy, even if it reduces unitary cost of production (the demand-pull inflationary effect outweighs the cost-driven disinflationary effect.). These insights highlight once more the importance of modelling disequilibria and the relative strengths of equilibrating mechanisms, as mentioned before. The details of the corresponding equations and parameters, as well as the complete set of graphs for sensitivity analysis, are presented in the Appendix.

3.1.7.3. LIMITATIONS AND FURTHER WORK

Even though the TEMPLE model provides multiple relevant insights into the dynamics of the energy transition, it keeps a rather low-dimensionality (between 12 and 20 differential equations) and presents only aggregated biophysical and macroeconomic trends. This constitutes its first limitation, since regional differences are prone to affect the course of global dynamics. Countries from the Global North, in particular, are likely to make their transition first while being less well endowed in terms of renewable energy resources. In this context, it is quite possible that they will seek to appropriate the highest-EROI resources from the Global South. This would make emerging and developing economies less able to achieve their own transition while being among the most affected by climate change and the least responsible for it. In its current version, the TEMPLE model is unable to simulate these dynamics, unlike Carnevali et al. (2021) for instance. Our article merely proposes to assess the economic consequences of a rapid energy transition on a global scale, questioning its feasibility in the context of a growing economy.

If it allows to conclude that the transition comes with major challenges, TEMPLE still remains very conservative in many aspects. Indeed, it neglects among others : (i) the issues related to the electrification of entire sectors (ii) the climate change damages on the global economy

and on the energy system (iii) geopolitical factors and competition for energy supply (iv) extreme events that might change the course of dynamics, e.g. a climatic tipping point is passed or peak oil is reached before being prepared to it (v) the multiple planetary limits not related to energy (e.g. biodiversity). Our work also focuses only on the impacts of the point-of-use EROI, and does not regard the decline of standard EROI of fossil fuels and the ties it may have with the energy price (King and Hall, 2011; Heun and de Wit, 2012).

Several factors tend to overestimate or underestimate the EROI values used in the study. They might for instance impact the EROI of fossil fuels but, in this case and as argued in Appendix D of de Castro and Capellán-Pérez (2020), the different factors tend to cancel out. Plus, the EROI of fossil fuels plays a minor role in our study as the transition to renewables is carried out quickly. Second, we assume that the best locations for wind and solar facilities on the global scale (for instance in the Sahara) are used first, which might prove to be unrealistic. Another feature that might lead to optimistic EROIs for renewables is the relatively low estimation for the grid and storage costs. This is however discussed in the literature (Carbajales-Dale et al., 2014; Diesendorf and Wiedmann, 2020; Schill, 2020; Ruhnau and Qvist, 2022) and calls for a more precise description of the electricity sector in a future version of TEMPLE. Furthermore, we neglect the probable increase in energy consumption per kilogram of extracted metal due to a falling ore grade which cannot eternally be compensated by technological progress, especially for copper. As discussed in Section 'Materials and methods', renewable technologies being very copper-intensive, including this decrease in ore grade could result into an EROI which decreases with time. Moreover, we assume that our scenario does not require carbon capture and storage technologies, overlooking their potential material, energy, economic and human requirements (Sgouridis et al., 2019). On the contrary, our assumption to neglect technological and industrial improvements might lead to underestimating the future EROI of PV and wind (Louwen et al., 2016; Steffen et al., 2018). Taken together, all these assumptions make our estimates optimistic, and generally above the general average one can obtain from the literature (Murphy et al., 2022). Still, the dynamic EROI of the energy production system is similar to other analysis, and its drop seems rather consistent (Capellán-Pérez et al., 2019).

All these points would require further work. Besides, we observe that rising employment is an important driver of the energy transition dynamics (via its effect on inflation). A more rigorous and in-depth investigation of the labour intensity of renewable energy production should thus be incorporated into the model, following for example the work of Perrier and Quirion (2018). Since one of our main findings is the necessity for a war economy oriented towards the energy transition, research should also be conducted on the multiple side-effects, the various political consequences and the required conditions for the implementation of such war economy. Namely, the feasibility of shrinking some sectors of the economy (related to consumption) and its effect on the stability of the entire system would need to be explored.

3.1.8. CONCLUSION

The transition to renewable energy sources represents a dual economic and energy challenge. In order to integrate this double perspective, we propose here a novel biophysical, stock-flow consistent macroeconomic model combining detailed bottom-up estimates for the high capital intensity of renewable energies, the decreasing energy return on investment (EROI) of fossil fuels and the evolution of the energy intensities of productive sub-sectors.

We are able to estimate the biophysical and macroeconomic dynamics that the world economy would undergo if an energy transition compatible with the 1.5°C objective of the Paris

	Workers	Capitalists	Energy firms		Final goods firms		Banks	Gov.	Σ
			Current	Capital	Current	Capital			
Consumption	$-C_{w,e} - C_{w,f}$	$-C_{c,e} - C_{c,f}$	$+C_{w,e} + C_{c,e}$		$+C_{w,f} + C_{c,f}$				0
Investment				$-I_e$	$+I_e + I_f$	$-I_f$			0
Intermediary consumption			$+E_f$		$-E_f$				0
Wages	$+W(L_e + L_f)$		$-W L_e$		$-W L_f$				0
Taxes and subsidies			$-T_e y_e$					$+T_e y_e$	0
Interests on loans			$-r D_e$		$-r D_f$		$+r(D_e + D_f)$		0
Banks dividends		$+\Pi_{b,d}$					$-\Pi_{b,d}$		0
Firms dividends		$+\Pi_{e,d} + \Pi_{f,d}$	$-\Pi_{e,d}$		$-\Pi_{f,d}$				0
Retained earnings			$-\Pi_{e,u}$	$+\Pi_{e,u}$	$-\Pi_{f,u}$	$+\Pi_{f,u}$			0
Σ (=Savings)	$+sav_w$	$+sav_c$	0	$+sav_e$	0	$+sav_f$	$+sav_b$	$+sav_g$	0
Change in capital stock				K_e		K_f			$K_e + K_f$
Change in inventories						n_f			n_f
Change in deposits		M					$-M$		0
Change in loans				$-D_e$		$-D_f$	$+D_e + D_f$		0
Change in public bonds	$+B_{g,w}$	$+B_{g,c}$						$-B_g$	0
Change in own funds		$+OF_b$					$-OF_b$		0
Change in equities		$+\mathcal{E}_e + \mathcal{E}_e$		$-\mathcal{E}_e$		$-\mathcal{E}_f$			0
Σ (=Change in net worth)	$+B_{g,w}$	$M + B_{g,c} + \mathcal{E}_e + \mathcal{E}_e + OF_b$		0		0	0	$-B_g$	$K_e + K_f + n_f$

TABLE 3.2: Transaction Flow Matrix

	Workers	Capitalists	Energy firms	Final goods firms	Banks	Government	Σ
Capital stock			K_e	K_f			$K_e + K_f$
Inventories				n_f			n_f
Deposits		M			$-M$		0
Loans			$-D_e$	$-D_f$	$D_e + D_f$		0
Public Bonds	$B_{g,w}$	$B_{g,c}$				$-B_g$	0
Banks' own funds		OF_b			$-OF_b$		0
Equity		$\mathcal{E}_e + \mathcal{E}_f$	$-\mathcal{E}_e$	$-\mathcal{E}_f$			0
Σ (=Net worth)	$B_{g,w}$	$M + B_{g,c} + \mathcal{E}_e + \mathcal{E}_f + OF_b$	0	0	0	$-B_g$	$K_e + K_f + n_f$

TABLE 3.3: Balance sheet

Agreement was undertaken. Since action needs to be taken rapidly, the model shows that the classical market-based mechanisms of price and quantity adjustment are not sufficient to force the required investments. We find in fact that (i) the transition can only be completed thanks to a high level of investment share, unseen in Western economies since WWII (ii) strong inflationary dynamics arise (iii) the overall EROI of the energy system decreases during the transition (iv) energy firms undergo a decline in profitability and therefore need substantial help from the government. This last finding questions the appropriateness of the privatization of the energy sector. Our results further indicate that a slower growth rate eases the transition by smoothing out the inflationary dynamics. We finally conduct a sensitivity analysis of our results and conclude that they prove to be robust to changes in the values of key parameters.

Our modeling assumptions can be considered generally conservative and yet, the simulations' results underline the significant challenges of the transition. Above all, they show that economic growth constitutes a handicap rather than an asset for achieving the energy transition. We therefore call for the study and design of transition scenarios in the frame of a post-growth economy.

APPENDIX

TRANSACTION FLOW MATRIX AND BALANCE SHEET

The Transaction Flow Matrix (TFM) is shown in Table 3.2. The first part of the TFM concerns all non-financial transactions, i.e. all transactions regarding the real economy as well as the redistribution of income through wages or dividends. The lower part of the TFM is the Flow-of-Funds (FOF) table, which shows how savings are allocated across the different financial assets of the economy. The corresponding balance sheet (i.e. how all stocks are allocated across sectors) is shown in Table 3.3.

NOMENCLATURE AND MATHEMATICAL NOTATIONS

For the sake of clarity, we will be using the following conventions for all the equations of the model:

- The two productive subsectors are referred to by the subscripts “ e ” (energy sector) and “ f ” (final goods sector).
- Workers, capitalists and banks are respectively referred to by the subscripts “ w ”, “ c ” and “ b ”.
- Energy quantities are expressed in SI units (i.e. Joules) and final goods quantities are expressed in monetary units. All quantities are denoted by uppercase letters when they are in nominal monetary terms and by lowercase letters when they are in real terms (i.e. either in energy units or in monetary units corrected for inflation).
- For a given variable a , we define $\dot{a} := \frac{da}{dt}$ and $\hat{a} := \frac{\dot{a}}{a}$

Variables For all variables written hereunder, we have $x \in \{e, f\}$ and $z \in \{w, c\}$.

$y_{x,p}$	=	yearly production of sub-sector x
e_x	=	yearly energy consumption of sub-sector x
L_x	=	number of workers in sub-sector x
k_x	=	capital stock of sub-sector x
u_x	=	utilization rate of capital in sub-sector x
$y_{e,d}$	=	total yearly energy demand
$y_{f,d}$	=	total yearly demand for final goods
$y_{f,p}^e$	=	expected yearly production of final goods
u_f^e	=	expected utilization rate of capital in the final goods sub-sector
$c_{z,e}$	=	energy consumption of households of type z
$c_{z,f}$	=	final goods consumption of households of type z
i_x	=	capital investment in sub-sector x
p_e	=	unit price of energy
p_f	=	unit price of final goods
n_f	=	level of inventories of final goods
W	=	nominal wages of workers in both productive sub-sectors
T_e	=	unitary tax on energy products

UC_x	=	firms' unit cost of production in sub-sector x
D_x	=	aggregated debt of firms in sub-sector x
r	=	interest rate
r^T	=	target interest rate of banks
r_{CB}	=	target interest rate of the central bank
$s_{F,w}$	=	forced saving rate of workers during the energy transition
$s_{F,c}$	=	forced saving rate of capitalists during the energy transition
B_g	=	stock of public bonds
OF_b	=	banks' own funds
$\Pi_{b,u}$	=	banks' retained earnings
$\Pi_{b,d}$	=	dividends distributed to shareholders by banks
Π_x	=	profits of firms in sub-sector x
Π_f^e	=	expected profits of final goods firms
$\Pi_{x,d}$	=	dividends distributed to shareholders by firms of sub-sector x
$\Pi_{x,u}$	=	retained earnings of firms in sub-sector x
i_x	=	investment into new capital stock in sub-sector x
\hat{k}_f	=	growth rate of the capital stock in sub-sector x
POP	=	world population
λ_x	=	employment rate in sub-sector x
λ	=	global employment rate
GDP	=	GDP of the global economy
s	=	investment share of the global economy
Ω	=	wage share of the global economy
$y_{nre,p}$	=	yearly energy production from non-renewable sources
$y_{re,p}$	=	yearly energy production from renewable sources
χ	=	degree of progress of the energy transition
$EROI_{nre}$	=	aggregated energy return on investment of non-renewable energy sources
$EROI_{re}$	=	aggregated energy return on investment of renewable energy sources

Non-dimensionalized variables For all variables written hereunder, we have $x \in \{e, f\}$ and $z \in \{w, c\}$.

- \mathcal{K}_e = ratio between the capital stock of energy firms and final goods firms
- \mathcal{P}_e = ratio between the price of energy and the price of final goods
- ν_f = inventory level divided by capital stock of final goods firms
- $\kappa_{z,f}$ = final goods consumption of households z divided by capital stock of final goods firms
- ω_x = wages divided by labour intensity in sub-sector x
- \mathcal{T}_e = real value of the government tax on energy
- uc_x = real unit cost of production in sub-sector x
- d_x = debt divided by the value of capital stock in sub-sector x
- of_b = banks' own funds divided by the value of capital stock of final goods firms
- $\pi_{b,u}$ = banks' retained earnings divided by the value of capital stock of final goods firms
- π_x = profit divided by the value of capital stock in sub-sector x
- π_f^e = expected profit of final goods firms divided by the value of their capital stock
- $\pi_{x,d}$ = dividends distributed divided by the value of capital stock in sub-sector x

Parameters For all parameters written hereunder, we have $x \in \{e, f\}$ and $z \in \{w, c\}$.

ϵ_x	=	energy intensity of sub-sector x
α_x	=	labour intensity of sub-sector x
γ_x	=	capital intensity of sub-sector x
δ_x	=	rate of depreciation of capital in sub-sector x
δ_n	=	rate of depreciation of final goods' inventories
n_f^T	=	target level of final goods' inventories
η	=	ratio of inventories to expected production of final goods
$\beta_{n_f,1}$	=	proportionality factor for the adjustment of expected final goods' production
$\beta_{n_f,2}$	=	proportionality factor for the adjustment of realized final goods' production
p_e^T	=	target price of energy
p_f^T	=	target price of final goods
μ_x	=	price markup of the firms in sub-sector x
β_{p_e}	=	adjustment speed in the price of energy
$\beta_{p_f,1}$	=	cost-push adjustment speed in the price of final goods
$\beta_{p_f,2}$	=	demand-pull adjustment speed in the price of final goods
u_e^T	=	target utilization rate of energy firms' capital stock
k_e^T	=	target level of energy firms' capital stock
β_{i_e}	=	adjustment speed in the investment decision of energy firms
$\kappa_{f,0}$	=	parameter in the investment decision of final goods firms
$\kappa_{f,1}$	=	parameter in the investment decision of final goods firms
Δ	=	fraction of the profits or expected profits paid as dividends to the shareholders
ω_0	=	parameter of the Phillips curve
ω_1	=	parameter of the Phillips curve
ω_2	=	parameter of the Phillips curve
α_0	=	parameter of the Kaldor-Verdoorn equation
α_1	=	parameter of the Kaldor-Verdoorn equation
r^*	=	"natural" rate of interest
φ	=	parameter in Taylor's rule
\hat{p}_f^T	=	inflation target of the central bank
μ_b	=	banks' prudential ratio
OF_b^T	=	banks' required level of own funds

β_b	=	adjustment speed of banks' own funds
β_r	=	adjustment speed of banks' interest rate
$\lambda_{r,T}$	=	parameter in the computation of banks' target interest rate
s_c	=	constant saving rate of capitalists
ϵ_{cons}	=	technological parameter for computation of households' direct energy consumption
$f(\cdot)$	=	function relating the households' energy consumption to the price of energy
a_0	=	parameter in function $f(\cdot)$
a_1	=	parameter in function $f(\cdot)$
a_2	=	parameter in function $f(\cdot)$
ϵ_{f,i_e}	=	energy intensity of the production of capital stock for the energy sub-sector
ϵ_{f,i_f}	=	energy intensity of the production of capital stock for the final goods sub-sector
ϵ_{f,c_f}	=	aggregated energy intensity of the production of final goods and services for consumption
$\epsilon_{f,c_f,g}$	=	energy intensity of the production of final goods (not services) for consumption
$\epsilon_{f,c_f,s}$	=	energy intensity of services (not final goods) for consumption
θ_g	=	share of goods in final consumption
θ_s	=	share of services in final consumption
ϵ_{nre}	=	energy intensity of non-renewable energy production
ϵ_{re}	=	energy intensity of renewable energy production
γ_{nre}	=	capital intensity of non-renewable energy production
γ_{re}	=	capital intensity of renewable energy production

EQUATIONS OF THE MODEL

Production and demand Let us call $y_{x,p}$ the production of sector x , e_x the energy required yearly for this production, L_x the required number of workers and k_x the capital stock of sector x ($x \in \{e, f\}$). Note that according to the convention used, $y_{x,p}$ and k_x are noted as lowercase letters, hence they are in real terms. We have the following production equations:

$$y_{e,p} = \frac{e_e}{\epsilon_e} = u_e \alpha_e \frac{L_e}{\gamma_e} = u_e \frac{k_e}{\gamma_e} \quad (3.2)$$

$$y_{f,p} = \frac{e_f}{\epsilon_f} = \alpha_f L_f = u_f \frac{k_f}{\gamma_f} \quad (3.3)$$

in which ϵ_x , α_x and γ_x denote respectively the energy, labour and capital intensity of production in sector x and u_x is the utilization rate of capital, which must always stay below unity. The number of workers required in the final goods sector is proportional to the production $y_{f,p}$. However, we assume that the number of workers in the energy sector is instead proportional to the capital stock k_e . Indeed, as it is made clear in Figure 3.5, the number of workers in

the energy sector is negligible before the energy transition and then increases as the energy sector becomes renewable. We make the assumption that in a renewable energy system, the number of jobs is proportional to the capital stock of the system and not to its energy production. In other words, the operation of wind turbines and solar panels creates jobs irrespective of whether they produce energy or not. So it is only k_e and not u_e which drives employment in the energy sector.

Let us call $y_{e,d}$ and $y_{f,d}$ the demand for energy and final goods, respectively. Energy demand can be split up in four components: (i) energy inputs for final goods production e_f ; (ii) energy inputs for energy production e_e ; (iii) energy consumption of workers $c_{w,e}$ and (iv) energy consumption of capitalists $c_{c,e}$. Similarly, final goods are required for (i) investment i_f in the capital of final goods firms; (ii) investment i_e in the capital of energy firms; (iii) consumption of workers $c_{w,f}$ and (iv) consumption of capitalists $c_{c,f}$ ²². We thus have the equations:

$$y_{e,d} = e_e + e_f + c_{w,e} + c_{c,e} \quad (3.4)$$

$$y_{f,d} = i_e + i_f + c_{w,f} + c_{c,f} \quad (3.5)$$

Let us further define p_f the unit price of final goods and p_e the unit price of energy. Note that following the convention described in Appendix 3.1.8, we have $C_{z,x} = p_x c_{z,x}$ ($x \in \{e, f\}$, $z \in \{w, c\}$, w =workers, c =capitalists). We then make the assumption that the final goods consumption and the energy consumption of workers and capitalists are related by the equation:

$$c_{z,e} = \epsilon_{\text{cons}} f\left(\frac{p_e}{p_f}\right) c_{z,f} \quad (z \in \{w, c\}) \quad (3.6)$$

where ϵ_{cons} is a technological parameter (which can vary with time) and $f(\cdot)$ is a monotonously decreasing function. This equation amounts to saying that the energy consumption of citizens decreases with technological progress and is sensitive to the real energy price.

By assumption, production and demand are always equal to each other in the energy market:

$$y_{e,p} = y_{e,d} \quad (3.7)$$

The final goods market, on the other hand, is at a disequilibrium. It is cleared by the inventories n_f , which depreciate at a constant rate δ_n .

$$\dot{n}_f = y_{f,p} - y_{f,d} - \delta_n n_f \quad (3.8)$$

To determine how much the final goods firms choose to produce, it is assumed that they have an expected level of production $y_{f,p}^e$, which is different from $y_{f,p}$. This expected level of production determines an expected utilization rate of capital u_f^e via the equation:

$$u_f^e = \frac{\gamma_f y_{f,p}^e}{k_f} \quad (3.9)$$

Firms expectations on production evolve according to two different factors: the current trend (represented by the growth rate of their capital stock) and the expected excess demand,

²²Note that $c_w + c_c$ is not firmly restricted to the consumption of households. These terms also include government spending.

through some proportionality factor $\beta_{n_f,1}$ ²³:

$$\dot{y}_{f,p}^e = \hat{k}_f y_{f,p}^e + \beta_{n_f,1} (y_{f,d} + \delta_n n_f - y_{f,p}^e) \quad (3.10)$$

Moreover, it is assumed that firms wish to keep their inventories at a certain level n_f^T , equal to a given fraction η of their expected production²⁴:

$$n_f^T = \eta y_{f,p}^e \quad (3.11)$$

Final goods firms therefore decide to produce more than their expected production level, so that their inventory level converges towards its target:

$$y_{f,p} = y_{f,p}^e + \beta_{n_f,2} (n_f^T - n_f) \quad (3.12)$$

where $\beta_{n_f,2}$ is a parameter.

Inflation Let us call W_e and W_f the nominal wages of workers in the energy and final goods sectors, respectively. We make the assumption that:

$$W_e = W_f = W \quad (3.13)$$

Let us also call δ_x the depreciation rate of the capital stock and UC_x , the firms' unit cost of production in sector x ($x \in \{e, f\}$). We have the following equation:

$$UC_x = \frac{W L_x + p_e e_x + p_f \delta_x k_x}{y_{x,p}} \quad (x \in \{e, f\}) \quad (3.14)$$

Inflation in the price of energy is driven by the cost of energy production and evolves according to:

$$\dot{p}_e = \beta_{p_e} (p_e^T - p_e) \quad (3.15)$$

$$p_e^T = \mu_e UC_e + T_e \quad (3.16)$$

This equation indicates that energy firms adjust their price p_e with a speed β_{p_e} , such that p_e tends towards a certain target price p_e^T . This target price is equal to the firms' unit cost of production multiplied by a markup μ_e ²⁵, plus a certain government tax T_e . The markup μ_e is strictly superior to one in order to ensure positive profits to the energy firms.

The price of final goods evolves according to a similar equation. However, its inflation has a second driver, which is linked to the level of inventories and which represents the unbalance on the market of goods and services:

$$\dot{p}_f = \beta_{p_f,1} (p_f^T - p_f) + \beta_{p_f,2} \left(p_f \frac{n_f^T - n_f}{k_f} \right) \quad (3.17)$$

$$p_f^T = \mu_f UC_f \quad (3.18)$$

²³In this paper, we follow Robinson (1969) in that firms might make mistakes in their estimation of output growth, creating unwanted excess capacity.

²⁴Such a desired inventory to expected sales ratio η is also used in Franke (1996); Chiarella and Flaschel (2000); Charpe et al. (2011)

²⁵This determination of prices by firms based on target-return pricing is inspired from Lavoie (1992)

Profits, investment and debt Let us define D_x , the aggregated debt of firms in sector x ($x \in \{e, f\}$) and r , the interest rate that they have to pay on this debt. The firms' profits in the energy and final goods sectors can be written as:

$$\Pi_e = y_e (p_e - UC_e - T_e) - r D_e \quad (3.19)$$

$$\Pi_f = y_{f,d} p_f - y_{f,p} UC_f - r D_f \quad (3.20)$$

Regarding the capital investment of energy firms, we assume that these firms have a certain target utilization rate u_e^T for their capital stock, which in turn determines the target level of capital stock k_e^T :

$$k_e^T = \frac{\gamma_e y_e}{u_e^T} \quad (3.21)$$

The investment i_e of the energy firms into new capital is thus given by:

$$i_e = \beta_{i_e} (k_e^T - k_e) + \delta_e k_e \quad (3.22)$$

where β_{i_e} is a constant adjustment speed and $\delta_e k_e$ serves to compensate for the depreciation of the existing capital stock. Note that this investment behaviour is independent of the profits of the energy companies.

The final goods firms, on the other hand, invest according to their expected profit rate. Let us define the profit Π_f^e expected by the final goods firms, which is different from their realized profit Π_f :

$$\Pi_f^e = y_{f,p} (p_f - UC_f) - r D_f \quad (3.23)$$

We then define the expected profit rate of final goods firms as:

$$\pi_f^e := \frac{\Pi_f^e}{p_f k_f} \quad (3.24)$$

The investment behaviour of final goods firms is given by the equation:

$$i_f = k_f (\kappa_{f,0} + \kappa_{f,1} \pi_f^e + \delta_f) \quad (3.25)$$

with $\kappa_{f,0}$, $\kappa_{f,1}$, constant parameters.

A constant fraction Δ of the profits of energy firms is paid as dividends to the shareholders (that is, the capitalists):

$$\Pi_{e,d} = \Delta \Pi_e \quad (3.26)$$

with the subscript d standing for "dividends".

As for final goods firms, it is a constant fraction of their expected profits which is redistributed to shareholders:

$$\Pi_{f,d} = \Delta \Pi_f^e \quad (3.27)$$

Let us define $\Pi_{x,u}$, the retained earnings of firms in sector x . We have:

$$\Pi_{x,u} = \Pi_x + p_f \delta_x k_x - \Pi_{x,d} \quad (x \in \{e, f\}) \quad (3.28)$$

In both producing sectors, the firms bridge the gap between retained earnings and investment by issuing debt:

$$\dot{D}_x = p_f i_x - \Pi_{x,u} \quad (x \in \{e, f\}) \quad (3.29)$$

Finally, the capital accumulation equation is as usual:

$$\dot{k}_x = i_x - \delta_x k_x \quad (x \in \{e, f\}) \quad (3.30)$$

Workers, banks, capitalists and public sector Let us call the world population POP and let us define the employment rate in sector x as

$$\lambda_x = \frac{L_x}{POP} \quad (x \in \{e, f\}) \quad (3.31)$$

We then define the global employment rate as:

$$\lambda = \lambda_f + \lambda_e \quad (3.32)$$

As previously stated, workers exchange their labour force for a nominal wage W . This wage is determined following a Phillips curve (Phillips, 1958), which depends on the global employment rate λ and the price of final goods p_f :

$$\widehat{W} = \omega_0 + \omega_1 \lambda + (1 - \omega_2) \hat{p}_f \quad (3.33)$$

where $0 < \omega_2 < 1$ and $(1 - \omega_2)$ is the money illusion of workers.

We assume that workers consume all of their wages, except a fraction $s_{F,w}$. This fraction corresponds to forced savings imposed by the government during the energy transition:

$$p_f c_{w,f} + p_e c_{w,e} = (1 - s_{F,w}) W \cdot L \quad (3.34)$$

Regarding the growth of labour productivity, we assume that it is equal for workers in the final goods and energy sectors. It is defined by a linear Kaldor-Verdoorn dynamics:

$$\hat{\alpha}_f = \hat{\alpha}_e = \hat{\alpha} = \alpha_0 + \alpha_1 \lambda \quad (3.35)$$

The interest rate of the central bank r_{CB} is set according to Taylor's rule:

$$r_{CB} = r^* + \hat{p}_f + \varphi (\hat{p}_f - \hat{p}_f^T) \quad (3.36)$$

where r^* is the constant "natural" rate of interest, φ is a parameter and \hat{p}_f^T is the inflation target of the central bank.

We define μ_b as the banks' prudential ratio. Banks' required level of own funds OF_b^T is then given by:

$$OF_b^T = \mu_b (D_f + D_e) \quad (3.37)$$

The banks' retained earnings $\Pi_{b,u}$ are thus computed such that their own funds OF_b converge

towards their required level, with a convergence speed β_b :

$$\Pi_{b,u} = \beta_b (OF_b^T - OF_b) \quad (3.38)$$

$$\dot{OF}_b = \Pi_{b,u} \quad (3.39)$$

The rest of their profits is then distributed to capitalists as dividends:

$$\Pi_{b,d} = r (D_f + D_e) - \Pi_{b,u} \quad (3.40)$$

The banks' ability to retain earnings depends on their revenues, which are themselves directly determined by the interest rate's level. The banks' target rate of interest is therefore computed in a similar way to their retained earnings, but with the addition of the central bank's rate of interest:

$$r^T = r_{CB} + \lambda_{r^T} \frac{OF_b^T - OF_b}{OF_b^T} \quad (3.41)$$

where λ_{r^T} is a constant parameter. Once they have determined their target interest rate, banks then progressively adjust their interest rate towards this target, with speed β_r :

$$\dot{r} = \beta_r (r^T - r) \quad (3.42)$$

The capitalists' revenues are composed of the dividends they receive from firms and from banks. If we assume that capitalists consume a fraction $(1 - s_c - s_{F,c})$ of their revenues, then their final goods consumption (in nominal terms) is given by:

$$C_{c,f} = (1 - s_c - s_{F,c}) (\Pi_{f,d} + \Pi_{e,d} + \Pi_{b,d}) \quad (3.43)$$

s_c is the constant fraction of their revenues that capitalists always save. $s_{F,c}$ is the extra (non-constant) fraction that the government forces them to save during the energy transition.

The only source of taxation by the government is found in equations 3.16 and 3.19. The tax on energy products, T_e can also be turned into a subsidy (by changing its sign and value) in order to support energy firms during the transition. So, the modeled taxes and subsidies lead to public bonds emissions or repayment:

$$-\dot{B}_g = T_e y_e \quad (3.44)$$

DERIVATION OF THE REDUCED FORM MODEL

The equations presented in the previous subsections constitute the *TEMPLE* model. Starting from these equations, a reduced form model can be derived. This reduced form model contains only variables that are ratios of other variables. This procedure of "non-dimensionalization" is similar to what is done in fluid mechanics in engineering. It gives new variables, which are easier to compare with other models and whose evolution is more meaningful to analyse. Moreover, the reduced form model is a more compact set of equations, which are easier to manipulate for numerical simulations. The following pages detail the method followed to obtain the reduced form model.

Let us define the following set of variables:

$$\mathcal{K}_e := \frac{k_e}{k_f} \quad \mathcal{P}_e := \frac{p_e}{p_f} \quad \omega_x := \frac{W}{\alpha_x p_x} \quad d_x := \frac{D_x}{p_f k_x} \quad (3.45)$$

$$\pi_x := \frac{\Pi_x}{p_f k_x} \quad \pi_{x,d} := \frac{\Pi_{x,d}}{p_f k_x} \quad \pi_{b,u} := \frac{\Pi_{b,u}}{p_f k_f} \quad of_b := \frac{OF_b}{p_f k_f} \quad (3.46)$$

$$uc_x := \frac{UC_x}{p_x} \quad \kappa_{z,f} := \frac{c_{z,f}}{k_f} \quad \nu_f := \frac{n_f}{k_f} \quad \mathcal{T}_e := \frac{T_e}{p_e} \quad (3.47)$$

where $x \in \{e, f\}$, $z \in \{w, c\}$.

Based on these new variables, we modify the equations from the previous subsections to obtain a reduced form model.

Given $\omega_x := \frac{W}{\alpha_x p_x}$, we have:

$$\hat{\omega}_x = \widehat{W} - \hat{\alpha}_x - \hat{p}_x \quad (x \in \{e, f\}) \quad (3.48)$$

which becomes, when we insert equations 3.33 and 3.35:

$$\hat{\omega}_e = \omega_0 + \omega_1 \lambda - \omega_2 \hat{p}_f + (\hat{p}_f - \hat{p}_e) - \alpha_0 - \alpha_1 \lambda \quad (3.49)$$

$$\hat{\omega}_f = \omega_0 + \omega_1 \lambda - \omega_2 \hat{p}_f - \alpha_0 - \alpha_1 \lambda \quad (3.50)$$

We know from equations 3.2 and 3.3 that²⁶:

$$L_e = \frac{k_e}{\alpha_e} \quad (3.51)$$

$$L_f = \frac{y_{f,p}}{\alpha_f} \quad (3.52)$$

Thus, given $\lambda_x := \frac{L_x}{POP}$, we have:

$$\hat{\lambda}_x = \hat{L}_x - \widehat{POP} \quad (x \in \{e, f\}) \quad (3.53)$$

$$\hat{\lambda}_e = \hat{k}_e - \alpha_0 - \alpha_1 \lambda - \widehat{POP} \quad (3.54)$$

$$\hat{\lambda}_f = \hat{y}_{f,p} - \alpha_0 - \alpha_1 \lambda - \widehat{POP} \quad (3.55)$$

$$\hat{\lambda}_f = \hat{k}_f + \hat{u}_f - \alpha_0 - \alpha_1 \lambda - \widehat{POP} \quad (3.56)$$

By inserting into equation 3.5 the definitions of \mathcal{K}_e , $\kappa_{w,f}$, $\kappa_{c,f}$ and equation 3.30, we also

²⁶As already explained above, the number of jobs in the energy sector is independent of the utilization rate of the energy capital stock. If production from wind turbines and solar panels needed to be curtailed regularly, this would not induce a loss of jobs. On the contrary, managing the variability of renewable energy production and the possible curtailment operations is a complex task which requires skilled workers.

have:

$$\frac{y_{f,d}}{k_f} = \frac{i_e + i_f + c_{w,f} + c_{c,f}}{k_f} \quad (3.57)$$

$$= \mathcal{K}_e \frac{i_e}{k_e} + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} \quad (3.58)$$

$$= \mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} \quad (3.59)$$

We then obtain from equations 3.9, 3.10 and 3.59:

$$\hat{u}_f^e = \hat{y}_{f,p}^e - \hat{k}_f \quad (3.60)$$

$$= \frac{-\beta_{n_f,1} (y_{f,p}^e - y_{f,d} - \delta_n n_f)}{y_{f,p}^e} \quad (3.61)$$

$$= -\beta_{n_f,1} \left(1 - \frac{\gamma_f}{u_f^e} \frac{y_{f,d}}{k_f} - \delta_n \frac{\gamma_f}{u_f^e} \frac{n_f}{k_f} \right) \quad (3.62)$$

$$= -\beta_{n_f,1} \left(1 - \frac{\gamma_f}{u_f^e} (\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f}) - \delta_n \frac{\gamma_f}{u_f^e} \nu_f \right) \quad (3.63)$$

$$\hat{u}_f^e = \beta_{n_f,1} (\gamma_f (\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} + \delta_n \nu_f) - u_f^e) \quad (3.64)$$

Similarly, by definition of ν_f and by equations 3.8 and 3.59, we have:

$$\hat{\nu}_f = \hat{n}_f - \hat{k}_f \quad (3.65)$$

$$= \frac{1}{n_f} (y_{f,p} - y_{f,d}) - \delta_n - \hat{k}_f \quad (3.66)$$

$$\hat{\nu}_f = \frac{y_{f,p}}{k_f} - \frac{y_{f,d}}{k_f} - (\hat{k}_f + \delta_n) \nu_f \quad (3.67)$$

$$= \frac{u_f}{\gamma_f} - (\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f}) - (\hat{k}_f + \delta_n) \nu_f \quad (3.68)$$

Moreover, $d_x := \frac{D_x}{p_f k_x}$ becomes, when we take the derivative:

$$\dot{d}_x = \frac{\dot{D}_x}{p_f k_x} - d_x (\hat{p}_f + \hat{k}_x) \quad (x \in \{e, f\}) \quad (3.69)$$

After inserting equations 3.28, 3.29, 3.30 and the definition of π_x , we obtain:

$$\dot{d}_x = \frac{i_x}{k_x} - \frac{\Pi_{x,u}}{p_f k_x} - d_x (\hat{p}_f + \hat{k}_x) \quad (3.70)$$

$$= \frac{i_x}{k_x} - \frac{\Pi_x + p_f \delta_x k_x - \Pi_{x,d}}{p_f k_x} - d_x (\hat{p}_f + \hat{k}_x) \quad (3.71)$$

$$= \hat{k}_x - \frac{\Pi_x - \Pi_{x,d}}{p_f k_x} - d_x (\hat{p}_f + \hat{k}_x) \quad (3.72)$$

We can then insert 3.26 and 3.27 into this equation to get:

$$\dot{d}_e = \hat{k}_e - (1 - \Delta) \pi_e - d_e (\hat{p}_f + \hat{k}_e) \quad (3.73)$$

$$\dot{d}_f = \hat{k}_f - \pi_f + \Delta \pi_f^e - d_f (\hat{p}_f + \hat{k}_f) \quad (3.74)$$

Given $of_b := \frac{OF_b}{p_f k_f}$ and equation 3.39, we have:

$$\dot{of}_b = \frac{\dot{OF}_b}{p_f k_f} - of_b (\hat{p}_f + \hat{k}_f) \quad (3.75)$$

$$= \pi_{bu} - of_b (\hat{p}_f + \hat{k}_f) \quad (3.76)$$

We can also transform equation 3.12 into:

$$\frac{k_f}{\gamma_f} u_f = \frac{k_f}{\gamma_f} u_f^e + \beta_{n_f,2} \left(\eta \frac{k_f}{\gamma_f} u_f^e - k_f \nu_f \right) \quad (3.77)$$

$$u_f = u_f^e + \beta_{n_f,2} (\eta u_f^e - \gamma_f \nu_f) \quad (3.78)$$

Given $uc_x := \frac{UC_x}{p_x}$ and equation 3.14, we further have:

$$UC_e = \frac{\gamma_e W}{\alpha_e u_e} + \epsilon_e p_e + p_f \frac{\gamma_e \delta_e}{u_e} \quad (3.79)$$

$$uc_e = \frac{\gamma_e}{u_e} \omega_e + \epsilon_e + \frac{\gamma_e \delta_e}{\mathcal{P}_e u_e} \quad (3.80)$$

and

$$UC_f = \frac{W}{\alpha_f} + \epsilon_f p_e + p_f \frac{\gamma_f \delta_f}{u_f} \quad (3.81)$$

$$uc_f = \omega_f + \epsilon_f \mathcal{P}_e + \frac{\gamma_f \delta_f}{u_f} \quad (3.82)$$

With $\pi_e := \frac{\Pi_e}{p_f k_e}$ and $\mathcal{T}_e := \frac{T_e}{p_e}$, equation 3.19 becomes:

$$\pi_e = \frac{\mathcal{P}_e u_e}{\gamma_e} (1 - uc_e - \mathcal{T}_e) - r d_e \quad (3.83)$$

Similarly, equation 3.23 leads to:

$$\pi_f^e = \frac{u_f}{\gamma_f} (1 - uc_f) - r d_f \quad (3.84)$$

Using equation 3.59, we can also rewrite equation 3.20 as:

$$\pi_f = \frac{p_f y_{f,d} - p_f y_{f,p} \left(uc_f + \frac{\gamma_f}{u_f} r d_f \right)}{p_f k_f} \quad (3.85)$$

$$= \mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} - \frac{u_f}{\gamma_f} uc_f - r d_f \quad (3.86)$$

With $\kappa_{w,f} := \frac{c_{w,f}}{k_f}$, we obtain, by combining equations 3.6 and 3.34:

$$c_{w,f} (p_e \epsilon_{\text{cons}} f(\mathcal{P}_e) + p_f) = (1 - s_{F,w}) W \cdot L \quad (3.87)$$

$$c_{w,f} = \frac{(1 - s_{F,w}) \omega_f}{\mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e) + 1} \alpha_f (L_f + L_e) \quad (3.88)$$

$$c_{w,f} = \frac{(1 - s_{F,w}) \omega_f}{\mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e) + 1} \left(y_{f,p} + \frac{\alpha_f}{\alpha_e} k_e \right) \quad (3.89)$$

$$\kappa_{w,f} = \frac{\omega_f}{\mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e) + 1} \left(\frac{y_{f,p}}{k_f} + \frac{\alpha_f}{\alpha_e} \mathcal{K}_e \right) \quad (3.90)$$

$$\kappa_{w,f} = \frac{(1 - s_{F,w}) \omega_f}{\mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e) + 1} \left(\frac{u_f}{\gamma_f} + \frac{\alpha_f}{\alpha_e} \mathcal{K}_e \right) \quad (3.91)$$

Similarly, with $\kappa_{c,f} := \frac{c_{c,f}}{k_f}$ and equations 3.26, 3.27, 3.40, equation 3.43 becomes:

$$\kappa_{c,f} = (1 - s_c - s_{F,c}) \left(\Delta \pi_f^e + \mathcal{K}_e \Delta \pi_e + r (d_f + \mathcal{K}_e d_e) - \pi_{b,u} \right) \quad (3.92)$$

Furthermore, by combining equations 3.4, 3.6 and the definition of u_e , we obtain:

$$u_e = \frac{\gamma_e}{(1 - \epsilon_e)} \left(\frac{e_f + c_{w,e} + c_{c,e}}{k_e} \right) \quad (3.93)$$

$$= \frac{\gamma_e}{(1 - \epsilon_e) \mathcal{K}_e} \left(\frac{\epsilon_f u_f}{\gamma_f} + \frac{c_{w,e} + c_{c,e}}{k_f} \right) \quad (3.94)$$

$$= \frac{\gamma_e}{(1 - \epsilon_e) \mathcal{K}_e} \left(\frac{\epsilon_f u_f}{\gamma_f} + \epsilon_{\text{cons}} f(\mathcal{P}_e) (\kappa_{w,f} + \kappa_{c,f}) \right) \quad (3.95)$$

Let us divide both sides of equation 3.22 by k_e . It gives:

$$\frac{i_e}{k_e} = \beta_{ie} \left(\frac{k_e^T}{k_e} - 1 \right) + \delta_e \quad (3.96)$$

$$\hat{k}_e = \beta_{ie} \left(\frac{u_e}{u_e^T} - 1 \right) \quad (3.97)$$

Finally, we combine equations 3.37 and 3.41 to have:

$$r^T = r_{CB} + \lambda_{r^T} \frac{\mu_b (D_f + D_e) - OF_b}{\mu_b (D_f + D_e)} \quad (3.98)$$

$$r^T = r_{CB} + \lambda_{r^T} \frac{\mu_b (d_f + \mathcal{K}_e d_e) - of_b}{\mu_b (d_f + \mathcal{K}_e d_e)} \quad (3.99)$$

Reduced form model The reduced form model is the set of differential equations:

$$\begin{aligned}
\dot{\mathcal{K}}_e &= \mathcal{K}_e (\hat{k}_e - \hat{k}_f) \\
\dot{\mathcal{P}}_e &= \mathcal{P}_e (\hat{p}_e - \hat{p}_f) \\
\dot{\omega}_f &= \omega_f (\omega_0 + \omega_1 \lambda - \omega_2 \hat{p}_f - \alpha_0 - \alpha_1 \lambda) \\
\dot{\omega}_e &= \omega_e (\omega_0 + \omega_1 \lambda - \omega_2 \hat{p}_f + (\hat{p}_f - \hat{p}_e) - \alpha_0 - \alpha_1 \lambda) \\
\dot{\lambda}_f &= \lambda_f \left(\hat{k}_f + \frac{v_f}{u_f} - \alpha_0 - \alpha_1 \lambda - \widehat{POP} \right) \\
\dot{\lambda}_e &= \lambda_e \left(\hat{k}_e - \alpha_0 - \alpha_1 \lambda - \widehat{POP} \right) \\
\dot{u}_f^e &= v_f \\
\dot{v}_f &= \frac{u_f}{\gamma_f} - \left(\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} \right) - (\hat{k}_f + \delta_n) v_f \\
\dot{d}_f &= \hat{k}_f - \pi_f + \Delta \pi_f^e - d_f (\hat{p}_f + \hat{k}_f) \\
\dot{d}_e &= \hat{k}_e - \pi_e + \Delta \pi_e - d_e (\hat{p}_f + \hat{k}_e) \\
\dot{r} &= \beta_r (r^T - r) \\
\dot{o}f_b &= \pi_{b,u} - o f_b (\hat{p}_f + \hat{k}_f)
\end{aligned}$$

with the following intermediate variables:

$$\begin{aligned}
u_f &= u_f^e + \beta_{n_f,2} (\eta u_f^e - \gamma_f v_f) \\
\pi_{b,u} &= \beta_b (\mu_b (d_f + \mathcal{K}_e d_e) - o f_b) \\
u c_f &= \omega_f + \epsilon_f \mathcal{P}_e + \frac{\gamma_f \delta_f}{u_f} \\
\pi_f^e &= \frac{u_f}{\gamma_f} (1 - u c_f) - r d_f \\
\hat{k}_f &= \kappa_{f,0} + \kappa_{f,1} \pi_f^e \\
\kappa_{w,f} &= \frac{(1 - s_{F,w}) \omega_f}{\mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e) + 1} \left(\frac{u_f}{\gamma_f} + \frac{\alpha_f}{\alpha_e} \mathcal{K}_e \right) \\
\kappa_{c,f} &= (1 - s_c - s_{F,c}) (\Delta \pi_f^e + \mathcal{K}_e \Delta \pi_e + r (d_f + \mathcal{K}_e d_e) - \pi_{b,u}) \\
u_e &= \frac{\gamma_e}{(1 - \epsilon_e) \mathcal{K}_e} \left(\frac{\epsilon_f u_f}{\gamma_f} + \epsilon_{\text{cons}} f(\mathcal{P}_e) (\kappa_{w,f} + \kappa_{c,f}) \right) \\
u c_e &= \frac{\gamma_e}{u_e} \omega_e + \epsilon_e + \frac{\gamma_e \delta_e}{\mathcal{P}_e u_e} \\
\hat{p}_e &= \beta_{p_e} (\mu_e u c_e + \mathcal{T}_e - 1) \\
\pi_e &= \frac{\mathcal{P}_e u_e}{\gamma_e} (1 - u c_e - \mathcal{T}_e) - r d_e \\
\hat{k}_e &= \beta_{i_e} \left(\frac{u_e}{u_e^T} - 1 \right) \\
\pi_f &= \mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} - \frac{u_f}{\gamma_f} u c_f - r d_f \\
\lambda &= \lambda_f + \lambda_e
\end{aligned}$$

$$\begin{aligned}
v_f &= \beta_{n_f,1} \left(\gamma_f \left(\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} + \delta_n \nu_f \right) - u_f^e \right) \\
\hat{p}_f &= \beta_{p_f,1} (\mu_f u_{c_f} - 1) + \beta_{p_f,2} \left(\eta \frac{u_f}{\gamma_f} - \nu_f \right) \\
r_{CB} &= r^* + \hat{p}_f + \varphi (\hat{p}_f - \hat{p}_f^T) \\
r^T &= r_{CB} + \lambda_{r^T} \frac{\mu_b (d_f + \mathcal{K}_e d_e) - o_{fb}}{\mu_b (d_f + \mathcal{K}_e d_e)}
\end{aligned}$$

On top of these equations, we can define the GDP of the global economy. The GDP is defined as follows:

$$GDP = I_e + I_f + C_{w,f} + C_{c,f} + C_{w,e} + C_{c,e} \quad (3.100)$$

$$\frac{GDP}{p_f} = i_e + i_f + c_{w,f} + c_{c,f} + (c_{w,e} + c_{c,e}) \mathcal{P}_e \quad (3.101)$$

$$\frac{GDP}{p_f k_f} = \mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) (\kappa_{w,f} + \kappa_{c,f}) \quad (3.102)$$

We also have, when combining equations 3.6 and 3.34:

$$(1 - s_{F,w}) W \cdot L = c_{w,f} (p_f + p_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) \quad (3.103)$$

$$\frac{W \cdot L}{p_f k_f} = \frac{\kappa_{w,f}}{(1 - s_{F,w})} (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) \quad (3.104)$$

The wage share Ω is defined as the wage bill over GDP in nominal terms:

$$\Omega = \frac{\kappa_{w,f}}{(1 - s_{F,w})} (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) \quad (3.105)$$

Similarly, the profit share Π , which encompasses the profits of both firms and banks, is given by:

$$\Pi = \frac{\pi_f + \delta_f + r d_f + \mathcal{K}_e (\pi_e + \delta_e + r d_e)}{\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) (\kappa_{w,f} + \kappa_{c,f})} \quad (3.106)$$

where δ_f and δ_e are added to the numerator to have gross profits instead of profits net of capital depreciation.

Wage share, profit share and the share of taxes and subsidies from the government sum up to 1:

$$1 - \Omega - \Pi = \frac{\frac{\mathcal{K}_e \mathcal{P}_e u_e}{\gamma_e} \mathcal{T}_e}{\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) (\kappa_{w,f} + \kappa_{c,f})} \quad (3.107)$$

The consumption share \mathcal{C} is:

$$\mathcal{C} = \frac{(\kappa_{w,f} + \kappa_{c,f}) (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e))}{\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) (\kappa_{w,f} + \kappa_{c,f})} \quad (3.108)$$

And investment rate \mathcal{I} is the fraction of GDP that is not allocated to consumption:

$$\mathcal{I} = 1 - \mathcal{C} \quad (3.109)$$

$$= \frac{\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f}{\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) (\kappa_{w,f} + \kappa_{c,f})} \quad (3.110)$$

ALTERNATIVE, SUPPLY-DRIVEN VERSION OF THE *TEMPLE* MODEL

In a supply-driven model, Say's law is postulated such that demand and supply are always equal to each other. In the *TEMPLE* model, it means that:

$$y_{e,p} = y_{e,d} := y_e \quad (3.111)$$

$$y_{f,p} = y_{f,d} := y_f \quad (3.112)$$

The constraint 3.111 was already enforced in the demand model from section 3.1.8. However, constraint 3.112 is new and implies the loss of one degree of freedom. This has three main consequences. First, there are no inventories in the supply-driven model and equations 3.8-3.12 do not apply. Second, the value of u_f is fixed and equal to one. Third, the investment i_f of final goods firms is not determined anymore by equation 3.25. Instead, it is defined as the residual of equation 3.112:

$$y_{f,p} = y_{f,d} \quad (3.113)$$

$$\frac{k_f}{\gamma_f} = i_e + i_f + c_{w,f} + c_{c,f} \quad (3.114)$$

$$i_f = \frac{k_f}{\gamma_f} - i_e - c_{w,f} - c_{c,f} \quad (3.115)$$

Reduced form of the supply-driven model The reduced form of the supply-driven model is the set of differential equations:

$$\begin{aligned}
\dot{\mathcal{K}}_e &= \mathcal{K}_e (\hat{k}_e - \hat{k}_f) \\
\dot{\mathcal{P}}_e &= \mathcal{P}_e (\hat{p}_e - \hat{p}_f) \\
\dot{\omega}_f &= \omega_f (\omega_0 + \omega_1 \lambda - \omega_2 \hat{p}_f - \alpha_0 - \alpha_1 \lambda) \\
\dot{\omega}_e &= \omega_e (\omega_0 + \omega_1 \lambda - \omega_2 \hat{p}_f + (\hat{p}_f - \hat{p}_e) - \alpha_0 - \alpha_1 \lambda) \\
\dot{\lambda}_x &= \lambda_x (\hat{k}_x - \alpha_0 - \alpha_1 \lambda - \widehat{POP}) && (x \in \{e, f\}) \\
\dot{d}_x &= \hat{k}_x - (1 - \Delta) \pi_x - d_x (\hat{p}_f + \hat{k}_x) && (x \in \{e, f\}) \\
\dot{r} &= \beta_r (r^T - r) \\
\dot{o}f_b &= \pi_{b,u} - o f_b (\hat{p}_f + \hat{k}_f)
\end{aligned}$$

with the following intermediate variables:

$$\begin{aligned}
\pi_{b,u} &= \beta_b (\mu_b (d_f + \mathcal{K}_e d_e) - o f_b) \\
uc_f &= \omega_f + \epsilon_f \mathcal{P}_e + \gamma_f \delta_f \\
\pi_f &= \frac{1}{\gamma_f} (1 - uc_f) - r d_f \\
\kappa_{w,f} &= \frac{\omega_f (1 - s_{F,w})}{\mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e) + 1 + \mathcal{T}_{w,f}} \left(\frac{1}{\gamma_f} + \frac{\alpha_f}{\alpha_e} \mathcal{K}_e \right) \\
\kappa_{c,f} &= \frac{1 - s_c - s_{F,c}}{1 + \mathcal{T}_{c,f}} (\Delta \pi_f + \mathcal{K}_e \Delta \pi_e + r (d_f + \mathcal{K}_e d_e) - \pi_{b,u}) \\
u_e &= \frac{\gamma_e}{(1 - \epsilon_e) \mathcal{K}_e} \left(\frac{\epsilon_f}{\gamma_f} + \epsilon_{\text{cons}} f(\mathcal{P}_e) (\kappa_{w,f} + \kappa_{c,f}) \right) \\
uc_e &= \frac{\gamma_e}{u_e} \omega_e + \epsilon_e + \frac{\gamma_e \delta_e}{\mathcal{P}_e u_e} \\
\hat{p}_e &= \beta_{p_e} (\mu_e uc_e + \mathcal{T}_e - 1) \\
\pi_e &= \frac{\mathcal{P}_e u_e}{\gamma_e} (1 - uc_e - \mathcal{T}_e) - r d_e \\
\hat{k}_e &= \beta_{i_e} \left(\frac{u_e}{u_e^T} - 1 \right) \\
\hat{k}_f &= \frac{1}{\gamma_f} - (\mathcal{K}_e (\hat{k}_e + \delta_e) + \delta_f + \kappa_{w,f} + \kappa_{c,f}) \\
\lambda &= \lambda_f + \lambda_e \\
\hat{p}_f &= \beta_{p_f} (\mu_f uc_f - 1) \\
r_{CB} &= r^* + \hat{p}_f + \varphi (\hat{p}_f - \hat{p}_f^T) \\
r^T &= r_{CB} + \lambda_{r^T} \frac{\mu_b (d_f + \mathcal{K}_e d_e) - o f_b}{\mu_b (d_f + \mathcal{K}_e d_e)}
\end{aligned}$$

CALIBRATION OF THE MODEL TO A STEADY-STATE

By definition, a system dynamics model is at a steady-state when all its variables remain in a constant relationship to each other. This is equivalent to saying that the derivatives of all variables of the reduced form model are null. Thus, in our case, we try to find a set of values for the model's variables and parameters, such that all differential equations from the reduced form model in section 3.1.8 equal zero and all the equations defining the intermediate variables are met. On top of that, we impose minimum and maximum values for each variable and parameter. The values of these lower and upper bounds are either drawn from our knowledge of economics or inspired from several data sources. The main data sources used are the Penn World Table 10.0, the IEA data tables, Dupont et al. (2021a) and the Bank for International Settlements' database²⁷. For processing the data from the IEA and making them compatible with our model, we used the approach described in section 6.1.2 of Dupont (2021).

The calibration is performed by solving a non-linear optimization problem. This problem was solved using the modelling language AMPL and the solver *ipopt*. Code is available upon request. Tables 3.4 and 3.5 describe the results of the calibration. Table 3.4 refers to the model's variables at steady-state (both the variables which have an associated differential equation and the intermediary variables). Table 3.5 refers to the model's parameters. For each variable and parameter, the lower and upper bounds are given, as well as the data source used for defining this range of admissible values (if no bounds are given, it means that a value was directly imposed based on the data source). Then, the value obtained after calibration is presented. Finally, a brief description of the variable or parameter is given²⁸, as well as its unit if it is not dimensionless. Note that the reduced form model was built such that practically all variables and parameters are dimensionless.

In the last rows of Tables 3.4 and 3.5, neither lower nor upper bounds are given, nor a data source. Indeed, the values of the last variables and parameters are simply deduced from the other ones through the steady-state conditions, to which we add the following identities:

$$\frac{\alpha_f}{\alpha_e} = \frac{\lambda_e}{\lambda_f} \frac{u_f}{\gamma_f} \frac{1}{\mathcal{K}_e} \quad (3.116)$$

$$\omega_e = \omega_f \frac{\alpha_f}{\alpha_e} \frac{1}{\mathcal{P}_e} \quad (3.117)$$

Moreover, the values of some of the last parameters are only loosely constrained by the steady-state conditions. In that case, we choose them a value by trial and error, which ensures realistic dynamics to the model. Finally, the function $f(\cdot)$ from equation 3.6 is assumed to be of the form:

$$f(\mathcal{P}_e) = a_0 \left(\frac{a_1}{\mathcal{P}_e} + a_2 \right) \quad (3.118)$$

The values of a_1 and a_2 are calibrated based on the IEA data tables, the Penn World Table 10.0 and BP (2020). The value of a_0 is computed based on the calibrated values from Tables 3.4 and 3.5. The values of a_0 , a_1 and a_2 are given in Table 3.5.

²⁷Used only for the amount of private debt: "Private Debt Non-Financial sector (All sectors, Market value, Percentage of GDP, and Adjusted for breaks)."

²⁸in which the abbreviation "f.g." is used to refer to the final goods subsector

Variable	Min	Max	Value	Source of range of values	Description (Unit)
\mathcal{K}_e	0.03	0.1	0.049	Dupont et al. (2021a)	Ratio of capital stocks
\mathcal{P}_e	10	70	10.49	Range of reasonable values	Energy price $\left(\frac{2017\text{US\$}}{\text{GJ}}\right)$
λ	-	-	0.437	Penn World Table 10.0	Global employment rate
$\frac{\lambda_e}{\lambda_f}$	0.005	0.02	0.02	IRENA (2018)	Ratio of employment rates
u_f^e	0.65	0.9	0.819	Range of reasonable values	Expected utilization rate - f.g.
u_f	0.65	0.9	0.820	Range of reasonable values	Real utilization rate - f.g.
u_e	0.75	0.95	0.926	Range of reasonable values	Utilization rate - energy
ν_f	0.014	0.02	0.014	Range of reasonable values	Inventory-to-capital ratio - f.g.
d_f	0.2	0.6	0.28	BIS	Debt-to-capital ratio - f.g.
d_e	0.2	0.6	0.24	BIS	Debt-to-capital ratio - energy
r	0.015	0.025	0.0242	Range of reasonable values	Interest rate
r^T	0.015	0.025	0.0244	Range of reasonable values	Banks' target interest rate
r_{CB}	0.015	0.025	0.0242	Range of reasonable values	Central bank's target rate
of_b	0.02	0.04	0.0252	Range of reasonable values	Banks own funds, normalized
$\pi_{b,u}$	0	1	0.0012	Range of reasonable values	Banks retained earnings, norm.
π_f^e	0.035	1	0.039	Range of reasonable values	Exp. profit-to-cap. ratio - f.g.
π_f	0.035	1	0.035	Range of reasonable values	Real profit-to-cap. ratio - f.g.
π_e	0.035	1	0.036	Range of reasonable values	Profit-to-cap. ratio - energy
\hat{k}_f	0.01	0.03	0.03	Range of reasonable values	Cap. stock growth rate - f.g.
\hat{p}_f	0.018	0.03	0.019	Range of reasonable values	Price inflation - f.g.
ω_f	-	-	0.684	-	Wage share - f.g.
ω_e	-	-	0.0085	-	Wage share - energy
λ_f	-	-	0.429	-	Employment rate - f.g.
λ_e	-	-	0.008	-	Employment rate - energy
uc_f	-	-	0.859	-	Unit cost of prod. - f.g.
uc_e	-	-	0.514	-	Unit cost of prod. - energy
$\kappa_{w,f}$	-	-	0.218	-	Workers cons., norm. - f.g.
$\kappa_{c,f}$	-	-	0.018	-	Capitalists cons., norm. - f.g.
\hat{k}_e	-	-	0.03	-	Cap. stock growth rate - energy
\hat{p}_e	-	-	0.018	-	Price inflation - energy
$\frac{\alpha_f}{\alpha_e}$	-	-	0.13	-	Ratio of labour productivities

TABLE 3.4: Results of the calibration - variables

Parameter	Min	Max	Value	Source of range of values	Description (Unit)
\overline{POP}	-	-	0.011	Penn World Table 10.0	Global pop. growth rate
r^*	0.005	0.015	0.0056	Range of reasonable values	“Natural” interest rate
\hat{p}_f^T	0.005	0.03	0.019	Range of reasonable values	Central bank’s target infl. rate
\mathcal{I}	0.22	0.26	0.26	World Bank database	Global investment share of the econ.
δ_f	-	-	0.05	Dupont et al. (2021a)	Capital depreciation rate - f.g.
δ_e	-	-	0.04	Dupont et al. (2021a)	Capital depr. rate - energy
δ_n	0.12	0.2	0.18	Range of reasonable values	Inventories depr. rate - f.g.
ϵ_f	1.8	2	1.935	IEA and Penn World Table 10.0	En. intens. of f.g. prod. $\left(\frac{\text{MJ}}{2017\text{US\$}}\right)$
ϵ_e	0.097	0.107	0.104	IEA and Dupont (2021)	En. intens. of en. prod.
γ_f	2.55	2.8	2.55	Inklaar and Timmer (2013)	Cap. intens. of f.g. prod.
γ_e	25	50	30.94	Dupont et al. (2021b)	Cap. intens. of en. prod. $\left(\frac{2017\text{US\$}}{\text{GJ}}\right)$
μ_f	1.1	2	1.17	Range of reasonable values	Price markup - f.g.
μ_e	1.1	2	1.27	Range of reasonable values	Price markup - energy
Δ	0.05	0.5	0.493	Range of reasonable values	Rate of dividends
s_c	0.3	1	0.31	Range of reasonable values	Saving rate of capitalists
$\beta_{pf,1}$	1	3	1.32	Range of reasonable values	cost-push infl. adj. speed - f.g.
$\beta_{pf,2}$	1	3	1.53	Range of reasonable values	demand-pull infl. adj. speed - f.g.
β_{pe}	1	3	2.56	Range of reasonable values	Inflation adjustment speed - energy
$\beta_{nf,1}$	0.5	2	1.23	Range of reasonable values	Expected prod. adj. factor - f.g.
$\beta_{nf,2}$	0.1	2	0.1	Range of reasonable values	Real prod. adjustment factor - f.g.
β_b	0.4	10	5.18	Range of reasonable values	Banks own funds adj. speed
μ_b	0.01	0.1	0.089	Range of reasonable values	Banks prudential ratio
η	0.05	1	0.058	Range of reasonable values	Inventory-to-exp. prod. ratio
$\frac{C_e}{C_f}$	0.03	0.06	0.03	Dupont et al. (2021a)	En.-to-f.g. cons. ratio $\left(\frac{\text{GJ}}{2017\text{US\$}}\right)$
\mathcal{T}_e	0	1	0.35	Range of reasonable values	Government tax on energy
$s_{F,w}$	-	-	0	-	Forced saving rate of workers
$s_{F,c}$	-	-	0	-	Forced saving rate of capitalists
ω_0	-	-	-0.0917	-	Parameter of the Phillips curve
ω_1	-	-	0.27	-	Parameter of the Phillips curve
ω_2	-	-	0.4	-	Parameter of the Phillips curve
α_0	-	-	-0.016	-	Param. of Kaldor-Verdoorn equ.
α_1	-	-	0.08	-	Param. of Kaldor-Verdoorn equ.
$\kappa_{f,0}$	-	-	0.02	-	Param. for invest. decision - f.g.
$\kappa_{f,1}$	-	-	0.25	-	Param. for invest. decision - f.g.
u_e^T	-	-	0.92	-	Target utilization rate - energy
β_{ie}	-	-	3	-	Param. for invest. decis. - energy
β_r	-	-	0.08	-	Interest rate adjustment speed
φ	-	-	0.4	-	Parameter in Taylor’s rule
$\lambda_{r,T}$	-	-	0.018	-	Param. in banks target int. rate
ϵ_{cons}	-	-	0.0024	-	Technology parameter from equ. 3.6
a_0	-	-	1.06	-	Param. of func. $f(\cdot)$ from equ. 3.6
a_1	-	-	3.2	-	Param. of func. $f(\cdot)$ from equ. 3.6
a_2	-	-	0.84	-	Param. of func. $f(\cdot)$ from equ. 3.6

TABLE 3.5: Results of the calibration - parameters

MODELING THE ENERGY TRANSITION

In order to model the energy transition, we first need to better define the energy intensity of the economy and model its future evolution. From equations (3.3) and (3.5), we have:

$$e_f = \epsilon_f y_{f,p} \quad (3.119)$$

$$y_{f,d} = i_e + i_f + c_{w,f} + c_{c,f} \quad (3.120)$$

By making the approximation $y_{f,p} \simeq y_{f,d}$, we obtain:

$$e_f = \epsilon_f y_{f,p} \quad (3.121)$$

$$\simeq \epsilon_f y_{f,d} \quad (3.122)$$

$$\simeq \epsilon_{f,i_e} i_e + \epsilon_{f,i_f} i_f + \epsilon_{f,c_f} (c_{w,f} + c_{c,f}) \quad (3.123)$$

$$\epsilon_f \simeq \epsilon_{f,i_e} \frac{i_e}{y_{f,d}} + \epsilon_{f,i_f} \frac{i_f}{y_{f,d}} + \epsilon_{f,c_f} \frac{c_{w,f} + c_{c,f}}{y_{f,d}} \quad (3.124)$$

$$\epsilon_f \simeq \epsilon_{f,i_e} \frac{i_e}{y_{f,d}} + \epsilon_{f,i_f} \frac{i_f}{y_{f,d}} + \left(\theta_g \epsilon_{f,c_f,g} + \theta_s \epsilon_{f,c_f,s} \right) \frac{c_{w,f} + c_{c,f}}{y_{f,d}} \quad (3.125)$$

where we defined

ϵ_{f,i_e} : the energy intensity of the production of capital stock for the energy sub-sector;

ϵ_{f,i_f} : the energy intensity of the production of capital stock for the final goods sub-sector;

ϵ_{f,c_f} : the aggregated energy intensity of the production of final goods and services for consumption.

$\epsilon_{f,c_f,g}$: the energy intensity of the production of final goods (not services) for consumption.

$\epsilon_{f,c_f,s}$: the energy intensity of services (not final goods) for consumption.

θ_g and θ_s : the share of goods and services, respectively, in final consumption ($\theta_g + \theta_s = 1$)

As explained in section 3.1.4.1, these energy intensities were modelled to decrease exponentially and their constant rates of degrowth until the year 2060 were computed. The calibrated values of these energy intensities for the year 2019 and their rates of degrowth are given in Table 3.6. The rate of degrowth of ϵ_{cons} is computed in a similar way and also presented in Table 3.6. Finally, thanks to equation (3.125), the evolution of ϵ_f can be deduced from the energy intensities defined above.

Now that we detailed the energy intensity of the economy and modeled its future evolution, we can focus on the production of energy itself. Let us split $y_{e,p}$ into $y_{nre,p}$, the energy production from non-renewable sources and $y_{re,p}$, the energy production from renewable sources (limited to wind and solar, by assumption):

$$y_{e,p} = y_{nre,p} + y_{re,p} \quad (3.126)$$

We then define the degree of progress of the energy transition χ as:

$$\chi = \frac{y_{re,p}}{y_{e,p}} \quad (3.127)$$

$\chi = 3\%$ in 2019; the transition is completed once $\chi = 1$. We can thus rewrite equation 3.126

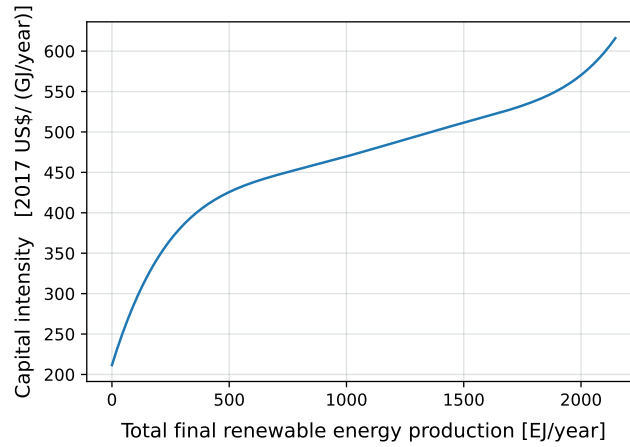


FIGURE 3.9: Capital intensity of renewable energy production worldwide γ_{re} as a function of total renewable energy production $y_{re,p}$

as:

$$y_{e,p} = y_{nre,p} + y_{re,p} \quad (3.128)$$

$$= (1 - \chi) y_{e,p} + \chi y_{e,p} \quad (3.129)$$

Similarly, if we define the capital and energy intensities of respectively non-renewable (γ_{nre} , ϵ_{nre}) and renewable (γ_{re} , ϵ_{re}) energy production, we have:

$$\gamma_e = (1 - \chi) \gamma_{nre} + \chi \gamma_{re} \quad (3.130)$$

$$\epsilon_e = (1 - \chi) \epsilon_{nre} + \chi \epsilon_{re} \quad (3.131)$$

ϵ_{re} is supposed to be constant, at the value computed for grid losses in Chapter 5.1.1 of Dupont (2021). γ_{re} is computed thanks to the following formula:

$$\gamma_{re} = \frac{1}{\text{EROI}_{re} \epsilon_{f,i_e} \delta_e} \quad (3.132)$$

In this formula, ϵ_{f,i_e} allows to transform the embodied energy from the EROI into final goods and $\frac{1}{\delta_e}$ is the lifetime of the energy capital stock²⁹

After replacing in equation 3.132 EROI_{re} by the EROI curves from Dupont et al. (2018, 2020), we obtain the capital intensity curve depicted in Figure 3.9³⁰.

As explained in section 3.1.4.2, this curve must finally be multiplied by the corrective factor $(1 + \frac{\chi}{9})$ in order to include the additional storage and grid costs required for a high penetration of intermittent renewable energies.

The calibrated values of γ_e and ϵ_e for the year 2019 are given in Table 3.6, while the com-

²⁹Note that we use ϵ_{f,i_e} and not ϵ_f in equation (3.132). This is a notable refinement compared to Dupont et al. (2021b) and Dupont (2021). This improvement implies that γ_{re} takes a much lower value (less than half the value computed by using ϵ_f in place of ϵ_{f,i_e}). Thus, our refined computations compared to Dupont et al. (2021b) and Dupont (2021) imply that the energy transition is much less costly than modeled in these papers.

³⁰In fact, the EROI curves presented in Dupont et al. (2018, 2020) give the EROI of the marginal wind turbine or solar panel installed as a function of total renewable energy production. The EROI curves used in our computation, on the contrary, represent the evolution of the mean EROI of all installed renewable facilities.

Parameter	Value	Source	Description (Unit)
ϵ_{f,i_e}	5.07	EXIOBASE and PWT 10.0	en. intens. of en. cap. stock. prod. $\left(\frac{\text{MJ}}{2017\text{US\$}}\right)$
ϵ_{f,i_f}	2.80	EXIOBASE and PWT 10.0	en. intens. of f. g. cap. stock. prod. $\left(\frac{\text{MJ}}{2017\text{US\$}}\right)$
$\epsilon_{f,c_f,g}$	3.67	EXIOBASE and PWT 10.0	en. intens. of f.g. prod. for cons. $\left(\frac{\text{MJ}}{2017\text{US\$}}\right)$
$\epsilon_{f,c_f,s}$	1.15	EXIOBASE and PWT 10.0	en. intens. of f.g. prod. for cons. $\left(\frac{\text{MJ}}{2017\text{US\$}}\right)$
θ_g	0.189	EXIOBASE and PWT 10.0	share of goods in final consumption
θ_s	0.811	EXIOBASE and PWT 10.0	share of services in final consumption
$\hat{\epsilon}_{f,i_e}$	-0.0169	EXIOBASE and PWT 10.0	constant rate of change of ϵ_{f,i_e}
$\hat{\epsilon}_{f,i_f}$	-0.0059	EXIOBASE and PWT 10.0	constant rate of change of ϵ_{f,i_f}
$\hat{\epsilon}_{f,c_f,g}$	-0.0096	EXIOBASE and PWT 10.0	constant rate of change of $\epsilon_{f,c_f,g}$
$\hat{\epsilon}_{f,c_f,s}$	-0.0084	EXIOBASE and PWT 10.0	constant rate of change of $\epsilon_{f,c_f,s}$
$\hat{\epsilon}_{\text{cons}}$	-0.0235	EXIOBASE and PWT 10.0	constant rate of change of ϵ_{cons}
χ	0.03	IEA	degree of progr. of the en. trans.
γ_e	30.94	Table 3.5	Cap. intens. of en. prod. $\left(\frac{2017\text{US\$}}{\text{GJ}}\right)$
γ_{re}	223.05	Equation 3.132	Cap. intens. of r.e. prod. $\left(\frac{2017\text{US\$}}{\text{GJ}}\right)$
γ_{nre}	24.98	Equation 3.133	Cap. intens. of n.r.e. prod. $\left(\frac{2017\text{US\$}}{\text{GJ}}\right)$
ϵ_e	0.082	Table 3.5	En. intens. of en. prod.
ϵ_{re}	0.087	Dupont (2021)	En. intens. of r.e. prod.
ϵ_{nre}	0.104	Equation 3.134	En. intens. of n.r.e. prod.

TABLE 3.6: Energy and capital intensities: calibrated values for the year 2019 and projected constant rates of change for the period 2019-2060

putation of γ_{re} and ϵ_{re} is described in the lines above. The values of γ_{nre} and ϵ_{nre} in 2019 can thus be deduced from the following formulae:

$$\gamma_{nre} = \frac{\gamma_e - \chi \gamma_{re}}{1 - \chi} \quad (3.133)$$

$$\epsilon_{nre} = \frac{\epsilon_e - \chi \epsilon_{re}}{1 - \chi} \quad (3.134)$$

Once the values of γ_{nre} and ϵ_{nre} have been computed for the year 2019, the evolution of these parameters up to the year 2060 can be obtained by assuming that they evolve proportionally to EROI_{nre} , the aggregated EROI of fossil fuels:

$$\gamma_{nre} = \gamma_{nre}(2019) \frac{\text{EROI}_{nre}(2019)}{\text{EROI}_{nre}} \quad (3.135)$$

$$\epsilon_{nre} = \epsilon_{nre}(2019) \frac{\text{EROI}_{nre}(2019)}{\text{EROI}_{nre}} \quad (3.136)$$

EROI_{nre} , in turn, is a function of the total cumulated non-renewable energy production since the year 2019, as explained in Section 3.1.4.1. This function takes the following form (x being the cumulative production since 2019, in exajoules):

$$\text{EROI}_{nre} = 1 + 6.50 \times e^{-0.00002 \cdot x} \quad (3.137)$$

Overall EROI of the energy system Next to the point of use EROI used above, the EROI of the entire energy system or of the (non-)renewable energy sub-system can also be computed. This system's EROI is defined as the total energy produced, divided by the energy inputs of the

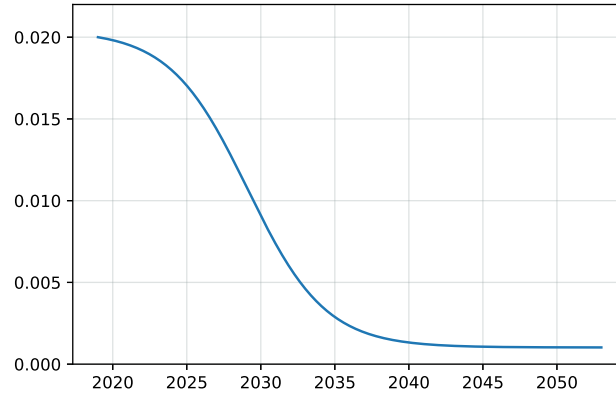


FIGURE 3.10: Imposed decrease for the parameter κ_{f0} from equation 3.25 in the “slow growth” scenario

energy (sub-)sector. These energy inputs can be separated into direct energy inputs and energy embodied into the capital stock. Using Equation 3.2, this translates into:

$$\begin{aligned} \text{EROI}_{sys} &= \frac{y_{e,p}}{e_e + \epsilon_{f,i_e} k_e \delta_e} \\ &= \frac{1}{\epsilon_e + \epsilon_{f,i_e} \frac{\gamma_e}{u_e} \delta_e} \end{aligned}$$

And similarly:

$$\begin{aligned} \text{EROI}_{sys,re} &= \frac{1}{\epsilon_{re} + \epsilon_{f,i_e} \frac{\gamma_{re}}{u_e} \delta_e} \\ \text{EROI}_{sys,nre} &= \frac{1}{\epsilon_{nre} + \epsilon_{f,i_e} \frac{\gamma_{nre}}{u_e} \delta_e} \end{aligned}$$

Note that we compute here an EROI (energy return on investment) and not a PROI (power return on investment, as defined in (Carbajales-Dale, 2019)). To get a PROI, we would need to replace δ_e by $(\delta_e + \hat{k}_e)$ in the denominator.

Scenario with slower economic growth As stated in section ‘Materials and methods’, another scenario is investigated, where the energy transition takes place in an economy which is growing at a slower pace. To model this second scenario, we assume that the parameter κ_{f0} from equation 3.25 is not constant anymore, but decreases in a sigmoid way, as shown on Figure 3.10. In this scenario, the final goods firms begin progressively to decrease their investment share into new capital stock (for whatever reason). By 2045, the remaining investment into new capital stock for final goods firms is determined solely by their profit rate i.e. by the second term of equation 3.25. This scenario enables us to discuss the impact of economic growth on the energy transition.

RESULTS OF THE SUPPLY-DRIVEN VERSION OF THE MODEL

Figure 3.11 gives the simulation results obtained with the supply-driven version of the model for the scenario of a rapid global energy transition compatible with the 1.5°C objective of the Paris Agreement. These results are extremely similar to the ones of the demand-driven version of the model, presented in Section 3.1.6.

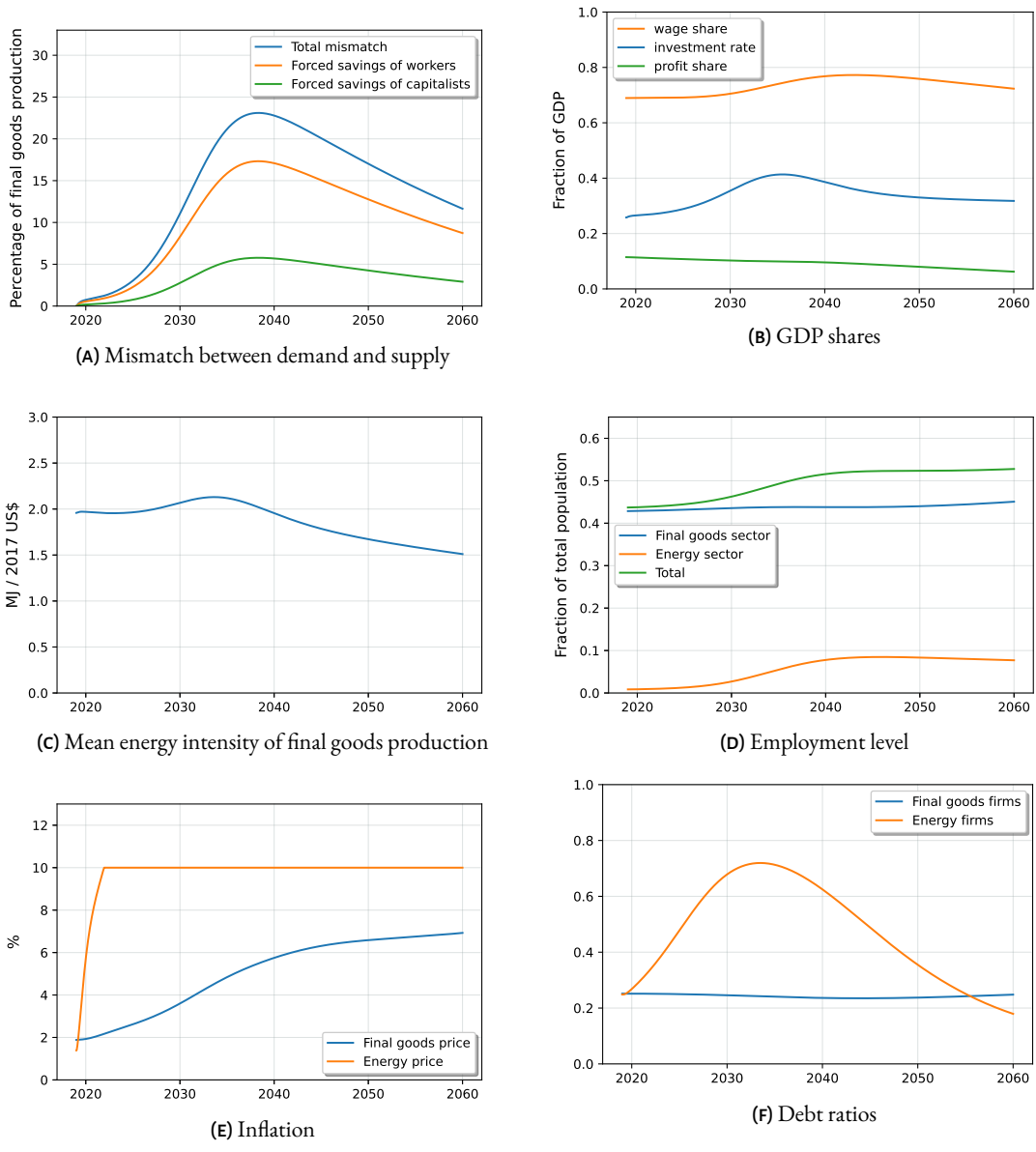


FIGURE 3.11: Simulated macroeconomic dynamics of the energy transition under the scenario of a rapid energy transition, obtained with the supply-driven version of the model.

SENSITIVITY ANALYSIS

The results of the sensitivity analysis are displayed in Figure 3.12. For concision, only the results for the investment share and the inflation in final goods price are shown. In Figure 3.12, the variation of the investment share is small so all curves are overlapped.

We also carry out sensitivity analyses on the adjustment speeds. First, we play with $\beta_{p_f,1}$ and $\beta_{p_f,2}$, which determine the relative weights of cost-push versus demand-pull inflation in the final goods' price. We make them vary jointly, such that the value of \hat{p}_f at the initial steady-state remains unchanged. That is, the values of $\beta_{p_f,1}$ and $\beta_{p_f,2}$ must respect the following condition at $t = 2019$:

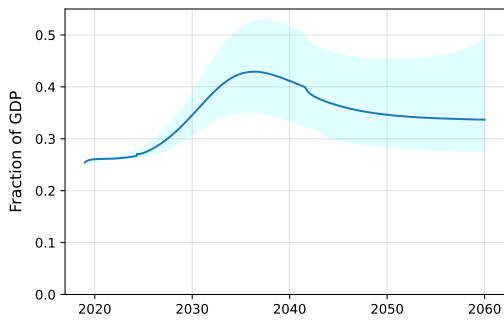
$$\beta_{p_f,1} (\mu_f u_{c_f} - 1) + \beta_{p_f,2} \left(\eta \frac{u_f}{\gamma_f} - \nu_f \right) = 0.019$$

Figure 3.14 displays the corresponding simulations' results.

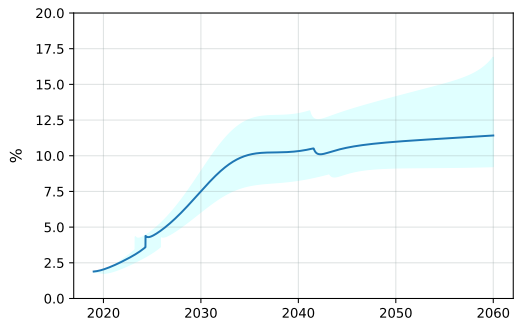
Second, we modify the value of $\beta_{n_f,1}$, which determines the speed at which the (expected) utilization rate of the capital stock of final goods' firms adjusts itself in reaction to a mismatch between demand and supply. Remember that $\beta_{n_f,1}$ appears in the following equations of the reduced-form model (see Section 3.1.8):

$$\begin{aligned} \dot{u}_f^e &= v_f \\ v_f &= \beta_{n_f,1} \left(\gamma_f \left(\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} + \delta_n \nu_f \right) - u_f^e \right) \end{aligned}$$

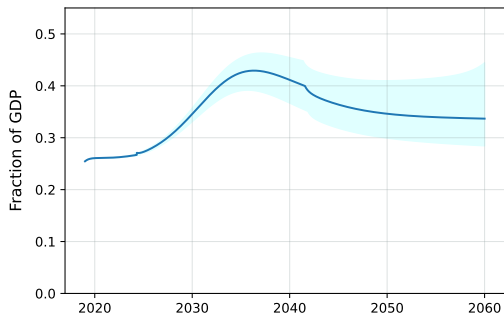
$v_f = 0$ at $t = 2019$ so changing the value of $\beta_{n_f,1}$ has no impact on the initial steady-state. Figure 3.15 shows the simulation results obtained when varying the value of $\beta_{n_f,1}$. We observe that for lower values of $\beta_{n_f,1}$, the utilization rate of final goods firms' capital stock increases less. The economy is thus less dynamic, the mismatch between demand and supply becomes less pronounced and inflation in the final goods' price is lower.



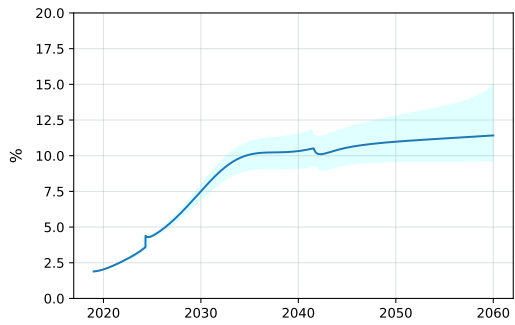
(A) Effect of γ_e on the investment share



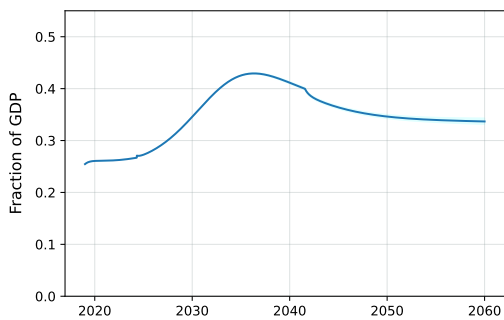
(B) Effect of γ_e on the inflation in final goods price



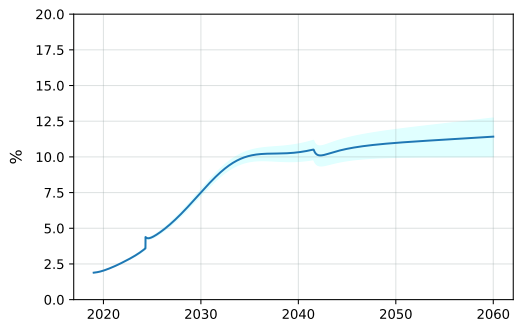
(C) Effect of the degrowth rate of the energy intensities on the investment share



(D) Effect of the degrowth rate of the energy intensities on the inflation in final goods price

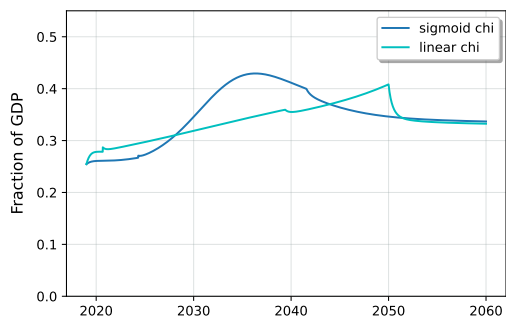


(E) Effect of population growth rate on the investment share

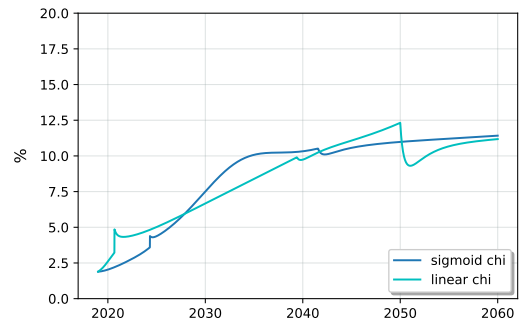


(F) Effect of population growth rate on the inflation in final goods price

FIGURE 3.12: Effect of different parameters on the investment share and on the inflation in final goods price

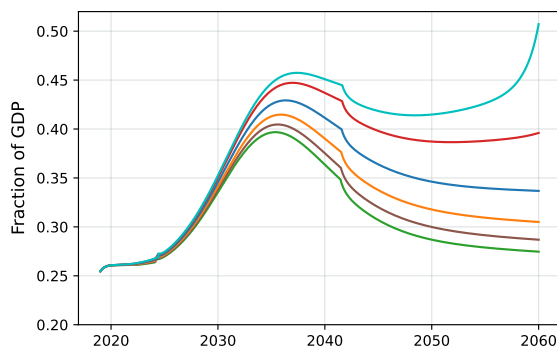


(A) Effect of the curve shape for χ on the investment share

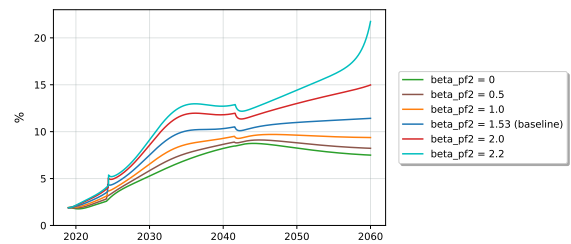


(B) Effect of the curve shape for χ on the inflation in final goods price

FIGURE 3.13: Effect of different parameters on the investment share and on the inflation in final goods price – continued

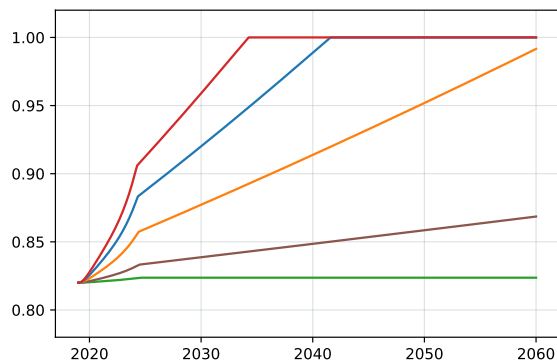


(A) Effect on the investment share

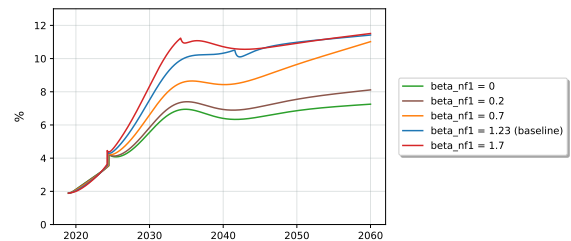


(B) Effect on the inflation in final goods price

FIGURE 3.14: Effects on the model's results of varying jointly the adjustment speeds for cost-push and demand-pull inflation in the final goods' price



(A) Effect on the utilization rate of capital in the final goods sector



(B) Effect on the inflation in final goods price

FIGURE 3.15: Effects on the model's results of varying the adjustment speed for the utilization rate of the final goods firms' capital stock

3.2. TOWARDS IMPROVED INTEGRATED ASSESSMENT MODELING

Delannoy, L., Auzanneau, M., Andrieu, B., Vidal, O., Longaretti, P.-Y., Prados, E., Murphy, D., Bentley, R., Carbajales-Dale, M., Raugei, M., Höök, M., Court, V., King, C., Fizaine, F., Jacques, P., Heun, M., Jackson, A., Guay-Boutet, C., Aramendia, E., Wang, J., Le Boulzec, H., and Hall, C. Emerging consensus on net energy paves the way for improved integrated assessment modeling. *Submitted to Energy and Environmental Science*, 2023a

ABSTRACT

Extracting, processing, and delivering energy requires energy itself, which reduces the net energy available to society and yields considerable socioeconomic implications. Yet, most mitigation pathways and transition models overlook net energy feedbacks, specifically related to the decline in the quality of fossil fuel deposits, as well as energy requirements of the energy transition. Here, we summarize our position across 8 key points that converge to form a prevailing understanding regarding EROI (Energy Return on Investment), identify areas of investigation for the Net Energy Analysis community, discuss the consequences of net energy in the context of the energy transition, and underline the issues of disregarding it. Particularly, we argue that reductions in net energy available can hinder the transition if demand-side measures are not implemented and adopted to limit energy consumption. We also point out the risks posed for the energy transition in the Global South, which, while being the least responsible for climate change, may be amongst the most impacted by both the climate crisis and net energy diminution. Last, we present practical avenues to consider net energy in mitigation pathways and Integrated Assessment Models (IAMs), emphasizing the necessity of fostering collaborative efforts among our different research communities.^a

^aThis is an extended version of the article submitted to Energy & Environmental Science.

3.2.1. INTRODUCTION

On April 4 2022, IPCC Working Group III finalized its contribution to the Sixth Assessment Report. Reviewing progress and commitments for climate change mitigation, the report calls for more sustainable consumption habits and a shift away from fossil fuels towards low-carbon energy systems (IPCC, 2022). This transition is nevertheless made difficult by the required energy investments for the new energy system, which can be examined through the lens of the Energy Return on (Energy) Invested or ERO(E)I (Hall, 2017; Haberl et al., 2019) metric. Recent developments in the Net Energy Analysis (NEA) research community have highlighted EROI implications for socio-economic scenarios (King and van den Bergh, 2018; Capellán-Pérez et al., 2020; Delannoy et al., 2021a; Jacques et al., 2023; Slameršak et al., 2022), in particular regarding the practical challenges of the low-carbon transition. Yet, in part due to a lack of

formal methodology prior to the 2010s (White and Kramer, 2019; Rana et al., 2020) and the delayed emergence of robust results, such studies have failed to influence transition scenarios. To remedy this situation, we provide an overview of the net energy approach, summarize the claimed emerging consensus around EROI, address how it relates to the low-carbon transition, and suggest ways to better integrate net energy in Integrated Assessment Models (IAMs).

3.2.2. THE NET ENERGY ANALYSIS APPROACH

Net energy, i.e. the energy supplied to society in the form of energy carriers after subtracting the energy invested for the production and distribution of those energy carriers, is a fundamental prerequisite to allow the production and exchange of goods and services. For a given amount of net energy, a key metric of the energy system is the EROI – defined as the ratio between the total energy returned ($E_{returned}$) and the total energy invested to accomplish the conversion ($E_{invested}$) over the entire life cycle of the system under study, i.e. $EROI = E_{returned}/E_{invested}$.

As with all analyses that can be performed at the macro (economy-wide) and micro (technology-specific) scales, EROI can have slightly different interpretations (Brandt and Dale, 2011; King et al., 2015a,b). For example, at the scale of the global economy, the EROI has a minimum of 0 based on the first law of thermodynamics. When analyzing a single technology or energy subsystem that produces a final energy carrier, the EROI ratio can be less than one to one (1:1) (e.g., in Figure 3.16, $E_{invested,2}$ is greater than $E_{returned,2}$). Such systems can still be locally or temporarily useful when they have compelling properties, for example delivering a specific energy carrier that is in particular demand, e.g., the industrial food system, but they cannot be a main supplier of energy for society. Although the equations involved are simple, their application entails theoretical and practical difficulties that call for a rigorous definition of the system’s boundaries (Murphy and Hall, 2011a; Raugei, 2019).

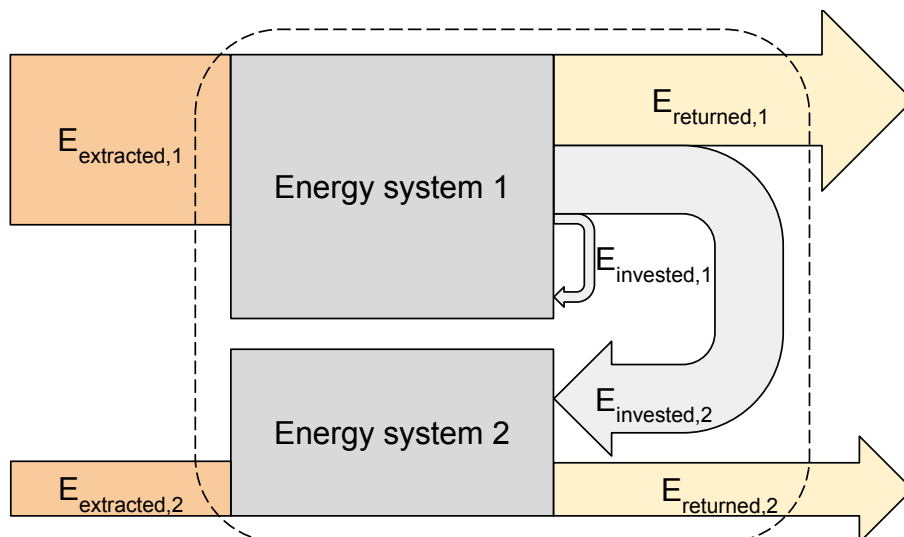


FIGURE 3.16: Returned energy as a function of the extracted and the invested energy for two systems. $EROI (global) = (E_{returned,1} + E_{returned,2}) / (E_{invested,1} + E_{invested,2})$. $EROI (energy\ system\ 2) = (E_{returned,2}) / (E_{invested,2})$. Energy losses are omitted for clarity.

The “standard” (or primary stage) EROI accounts for the energy used in the extraction process only. It is useful for studying the energy demand of a primary energy extraction sector or technology.

The point-of-use (or final stage) EROI includes the energy used in not only extracting, but also processing and delivering an energy carrier. Therefore, for a given energy carrier, the point-of-use EROI is substantially lower than the standard EROI since additional energy inputs are considered. Focusing on the point of use is gaining in importance, as: (i) the energy requirements of the processing, refining and other downstream processes for fossil fuels may be larger than that for their extraction, and (ii) most renewable energy systems directly deliver final energy carriers, i.e., typically electricity, making the analysis at the final energy stage essential to compare renewable and fossil fuel energy systems like for like.

The dynamic EROI of the full energy system corresponds to the energy delivered by a country's (or the entire world's) energy system divided by its energy consumption at a given time, and is in that respect a Power Return on Investment (PROI) as the calculation is performed for a delimited time interval (one year usually) (King et al., 2015a; Carbajales-Dale, 2019).

3.2.3. EMERGING CONSENSUS ON NET ENERGY CONSTRAINTS

As researchers in the field of NEA, we summarize our position with the following 8 key points, which approximate a current consensus around EROI:

1. The standard EROI of oil is usually lower than that of gas, which is lower than that of most coal (Court and Fizaine, 2017).
2. Conventional fossil fuels may have lower standard EROIs than tight gas and oil produced from fracking (Brandt et al., 2015b; Moeller and Murphy, 2016) but higher than other unconventional fuels (tar sands, mined shale oil, coal bed methane, etc.) (Brandt et al., 2015a; Delannoy et al., 2021a,b).
3. The standard EROI of new fossil energy resources is expected to improve initially as technology develops, before decreasing due to a decline in the quality of the extracted resource (Dale, 2011; Masnadi and Brandt, 2017). For instance, the standard EROI of oil sands-derived crude has been increasing since the first bitumen-producing mines became operational (Guay-Boutet, 2023). On the contrary, many major conventional oil fields have already seen marked decreases in their standard EROI due to the requirements for enhanced recovery (Tripathi and Brandt, 2017) and global resource depletion, as evidenced by the decline in the quantity of the remaining "2P" (proven and probable) reserves (The Shift Project, 2020; Laherrère et al., 2022).
4. The aggregate EROI of fossil fuels at the point of use declines over time, albeit at a slower pace than at the source, since the largest investment (at the denominator of the EROI ratio) is not the energy required for extraction (that increases over time as resource quality decreases) but the subsequent energy required for processing and delivery (which remains approximately constant over the long-term) (Brockway et al., 2019).
5. Today, the EROI of fossil-fueled electricity at point of end-use is often found to be lower than those of PV, wind and hydro electricity, even when the latter include the energy inputs for short-term (e.g., 8h) storage³¹ technologies (Raugei et al., 2020; Murphy et al., 2022). Average EROI values however hide strong regional variability, particularly for solar and wind technologies (Dupont et al., 2018, 2020).

³¹The inclusion of storage devices in the system boundary (rather than at the level of an individual power generation technology), however, is more relevant at the country, regional, or grid level, because each technology, if deployed in isolation, would require some storage capacity to successfully keep up with the pattern of electricity demand. This holds for instance true for CCGT plants, requiring natural gas storage capacity to deal with winter peak in demand, and summer lower peak.

6. The EROI of nuclear and hydropower have historically been high, the former is constrained by slow deployment times, and the latter is limited in terms of availability of suitable locations.
7. Renewable fuels have lower EROI at point of end-use than fossil fuels, except biomass in the form of raw wood or woodchips (Murphy et al., 2022).
8. A rapid large-scale deployment of renewable electricity and associated infrastructure will likely temporarily reduce the dynamic EROI (i.e., PROI) of the energy system as it requires a significant up-front energy investment embodied in infrastructure (Dale and Benson, 2013; Sgouridis et al., 2016; Capellán-Pérez et al., 2019; Jacques et al., 2023; Slameršák et al., 2022; Fabre, 2019).

In parallel to this emerging consensus, several areas are under investigation. For instance, the EROI of wind and solar PV might be negatively affected by the increase in energy requirements per unit of valuable mineral extracted due to geological depletion (Fizaine and Court, 2015), whereby the quality of mineral deposits extracted (e.g., in terms of ore grade) decreases as a function of cumulative production. On the other hand, technological improvements may favorably affect the EROI of wind and solar PV (Steffen et al., 2018). The same is true for increasing the recycling capacity of renewable energy technologies, but the delay is significant because of the time required to build up a stock of materials suitable for recycling.

Another area under scrutiny is the extension of the analysis to the useful stage of energy use, i.e. at the stage when energy is actually exchanged for energy services (Aramendia et al., 2021) (see Figure 3.17) as some energy carriers may be used for similar end-uses with very different final-to-useful efficiencies (Aramendia, 2023). For example, electricity might fuel a car at a lower $EROI_{point-of-use}$ than gasoline, but an electric vehicle motor has a considerably higher final-to-useful efficiency in converting its fuel input into mechanical drive when compared to a traditional internal combustion engine, such that an electric vehicle can have higher EROI at the useful stage.

Of particular interest is the use of net energy analysis at the useful stage for a comprehensive understanding of the rebound effect at different geographic and time scales. More precisely, this approach can help explain why global data shows energy use continuing to increase as individual technologies become more efficient (greater than 100% rebound), even though studies focusing on a specific country or set of countries indicate mixed results of sometimes greater and usually less than 100% rebound (Brockway et al., 2021).

3.2.4. IMPLICATIONS OF NET ENERGY FOR THE LOW-CARBON TRANSITION

The net energy approach provides an enhanced understanding of the role of energy in economic processes, and as such, the EROI concept is increasingly used to model the energy–economy nexus. This growing modeling effort highlights two main net energy aspects which have implications for the low-carbon transition. On the one hand, the decline in the standard EROI of oil and gas may entail a rise in emissions per unit of net energy supplied to society (Manfroni et al., 2021a), and long-term energy price increases (King and Hall, 2011; Heun and de Wit, 2012), leading to periods of unfavorable growth, deflation or recession, especially for slow transition scenarios. On the other hand, the—perhaps only temporary—reduction in net energy available for society in rapid transition scenarios may result in a high investment share and employment rate in low-emissions technologies, which could generate inflation (Režný and

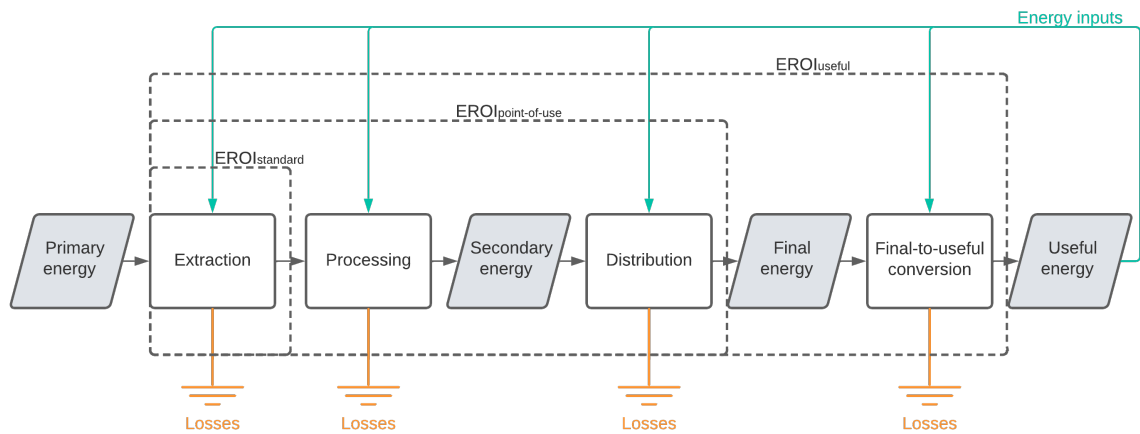


FIGURE 3.17: Standard, or primary stage EROI ($EROI_{standard}$), point-of-use or final stage EROI ($EROI_{point-of-use}$) and useful EROI ($EROI_{useful}$).

Bureš, 2019; Jackson and Jackson, 2021; Jacques et al., 2023), which altogether raise questions of socio-political acceptance.

The pace of transition is bounded at the upper limit by the energy needed to sustain society without disruption (additional supply bottlenecks aside), and at the lower limit by the minimum speed required to meet climate targets (see Figure 3.18). Both limits are expected to move closer as the transition is delayed, reducing the window of opportunity for a global transition compatible with ambitious climate targets. Indeed, the upper is likely to worsen over time due to the geological depletion of fossil fuels, the fact that a more rapid low-carbon investment consumes a higher proportion of energy, and that more high-carbon investment needs replacement or becomes stranded. The implementation of demand-side policies (Creutzig et al., 2018) to reduce discretionary energy use, as highlighted by IPCC WG III (IPCC, 2022), is becoming increasingly relevant in this regard. Moving away from unnecessary uses and switching to more efficient conversion chains (e.g., from gasoline-powered to electric cars or bicycles) helps reduce discretionary energy use as long as rebound effects are mitigated. Further, recent research suggests that a decent life for all can be sustained at much lower levels of energy use than at present within wealthy nations (Cullen et al., 2011; Millward-Hopkins et al., 2020; Kikstra et al., 2021).

The energy transition has implications for equity. In particular, the upcoming reductions in net energy will necessarily amplify energy transition costs due to fossil fuel inflation and rapid low-carbon investment. Such reductions will in turn exacerbate competition for the energy and material resources necessary for the transition, a competition in which low-income countries are already at a clear disadvantage (Hall et al., 2008). Every Northern country that delays action thus risks compromising its ability to complete a transition and maintain or achieve high levels of material well-being, both for itself and other countries. This political situation raises inequity issues as countries from the Global North are likely to make their transition first. In this context, countries of the Global South risk lacking access to energy and getting slowed down – or even trapped – in their progress towards modern low-carbon energy, while being among the least responsible for and most affected by climate change (Oswald et al., 2020; Carley and Konisky, 2020; Hickel et al., 2022b,a; Hickel and Slamersak, 2022). Accelerating the energy transition for the Global South is therefore a major stumbling block to a “just” transition, and requires massive financial support and technology transfer (Cantarero, 2020; Newell et al., 2021; Poblete-Cazenave et al., 2021; Fanning and Hickel, 2023).

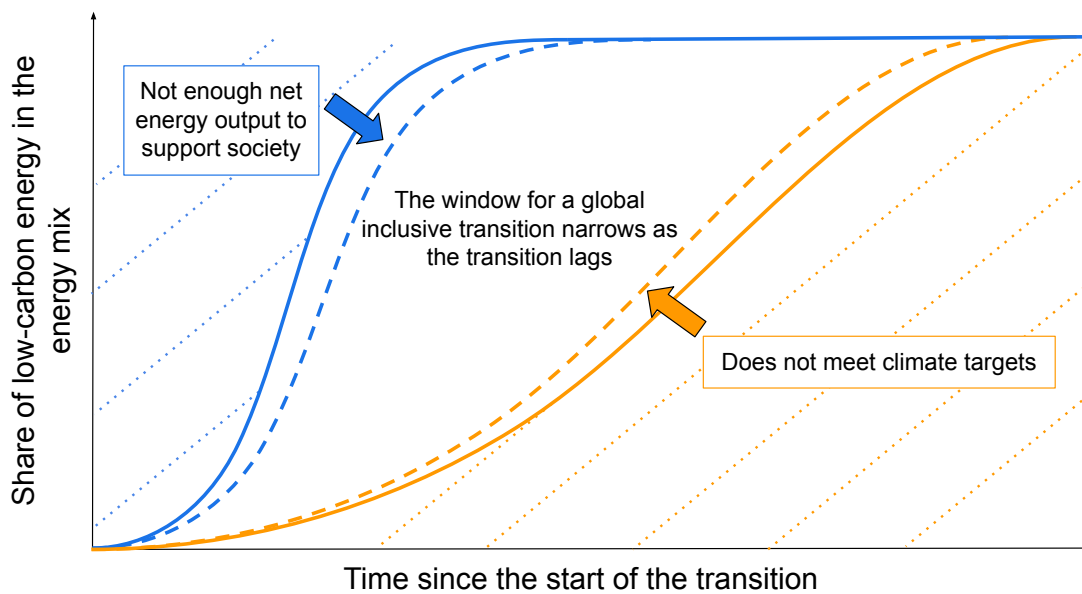


FIGURE 3.18: Sketch of principle of an evolving window of opportunity for the global inclusive transition to low-carbon energy as a function of normalized time at the start of the transition. The solid lines delineate the current window of opportunity. The dashed lines represent a future window in which action has not been taken quickly enough such that climate and net energy increasingly constrain the window of opportunity.

3.2.5. PROPER CONSIDERATION OF ENERGY BALANCE IS REQUIRED IN MITIGATION PATHWAYS

While significant progress has been made in research on mitigation pathways, net energy has been addressed only marginally. The latest IPCC report (IPCC, 2022), for instance, mentions EROI issues in one paragraph (ch. 6, p. 44) and leaves out the evolution of the related literature, in part because the 8 key points developed earlier have only recently emerged. This situation results in insufficient discussion on the consequences of a decrease in the EROI of the energy system. The overlooking of net energy is also apparent in Integrated Assessment Models (IAMs), the main tools used to produce global, regionally disaggregated mitigation pathways (van Beek et al., 2020).

First, most IAMs lack precision in the energy sector. They widely assume that fossil fuel resources are accessible with only economic restrictions (apart from dynamic constraints on extraction rates as in REMIND (Baumstark et al., 2021) or TIAM-UCL (Pye et al., 2020) models). Typical upward sloping cost-supply curves used in IAMs are indeed subject to criticism for potentially outdated, simplistic and over-optimistic assumptions in the recoverability of fossil resources (Brecha, 2008; Kharecha and Hansen, 2008; Nel and Cooper, 2009; Höök et al., 2010; Verbruggen and Marchohi, 2010; Chiari and Zecca, 2011; Höök, 2011; Dale et al., 2012b; Mercure and Salas, 2012; Berg and Boland, 2013; Höök and Tang, 2013; Murray and Hansen, 2013; Capellán-Pérez et al., 2014; Chapman, 2014; Mohr et al., 2015; Murray, 2016; Bauer et al., 2016; Capellán-Pérez et al., 2016; Ritchie and Dowlatabadi, 2017; Wang et al., 2017b; Capellán-Pérez et al., 2020). For instance, the MESSAGE (IIASA, 2020) and IMACLIM-R (Waisman et al., 2012a) (partly) models continue to depend on the data provided by Rogner (1997) for global fossil fuel reserves and resources, while the EPPA model (Chen et al., 2022) includes simple recursive endogenous resource supply functions, despite the availability of multiple updates from various sources. The use of cost-supply curves also impedes the analysis of the economic consequences of a plateau or decline in oil production (Bentley et al., 2020)—for example left out in the EMF27 (McCollum et al., 2013) and RoSE (Bauer et al., 2016; Cherp et al., 2016; De

Cian et al., 2016; Kriegler et al., 2016) intercomparison exercises. The significance of this oversight is amplified by the considerable impact that assumptions regarding the accessibility of fossil fuel resources have on scenarios. Evidence is found in the evaluation of AR5 scenarios against consistent growth rates of emissions from the fossil fuels industry (Burgess et al., 2020; Pielke Jr et al., 2022), the analysis of the GCAM-MAGICC integrated assessment model's sensitivity to revised cost-supply curves (Capellán-Pérez et al., 2016), the comparison of WoLiM (Capellán-Pérez et al., 2014, 2015) or MEDEAS (Capellán-Pérez et al., 2020) energy-constrained model results with scenarios from the literature, the incorporation of thorough oil production profiles in IMACLIM-R (Rozenberg et al., 2010; Waisman et al., 2012b); and the examination of various fossil resource availabilities in RoSE. Cost-supply curves also do not impose significant limitations as they operate under the assumption that the most economically viable reserves will be exploited first. As a result, they disregard the complex interplay of socioeconomic and geopolitical factors that shape the reality of producing companies (Heede and Oreskes, 2016), countries (Johnsson et al., 2018), and regions (Verbruggen and de Graaf, 2013; Norouzi et al., 2020).

Second, IAMs dismiss comprehensive energy-economic feedbacks. They indeed assume that decreasing net energy, or increasing energy costs, does not influence economic growth whatsoever as in the IMAGE (Stehfest et al., 2014), GCAM (Calvin et al., 2019) or POLES (European Commission Joint Research Centre, 2018) models, or has minimal impact when the output is recursively calculated, for instance using nested constant elasticity of substitution (CES) functions found in models like EPPA, GTEM-C (Cai et al., 2015), REMIND, and WITCH (Bosetti et al., 2006). These functions have moreover faced criticism for their inability to accurately align with historically observed patterns in the dynamics of energy transition (Heun et al., 2017; Kaya et al., 2017). Another critical modeling assumption is the absence of disaggregation of the industrial sector from all others, as in MESSAGE or IMACLIM-R, which makes it difficult or impossible to provide a coherent representation of the net energy impact on the economy. Overall, we find this lack of precision and/or energy-economic feedbacks particularly troublesome as the decrease in the EROI of the energy system will make it increasingly necessary to implement demand-side measures.

The lack of energy-economy feedback is even more crucial since some authors have found that IAMs favor Bioenergy with Carbon Capture and Storage (BECCS) over the use of renewable energy, notably by underestimating the cost reduction potential of renewables and especially PV (Creutzig et al., 2017; Victoria et al., 2021; Grant et al., 2021; Xiao et al., 2021; Way et al., 2022), while in fact bioenergy and CCS technologies result in a significant decline in net energy (Fajardy and Dowell, 2018; Sekera and Lichtenberger, 2020). The importance of the net energy-economy feedback becomes even more apparent when considering the substantial energy requirements associated with the deployment of Direct Air Carbon Capture and Storage (DACCS), which are estimated to consume up to 300 EJ/yr by 2100 (Realmonte et al., 2019). Note that due to residual fossil emissions, 640–950 Gt CO₂ carbon dioxide removal (CDR)–BECCS, DACCS and afforestation–is required for a likely chance of limiting end-of-century warming to 1.5°C, when strengthened pre-2030 mitigation action is combined with very stringent long-term policies (Luderer et al., 2018).

A notable exception is the MEDEAS (Capellán-Pérez et al., 2020; Samsó et al., 2020; Solé et al., 2020) model (now developed as the WILLIAM model in the scope of the LOCOMOTION project), which appears to be the sole multi-scale³² IAM that explores, from a heterodox perspective (Nieto et al., 2020a), the implications that energy required for the transition

³²The SFCIO-IAM (Sers, 2022) and WORLD7 (Sverdrup et al., 2021) are for instance only global models.

may have on the energy system and the economy (Hafner et al., 2020). Unlike other IAMs, MEDEAS includes an energy-economy feedback that allows energy availability to limit GDP growth in the event that it falls short of demand (Nieto et al., 2020a). When compared with AR5 business-as-usual scenarios, the results obtained with MEDEAS show a larger intensity of total primary energy supply, as well as lower CO₂ intensity of primary energy, GDP per capita, and temperature change over pre-industrial levels (Capellán-Pérez et al., 2020). In case of national transition scenarios, MEDEAS results are comparable with TIMES or LEAP models, but diverge on the rate of implementation of renewables (Perissi et al., 2021). Such a modeling approach not only enables the characterization of the interaction between energy and the economy, such as the rebound effect (de Blas et al., 2020), in a more historically consistent way (de Blas et al., 2019), but also the probability of GHG scenarios from other IAMs (Huard et al., 2022), as well as degrowth scenarios (de Blas et al., 2020; Nieto et al., 2020a; Pulido-Sánchez et al., 2022).

The reasons why net energy is not comprehensively accounted for in IAMs are multiple and, in our view, fall primarily into three categories.

First, the notable lack of consideration given to life-cycle assessment (Pedersen et al., 2022) within IAMs neglects material cycles and recycling processes, and leads to the incoherent representation of life-cycle impacts of various technologies and the omission of linkages for buildings and infrastructures (Pauliuk et al., 2017; Desing et al., 2023). Since global supply chains and capital investment remain incompletely depicted—either through a single or a few composite macroeconomic goods in monetary units—IAMs are structurally unable to consider the full life-cycle energy-economy linkages brought to the fore by net energy analysis. Some examples of direct consequences are the focus on supply-side solutions for mitigating climate change, the overestimation of the potential for reducing energy intensity (thus assuming possibly unrealistic decoupling rates between GHG and energy/material use), and the underestimation of the impact of rebound effects on energy demand (Gambhir et al., 2017; de Blas et al., 2020; Brockway et al., 2021; Semieniuk et al., 2021; Andrieu et al., 2022b).

Second, most IAMs—either energy system models coupled with macroeconomic growth models or multi-sectorial Computable General Equilibrium (CGE) models—still employ neoclassical economics' optimal growth theory. As perfect foresight and limited market imperfections are assumed, the lack of (net) energy and material availability is not considered a major concern for economic growth, and is therefore modeled with limited granularity. More specifically, neoclassical-based models assume energy cost increases cannot appreciably affect GDP growth because either GDP or technological change are exogenously assumed or the cost share of energy (as percentage of GDP) is assumed to have negligible feedback on GDP. Ultimately, the current crop of IAMs greatly downplays the contribution of energy and exergy in economic processes (Kümmel and Lindenberger, 2014; Santos et al., 2018; Spangenberg and Polotzek, 2019), but also sets aside its interaction with money and the financial sector, as these are both largely unmodeled in IAMs (Pollitt and Mercure, 2017; Sanders et al., 2022). This omission precludes any attempt to understand how high levels of debt, which can increase financial instability risks, can be associated with net energy constraints or high energy costs (e.g. the global financial crisis of 2007-2008) (Svartzman et al., 2019).

Third, the current climate change scenarios framework nurtures a depoliticized, not systemic vision of technology and the economy, which results in the isolation of population and economic growth from other socio-economic parameters that hinders the incorporation of net-energy related feedback mechanisms (Asefi-Najafabady et al., 2020; Purvis, 2021; Court and McIsaac, 2020; Pielke and Ritchie, 2021b,a; Kuehnlenz et al., 2022). This furthermore raises concerns regarding the IPCC framework's ability to adequately assess societal transformations

(Trutnevyte et al., 2019), (in)justice (Ackerman et al., 2009; Rivadeneira and Carton, 2022), and other systemic risks (Rising et al., 2022). More generally, the aforementioned limitations can be attributed to a lack of reflexivity, plurality, transparency and transdisciplinarity within the IAM community, as acknowledged by some experts (Doukas et al., 2018; Hirt et al., 2020; O'Neill et al., 2020; Robertson, 2020; Skea et al., 2021; van Beek et al., 2022; Pedersen et al., 2022; Sgouridis et al., 2022; Koasidis et al., 2023).

3.2.6. AVENUES OF IMPROVEMENT TO CONSIDER NET ENERGY IN IAMs

Several initiatives are underway to better account for industrial energy, and represent the interactions between energy and the economy in macroeconomic models and/or IAMs (Keppo et al., 2021). Some IAMs, for instance, have adopted the use of more reliable data pertaining to fossil energy resources, as exemplified by the incorporation of a comprehensive bottom-up dataset from Rystad Energy in E3ME-FTT-GENIE (Mercure et al., 2021; Semieniuk et al., 2022) or the construction of detailed field-level analysis supply curves in TIAM-UCL (Welsby et al., 2021). Others have also introduced specific rules trying to mimic the behavior of swing producers, as in IMACLIM-R or IMAGE, yet in a very simplified way and mostly the oil market (Faehn et al., 2020; Foure et al., 2020). In an attempt to bridge the gap with Industrial Ecology (IE), several IAMs (notably REMIND and MESSAGE) have explored the implications of incorporating life cycle assessment coefficients from input–output (I–O) tables such as THEMIS (Pehl et al., 2017; Arvesen et al., 2018; Luderer et al., 2019) or EXIOBASE (Budzinski et al., 2023). Efforts are also underway for examining the contribution of material flow analysis (MFA), either through the coupling of MFA-augmented Energy System Models (ESM) (Huang and Eckelman, 2020; Kullmann et al., 2021), the introduction of a metal–energy–climate nexus framework (Wang et al., 2022), or the development of dynamic MFA modules, such as STURM for MESSAGE (Mastrucci et al., 2021; Awais et al., 2023). In doing so, these IAMs have begun to examine material requirements (Wang et al., 2023b), and mineral constraints (Wang et al., 2022). Still, most IAMs operate within the neoclassical equilibrium framework, and do not consider the feedback from the energy system on the economy. For instance, Pehl et al. (2017) integrate a life-cycle assessment perspective in the REMIND model, and find that “fully considering life-cycle greenhouse gas emissions has only modest effects on the scale and structure of power production in cost-optimal mitigation scenarios”. However, the authors rely on a model that uses a CES function, with limited feedback from the energy system (including its energy requirements) on the economy, and focus exclusively on the power sector.

In an attempt to remedy this situation, we highlight six avenues for improving IAMs: (i) the integration of Industrial Ecology modules such as DyMEMDS (Vidal et al., 2021; Le Boulzec et al., 2022)—which continues to be developed as MATER (Le Boulzec et al., 2023), ODYM-RECC (Pauliuk and Heeren, 2019; Pauliuk et al., 2020), or QTDIAN (Süsser et al., 2021); (ii) the use of a multi-sectoral exergy framework for instance relying on primary-final-useful (PFU) energy databases (Heun et al., 2020; Steenwyk et al., 2022; Pinto et al., 2023; Marshall et al., 2023); (iii) the integration of energy systems models which deal with environmental and biophysical indicators (Sherwood et al., 2020) in a more comprehensive way, such as ENBIOS (Martin et al., 2022)—which relies on the MuSIASEM (Manfroni et al., 2021a,b) approach, EnergyScope (Limpens et al., 2019) or the one developed by (Crownshaw, 2023); (iv) the explicit reporting of net energy in Shared Socioeconomic Pathways (SSP) narratives (Neumeyer and Goldston, 2016; Riahi et al., 2017; Slameršak et al., 2022); (v) an exploratory phase, in which IAMs should study how a net energy feedback would affect their results (Palmer, 2018)

to assess to what extent energy and economic feedbacks are internally inconsistent across mitigation pathways; and (vi) the exploration of new mitigation pathways limiting the deployment of carbon dioxide removal (van Vuuren et al., 2018; Sers, 2022), such as equitable post-growth scenarios (Floyd et al., 2020; Keyßer and Lenzen, 2021; Warszawski et al., 2021; Hickel et al., 2021). However, if these measures are to be properly implemented, they must be carried out simultaneously and without neoclassical theories that we see as incompatible (Brand-Correa et al., 2022; Stern et al., 2022).

3.2.7. CONCLUSION

Consideration of net energy is crucial to assess and design comprehensive and coherent climate mitigation scenarios. Yet, in part due to the late emergence of robust results in the EROI literature, such consideration has not yet spread beyond the Net Energy Analysis community. Here we try to address this issue by outlining the emerging EROI consensus, exploring key areas under investigation, and identifying further work needed.

Our summary underlines that, in a fossil fuel dominated world, the initial energy investment to power the transition to a low-carbon future will inevitably come from fossil fuels. This does not mean, though, that renewables cannot eventually support themselves. However, net energy may limit the energy available to invest in the energy infrastructure and the energy available for discretionary uses, absent more sustainable production and consumption habits. This situation may be particularly destabilizing for industrializing countries, which might stay at the doorstep of the energy transition, unable to increase their reliance on modern low-carbon energy, while being among the least responsible and among the most impacted by climate change. As such, these dynamics should not be ignored in transition scenarios, and we therefore call on fellow researchers to integrate net energy into Integrated Assessment Models using theories outside of the neoclassical paradigm, and believe that fostering collaborative efforts among our different research communities could prove decisive.

CHAPTER 4 | CONCLUSION

The scarcest resource is not oil, metals, clean air, capital, labour, or technology. It is our willingness to listen to each other and learn from each other and to seek the truth rather than seek to be right.

Donella Meadows

4.1. BACKGROUND

No longer do we speak of a crisis succeeding other crises - and heralding others still - but of "the crisis" affecting not only the climate, ecosystems, the economy, but also the culture, and relationships. With the purpose of gaining a deeper comprehension of the underlying roots of this contemporary polycrisis and devising potential solutions, this thesis extends the incipient field of ecological macroeconomics by delving into the intricate interplay among energy, finance, and the economy. While the field has made significant strides in elucidating the intertwined environmental and social crisis, it has attracted growing criticism for its insufficient consideration of the energy constraints that underlie modern economies, as well as their link with the financial and economic systems.

Therefore, the research aim of this thesis was to understand the processes and ramifications of systemic risks arising from reaching—or even exceeding—limits, exemplified by the rising energy costs associated with the depletion of high-quality fossil fuels. In more concrete terms, the aim was to construct a qualitative and semi-quantitative understanding of the crucial feedback loops and vulnerable components within the energy—finance—economy nexus.

4.2. SUMMARY OF THE CHAPTERS AND HOW THEY TIE TOGETHER

The approach adopted to achieve the research aim is twofold. Primarily, the energy constraints of the modern economies are analyzed through a series of three studies:

- The first article assesses the extent to which the net-energy supply of oil products is affected by the use of lower quality energy sources. Its novelty resides in the incorporation of standard EROI (energy-return-on-investment) estimates and dynamic decline functions in the GlobalShift all-liquids bottom-up model, from 1950 to 2050. We determine the energy necessary for the production of oil liquids (including direct and indirect energy costs) to represent today 15.5% of the energy production of oil liquids, and growing at an exponential rate: by 2050, a proportion equivalent to half of the gross energy output will be engulfed in its own production.
- The second article treats the same research question and with a similar approach but for fossil gas. We find that the energy necessary to produce gas (including direct and indirect energy and material costs) corresponds to 6.7% of the gross energy produced at present, and is growing at an exponential rate: by 2050, it will reach 23.7%.
- The third article presents a dynamic model of the global fossil fuels production infrastructures and materials requirements for each segment of the supply chain, as well as the embedded energy and CO₂ emissions from 1950 to 2050. We find that (i) the material intensities of oil, gas and coal supply chains have stagnated for more than 30 years; (ii) gas is the main driver of current and future material consumption; and (iii) recycled steel from decommissioned fossil fuels infrastructures could meet the cumulative need of future low-carbon technologies and reduce its energy and environmental toll.

Secondly, Chapter 3 presents two studies dealing with the modeling of energy constraints in macroeconomic models, relying on the methods previously developed.

- The first article introduces a new ecological, stock-flow consistent macroeconomic model, named TEMPLE, designed to assess the economic consequences of a global energy transition scenario compatible with the 1.5°C target of the Paris Agreement. Our results indicate that achieving this transition will generate dynamics similar to those of a wartime economy, with high inflation, investment and employment rates. Another important finding is that a slowdown in the economy's growth rate reduces inflation and therefore facilitates the transition. We therefore call for the study and design of transition scenarios in the frame of a post-growth economy.
- The second article is a comment piece federating an important fraction of the net energy analysis community. By clarifying the emerging consensus between the authors, the article identifies areas of investigation for the community, discusses the consequences of net energy in the context of the energy transition, and highlights the problems stemming from ignoring net energy issues in existing analyses. In this sense, it presents a critical assessment of the way in which industrial energy in the energy production sector is taken into account, and how the interactions between energy and the economy are modeled in integrated assessment models (IAM). Finally, it suggests practical ways forward, highlighting the need to integrate a net energy perspective into IAMs, and encourage collaborative efforts between our different research communities.

4.3. ANSWERING THE RESEARCH QUESTIONS

In summary, these two chapters have facilitated a more precise evaluation of the effects of long-term biophysical processes on modern economies, as well as their comprehensive integration into macroeconomic models. They have notably demonstrated that diminishing net energy levels can impede the investment of energy towards energy infrastructure, and reduce the energy available for discretionary use, unless accompanied by more sustainable production and consumption practices. Given the anticipated deterioration of the quality of fossil fuel reserves over time, countries that delay taking action, in a context of competition for energy resources, may compromise their ability to successfully transition and sustain or achieve high levels of material well-being. This predicament could be especially destabilizing for countries of the Global South, as they may find themselves on the cusp of the energy transition, unable to advance towards modern low-carbon energy sources, despite bearing lesser responsibility for climate change and experiencing a disproportionate impact from its effects.

While significant progress has been made in research on mitigation pathways, net energy has been addressed only marginally in the IPCC report and by Integrated Assessment Models (IAMs), the main tools used to produce global, regionally disaggregated mitigation pathways. Overlooking net energy issues has resulted in discrepant account of the industrial energy of the energy production sector, inconsistent modeling of the interactions between energy and the economy, insufficient discussion on the consequences of a decrease in aggregate EROI, and a disregard to the (in)justice dimension of the transition. The reasons why net energy is not comprehensively accounted for in IAMs are multiple, and fall primarily into three categories: (i) the notably little consideration given to life-cycle assessment, (ii) the reliance on inadequate neoclassical economics' optimal growth theory, (iii) a depoliticized vision of technology and the absence of systems thinking in the current climate change scenario framework.

In an attempt to remedy this situation, I highlight six avenues for improvements for the IAM community: (i) the integration of Industrial Ecology modules, (ii) the use of a multi-sectoral exergy framework, (iii) the integration of energy systems models which deal with environmental and biophysical indicators in a more comprehensive way, (iv) the explicit reporting of net energy in Shared Socioeconomic Pathways (SSP), (v) an exploratory phase, in which IAMs should study how a net energy feedback would affect their results, and (vi) the exploration of new mitigation pathways limiting the deployment of carbon dioxide removal such as equitable post-growth scenarios. However, if these measures are to be properly implemented, they must be carried out simultaneously and in a way that steps back from neoclassical theories, as already called for by several members of the IAM community. Finally, in this regard, I believe that fostering collaborative efforts among our different research communities could help improve integrated assessment modeling, the rapprochement being all the more supported by the convergence of views on demand-side measures and alternative economic pathways.

4.4. LIMITATIONS OF THE RESEARCH

The research undertaken during the thesis is subject to limitations at two different levels. The first one is methodological: each modeling choice and data integration is of course subject to criticism, something which we have been duly trying to expose in each of the articles. The

second level is epistemological. By focusing on models and data, we leave out considerable aspects of the discussion that could prove decisive. In particular, the critical modeling approach could enable the knowledge produced not to be confined to the technocratic esotericism of black boxes (Bouleau, 2010). I also rely upon a whole field of human and social sciences, from environmental humanities to political ecology, to question our relationship with quantitative results, and more specifically our blindness to their limits and pernicious use (Supiot, 2020).

4.5. FUTURE WORK PERSPECTIVES

A first line of future research would be a contribution to the implementation of the six avenues of improvement for the IAM community given previously, and the analysis of the impact of the presupposed inconsistency of the energy—economy relationship in climate scenarios. Such a task would require an iterative, collaborative and transdisciplinary process that could lead to the renewal of existing IAMs, the development of a new, more coherent IAM, and new mitigation pathways—for instance coming from the post-growth community (Hickel et al., 2021). Following this route would also entail a more realistic conception of feasible scenarios for the transition to a low-carbon economy, as well as recommendations for appropriate policy measures. The resulting scenarios would however need to be explored from a political ecology perspective, in order to assess environmental justice issues and investigate compensation schemes for ambitious mitigation pathways in a zero net emission perspective at the 2050 horizon. This would require a parallel examination of the socio-technical-institutional barriers to ambitious change in the Global North.

Another substantial contribution, in line with the literature review performed in the introduction (pp. 27), would be the investigation of how tensions on fossil fuel flows (particularly oil flows) impact the macro-economy directly and indirectly via financial speculation, over time horizons of the order of a year to a decade, with a possible focus on possible tilts between inflationary and deflationary regimes. This could be done, for example, by developing a new ecological stock-flow consistent macroeconomic model, enriched with system dynamics and agent-based to represent the speculative behavior of financial agents. Such a model is in fact in an advanced stage of development, in collaboration with Hugo Martin, Pierre-Yves Longaretti and Emmanuel Prados.

This model—named CRISIS (*Cascading Reactions in Society's Interconnected Systems*)—is designed to assess the macro-dynamics emerging in a context of rising energy extraction costs associated with the depletion of non-renewable resources, for a financialized economy. It relies on the model of Gibson and Setterfield (2018), but adds to it (i) an endogenous dynamic employment circuit — using the Philipps' curve, (ii) the introduction of an anticipated demand that stimulates the economy, limited by a supply which takes into account production constraints through capital capacity, the number of workers, and energy, and (iii) the creation and destruction of money — through the repayment of previous loans and principals as proposed by Cottin-Euziol and Piluso (2021). What really sets this model apart, however, is the differentiation of the productive and extractive sectors with the financial sphere.

Indeed, financial agents—linked in a network—bet on whether the price of energy will rise or fall, depending on the forecasts of neighboring agents (weighted by their past ability to predict) and the trends emerging from the real economy (i.e., productive and extractive firms). They then decide whether or not to lend money again, if they have access to the necessary liquidity

and if firms ask for it. The animal spirits of financial agents thus give rise to optimistic and pessimistic phases, driving price trends for consumer and extraction goods. In addition to financial speculation, however, the latter are facing a long-term increase due to the continuing decline in the quality of fossil fuels deposits. It remains to be seen whether the contraction of liquid fossil fuels will lead to inflationary or deflationary dynamics.

4.6. END NOTE

As Frank Herbert puts it: “There is no real ending. It’s just the place where you stop the story.” Here, I would like to stop on an optimistic-realistic note about how the world will evolve over the next years, which promise to be decisive for society as we know it.

I hold a firm belief that the challenges associated with the transition ahead are formidable, and our present situation is indeed precarious. This can largely be attributed to the limited understanding of systemic issues, following Hanlon’s razor, exhibited by those in positions of authority, coupled with the shortcomings of existing institutional systems. Yet, I believe in our collective ability to resolve this conundrum is within our reach, as each misstep brings us closer to embracing radical change and building a sustainable, just society.

Nevertheless, I express concerns regarding the simultaneous resurgence of what Umberto Eco theorized as *Ur-fascism* — a primitive and timeless form of fascism. This resurgence, cloaked under the pretext of ecological protection, has the potential to expedite the capture of resources and undermine democracy in favor of the interests of an oligarchic caste. The risk of ecofascist regimes well and truly exists, and must be approached with the utmost intellectual honesty (Dubiau, 2022; Madelin, 2023). This perspective is all the more supported by the historic implication of the far right in the climate crisis (Malm and Zetkin Collective, 2021), and the authoritarian drift not only in so-called liberal democracies but also in dictatorships. Instances of brutally suppressed uprisings, such as the Yellow Vests movement in France or more recent events in Iran, provide striking examples of the breakdown of modern socio-political democratic progress.

In this regard, it becomes paramount to foster an increasing awareness and understanding of the contemporary conditions of servitude, as well as strategies to break free from its grip. And as André Gorz so aptly pointed out, doing so requires to “accept being finished: to be here, and nowhere else, to do this, and nothing else, now, and not ever or always to have this life only”.

ANNEX

Andrieu, B., Vidal, O., Le Boulzec, H., Delannoy, L., and Verzier, F. Energy intensity of final consumption: the richer, the poorer the efficiency. *Environmental Science & Technology*, 56(19):13909–13919, 2022b. doi:10.1021/acs.est.2c03462

ABSTRACT

To maintain perpetual economic growth, most energy transition scenarios bet on a break in the historical relationship between energy use and gross domestic product (GDP). Practical limits to energy efficiency are overlooked by such scenarios, in particular the fact that high-income individuals tend to buy goods and services that are more energy intensive. Detailed assessments of the energy embodied in regional final consumption are needed to better understand the relationship between energy and GDP. Here, we calculate the energy necessary to produce households and governments' final consumption in 49 world regions in 2017. We correct prices at the sector level and account for the energy embodied in the whole value chain, including capital goods. We find that high-income regions use more energy per unit of final consumption than low-income ones. This result contradicts the common belief that a higher GDP is correlated with a better efficiency and questions the feasibility of mainstream energy transition scenarios based on universal GDP growth.

INTRODUCTION

International treaties on climate change aim to hold global average temperature to well below 2°C above pre-industrial levels (UNFCCC, 2015) while taking into account “the need to maintain strong and sustainable economic growth” (UNFCCC, 1992), eluding the possibility of these imperatives being contradictory. Meeting climate mitigation targets requires to limit global energy demand, as the deployment of decarbonization technologies alone is not sufficient to reduce emissions at an adequate rate (Gambhir et al., 2017). To allow continuous GDP (Gross Domestic Product) growth, scenarios thus rely on important energy intensity (energy use per unit of GDP) cuts. For the next decade, a yearly decrease of primary energy

intensity from 2.4 to 6.8% is assumed (Gambhir et al., 2017), breaking from historical trends of 1.5% for the 1990-2017 time period (Ahmad and Zhang, 2020). Not only does this hypothesis raise feasibility queries (Brockway et al., 2021; Semieniuk et al., 2021), but it also threatens some low-income regions to lack the energy required to maintain decent living standards (Semieniuk et al., 2021; Hickel and Slamersak, 2022). In a context where resources of the global South are drained by the global North (Hickel et al., 2022a) and environmental impacts are displaced through trade (Wood et al., 2018), understanding precisely current differences in energy intensities is essential to assess the risks associated with scenarios.

Energy allows the production and exchange of services or goods. Its consumption increases together with income, which in turns provides wellbeing (Kalt et al., 2019), within certain limits (Easterlin, 1974). Although the emergence of ecological economics can be traced back to the 1970's (Georgescu-Roegen, 1971; Cleveland, 1987), most studies fail to consider energy as a central factor of production (Wiedenhofer et al., 2020). For example, most research on the energy-GDP interrelationship still do not account for energy embodied in trade (Wiedenhofer et al., 2020; Haberl et al., 2020). Many focus on the causality between both factors (Wiedenhofer et al., 2020) while some advocate that economic value will be decoupled from energy consumption. An edifying example is a study assuming the existence of a Kuznet's curve between energy and GDP—an inverted U-shaped curve implying that total energy use tends to zero in an infinite economy—and predicting a peak of energy demand at US\$107,000 per capita (Bogmans et al., 2020). Yet, to analyse energy intensities, it is essential to see energy neither as a cause or consequence of GDP, nor as an indicator independent of GDP, but as a provider of energy services (Fell, 2017) which are subsequently estimated through the GDP prism. Energy intensity must therefore be understood as the ratio of all the energy necessary to produce a good or service divided by its associated value. This approach makes it necessary to study sector-level energy intensities as a function of affluence, to better pinpoint how different consumption patterns lead to unequal energy use (Galvin and Sunikka-Blank, 2018; Shove and Walker, 2014; Chen et al., 2019a).

So far, only three studies (Chen and Wu, 2017; Oswald et al., 2020; Vita et al., 2021) have carried out multi-sectoral and multi-regional comparisons of footprint energy intensities of goods and services. Oswald et al. (2020) have calculated sectoral final energy intensities and concluded that higher-income individuals tend to buy goods that are more energy intensive. Vita et al. (2021) have established that energy footprints were mostly driven by durables (goods that are not purchased frequently). Chen and Wu (2017) have calculated energy intensities in 26 sectors of 186 regions and showed that intensities vary greatly between sectors. All three analyses account for the energy embodied in intermediate consumption but do not consider the capital goods used in the production process. If the footprint of a strawberry pie is thereby calculated, the energy embodied in the flour and in the strawberries will be accounted for, but not that necessary for the production of the bakery. It is significant because capital goods have a key role in footprint reallocation (Wu et al., 2021), representing up to two-thirds of the carbon footprint of specific sectors (Södersten et al., 2018). Furthermore, as factories producing goods bought abroad are not accounted for, the footprints of regions that have delocalized their production are underestimated. Another limit to these studies is that they rely on country-level purchasing power parity (PPP) (Oswald et al., 2020; Vita et al., 2021) to eliminate national price level differences but not on sector-level PPP, hindering precise comparisons between product categories as different sectors in a given country have different PPPs (World Bank, 2020a). For example, the PPP of the clothing sector in China is 77% above that of the Chinese average PPP, which in turn is 80% above that of the health sector (World Bank, 2020a). Using the GDP-level PPP for China would thus underestimate the energy intensity of the clothing sector and overestimate

that of the health sector. Finally, neither study reports the variations of energy intensity per category of product as a function of affluence (hereby defined as GDP per capita). This hampers to quantify the relationship between regional GDP and regional energy-intensity.

This study aims to calculate footprint energy intensities of households and governments' final consumption over 12 sectors in 49 world regions and compare them to affluence. To do so, we combine price level indexes with a multi-regional input-output (MRIO) database in which we endogenize capital.

MATERIALS AND METHODS

We calculate energy intensities according to three different definitions: production-based account (pba), consumption-based account (cba) and final consumption account. We focus on final energy as it is closer to useful energy than primary energy (Haberl et al., 2020; Mastrucci et al., 2020). In the following, "energy" will thus refer to "final energy".

The pba energy intensity is the ratio of the energy used in a region by the households (E_{hh}) and by the local industries, (E_{pba}) divided by the GDP (Y) of that region calculated in \$PPP:

$$I_{pba} = \frac{E_{hh} + E_{pba}}{Y} \quad (4.1)$$

The cba energy use (E_{cba}) (Miller and Blair, 2009; Owen et al., 2017) is defined as the global energy used by industries to produce the GDP of a given region. The cba energy intensity (I_{cba}) is a better indicator of efficiency than (I_{pba}) as it accounts for the offshored energy use:

$$I_{cba} = \frac{E_{hh} + E_{cba}}{Y} \quad (4.2)$$

However, two limits are associated with I_{cba} 's calculation convention. First, in the classic input-output formalism, the energy used to produce capital goods is not imputed to the footprint of final consumption but to the gross fixed capital formation (GFCF), a measure of investment (Fig. 4.1 a). If a factory is built in China to produce goods bought in the United States, the embodied energy of the factory is allocated to China's investments and not to the United States. It follows that the energy necessary to produce the factory is omitted in the US footprint of final consumption expenditures. Second, E_{hh} is included in the calculation process of I_{cba} . However, E_{hh} is not in the input-output value chain and may have a different dynamic than E_{cba} .

To overcome these limits, we define the final consumption energy intensity (I_{fc}^K) as the ratio of the energy footprint of final consumption with capital endogenized (E_{fc}^K)—without accounting for E_{hh} — and the final consumption expenditures corrected for PPP (Y_{fc}):

$$I_{fc}^K = \frac{E_{fc}^K}{Y_{fc}} \quad (4.3)$$

The superscript K means that capital is endogenized. Capital endogenization consists in adding the consumption of fixed capital (CFC)—investments to replace end-of-life capital goods—to the input-output framework (Fig.4.1 b,c), thereby allocating the energy necessary to produce infrastructures to final consumption.

As a case example, results for these three types of energy intensities are compared for the two regions with extreme levels of affluence in EXIOBASE (Luxembourg and "Rest of Africa", defined as the African continent without South Africa and Egypt). The choice to include or

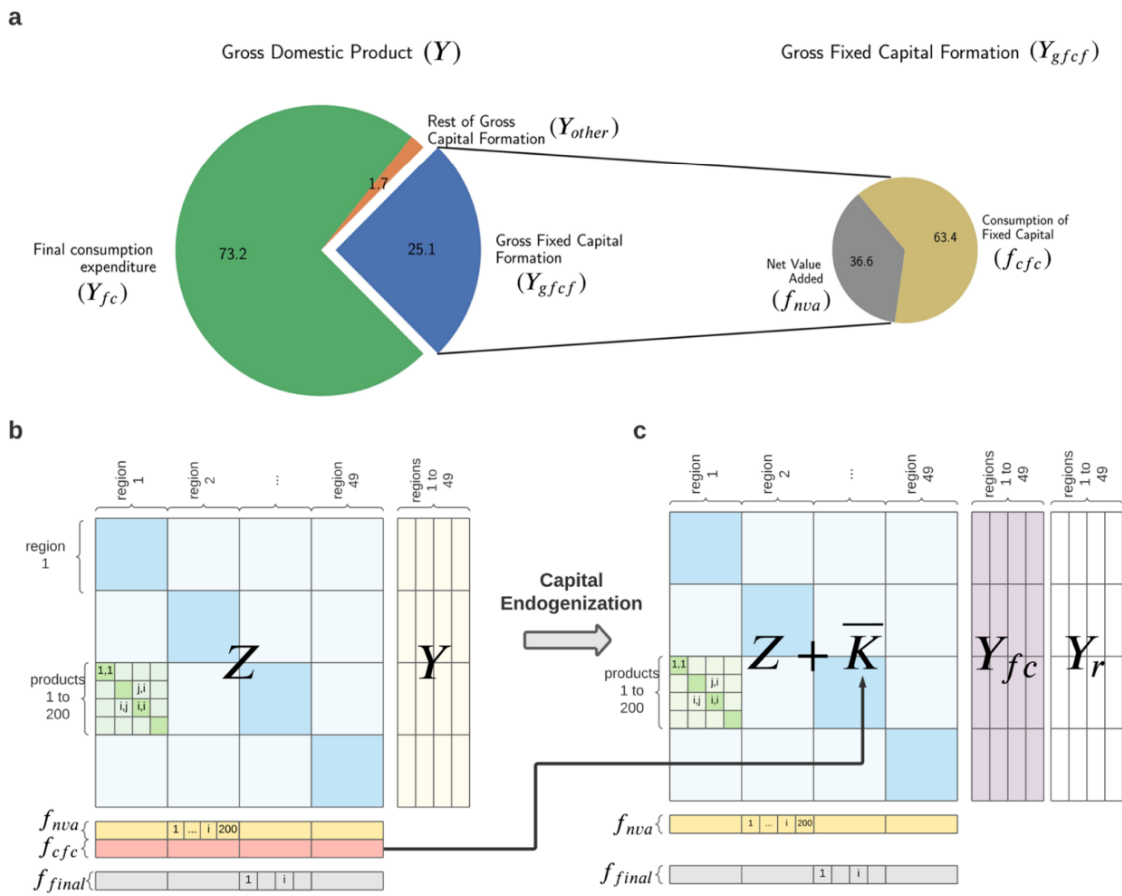


FIGURE 4.1: Input–output framework. (a) GDP and GFCF decomposition. (b) Input–output framework. Z is the transaction matrix, Y is the final demand matrix, f_{nva} is the net value-added vector, f_{cfc} is the CFC vector and f_{final} is the final energy extension. (c) Input–output with capital endogenized. The CFC (f_{cfc}) is transformed into matrix \bar{K} and added to matrix Z . Y_{fc} is the final consumption by households and governments, and Y_r is the residual final demand.

exclude E_{hh} in the calculation is then discussed based on regressions of E_{hh} per capita as a function of affluence and the share of E_{hh} in I_{cba} as a function of affluence.

We then test the results for correlations between energy intensities and affluence at an aggregated level (GDP level for I_{pba} and aggregated final consumption for I_{fc}^K). If there is a correlation, it can be explained either by a sector-level energy intensity and affluence correlation or by a change in final consumption composition with affluence. We evaluate how much each of the 12 sectors studied contribute to the change in energy intensity by calculating elasticities. Finally, we combine the dynamics of E_{hh} and I_{fc}^K as a function of affluence to estimate how much energy is associated with 1% of economic growth in each of the 49 regions.

INPUT-OUTPUT

Input-output modelling allows to calculate the total industrial output (x) necessary to produce final demand Y . Z is the transaction matrix, representing the inter-industry transactions between sectors and regions (for a detailed explanation of how Z is compiled, see Miller and Blair (2009) and supplementary information of Stadler et al. (2018)). Z can be subdivided into 49×49 submatrices of dimensions 200×200 representing the flows of intermediate products between each pair of regions (Fig. 4.1 b). Y contains vectors of final demand for each region. This final demand is disaggregated by sector and region of origin. The sum of a row of Z and Y gives the total output for a given sector in a given region. x thus writes:

$$x = Ze + Ye \quad (4.4)$$

with e a summation vector of appropriate dimension. The direct requirement matrix A is defined as:

$$A = Z\hat{x}^{-1} \quad (4.5)$$

with \hat{x}^{-1} meaning that the vector is diagonalized. We therefore have:

$$x = Ax + Ye \quad (4.6)$$

The Leontief inverse (L) is the inverse of matrix $(I - A)$, obtained when solving for x :

$$x = LYe \quad (4.7)$$

The production-based factors of production are given by matrix F . A row of F , called an extension, represents a given environmental or social impact associated with production. EX-IOWBASE3 provides several types of energy extensions. We build a final energy extension (f_{final}) by subtracting the extension "Energy Carrier Net LOSS" to the extension "Energy Carrier Net Total". For a discussion of the implications of different energy extension choices, see Owen et al. (2017). The regional aggregation of f_{final} gives us E_{pba} .

The associated coefficients of production are given by:

$$s_{\text{final}} = f_{\text{final}}\hat{x}^{-1} \quad (4.8)$$

To obtain a region's consumption-based energy use ($E_{(cba, \text{region})}$), we trace the total output associated to that region's GDP (Y_{region}) and multiply it by the coefficients of production. From the last two equations:

$$E_{(\text{cba,region})} = s_{\text{final}} L Y_{\text{region}} e \quad (4.9)$$

CAPITAL ENDOGENIZATION

E_{fc}^{K} must be calculated using an input-output table with capital endogenized. Capital endogenization consists in allocating a share of the production of capital goods to final consumption expenditures. This share must be representative of how much capital goods are depreciated a given year due to the production of intermediate consumption. To do so, we choose to endogenize the consumption of fixed capital (CFC), defined as the decline in value of the capital stock due to normal wear and tear and obsolescence or normal accident damage (Glossary, 2022).

Södersten et al. (2020) built a capital transaction matrix \bar{K}_{15} with the same dimensions as Z , from the vector f_{fc} of year 2015 (Södersten, 2020). Once added to Z , this matrix allows to consider CFC not as a sub-share of Y_{gfcf} (Fig. 4.1) but as intermediate consumption. A column total of \bar{K}_{15} equals CFC_{15} . To nowcast \bar{K}_{15} to 2017 using CFC_{17} , we transform it into a matrix of coefficients \bar{K}'_{15} with:

$$\bar{k}'_{i,j,15} = \frac{\bar{k}_{i,j,15}}{\sum_i \bar{k}_{i,j,15}} \quad (4.10)$$

where i is a row index and j a column index. \bar{K}_{15} is obtained by multiplying \bar{K}'_{15} by the f_{fc} vector of year 2017 ($f_{(\text{fc},17)}$). EXIOBASE provides this extension. However, as pointed out by Södersten et al. (2020), inconsistencies exist between EXIOBASE and World Bank data for the ratio $f_{\text{fc}}/Y_{\text{gfcf}}$. The World Bank gives an aggregate value per region of CFC (cfc^{WB}) and GFCF (gfcf^{WB}) which is deemed more reliable than EXIOBASE data (Södersten et al., 2020). We therefore scale up $f_{(\text{fc},17)}$ by a scalar β for every region so that:

$$\frac{\sum_{\text{products}} Y_{\text{gfcf, region}}}{\beta_{\text{region}} \sum_{\text{products}} f_{\text{fc, region}}} = \frac{\text{gfcf}_{\text{region}}^{\text{WB}}}{\text{cfc}_{\text{region}}^{\text{WB}}} \quad (4.11)$$

We thus obtain \bar{K}_{17} is the from coefficients $\bar{k}_{17,i,j}$:

$$\bar{k}_{17,i,j} = \bar{k}'_{15,i,j} \beta_j f_{\text{fc},17,j} \quad (4.12)$$

The mean of β values obtained is 0.99 but regional values range from 0.31 to 2.2, confirming the inconsistencies between both sources. \bar{K} is added to Z to have a total transaction matrix with capital endogenized. The direct requirement matrix with capital endogenized (A^{K}) is thus:

$$A^{\text{K}} = (Z + \bar{K} \hat{x}^{-1}) \quad (4.13)$$

And the Leontief inverse with capital endogenized becomes:

$$L^{\text{K}} = (I - A^{\text{K}})^{-1} \quad (4.14)$$

The total energy necessary to produce final consumption in a given region is thus:

$$E_{\text{fc}}^{\text{K}} = s_{\text{final}} L^{\text{K}} Y_{\text{fc}} \quad (4.15)$$

PURCHASING POWER PARITIES

Energy intensities are calculated using E_{pba} , E_{cba} , E_{fc}^K and economic data corrected for purchasing power parity. As I_{pba} and I_{cba} are calculated at an aggregated regional-level and not at the sector level, we directly use GDP data from World Bank (2020a). For the EXIOBASE rest of the world regions, country-level data is aggregated using the python module `country_converter` (Stadler, 2017).

However, I_{fc}^K is calculated at the sector level. We aggregate the 200 EXIOBASE products into the 12 sectors of the Classification of Individual Consumption According to Purpose (COICOP) as they are the ones used by the ICP. To do so, we modified the table of concordance built in Castellani et al. (2019) in order to include all 200 EXIOBASE products. As differences exist between data in current dollars from EXIOBASE and ICP, we do not directly use ICP data in constant dollars but apply ICP price index to the EXIOBASE data. This prevents outliers to appear due to different sector allocations between EXIOBASE and ICP.

ELASTICITIES

Elasticity is defined as the percentage change of a variable due to a percentage change of another variable. It can be calculated as the slope of a log-log regression, see Oswald et al. (2020) for proof. We consider an elasticity only if the coefficient of regression is higher than 0.2. In this section we give the equations used to calculate the contribution of each of the 12 sectors studied to the change in I_{fc}^K , both due to the change of I_{sect}^K (I_{fc}^K for a given sector) and to the change of this sector's share in final consumption expenditures (θ_{sect}).

Let ϵ_{sect}^I be the elasticity of I_{sect}^K as a function of affluence. It is obtained by the following regression, with a constant:

$$\log(I_{sect}^K) = \epsilon_{sect}^I \log\left(\frac{Y}{pop}\right) + a \quad (4.16)$$

A variation of I_{sect}^K implies a variation of I_{fc}^K . We define η_{sect}^I as the percentage change of I_{fc}^K resulting from the variation of I_{sect}^K due to an increase of 1% of affluence. By definition of ϵ_{sect}^I and θ_{sect} :

$$\eta_{sect}^I = \frac{\epsilon_{sect}^I I_{sect}^K \theta_{sect}}{I_{fc}^K} \quad (4.17)$$

Let ϵ_{sect}^θ be the elasticity of θ_{sect} as a function of affluence. It is obtained by the following regression, with b constant:

$$\log(\theta_{sect}) = \epsilon_{sect}^\theta \log\left(\frac{Y}{pop}\right) + b \quad (4.18)$$

A variation of θ_{sect} also implies a variation of I_{fc}^K . We define η_{sect}^θ as the percentage change of I_{fc}^K resulting from the variation of θ_{sect} due to an increase of 1% of affluence. By definition of ϵ_{sect}^θ and θ_{sect} :

$$\eta_{sect}^\theta = \frac{\epsilon_{sect}^\theta \theta_{sect} (I_{sect}^K - I_{fc}^K)}{I_{fc}^K} \quad (4.19)$$

Changes in I_{sect}^K for the 12 ICP sectors could be explained by changes of consumption patterns in sub-sectors or changes in energy intensities in sub-sectors. To find out if such is the

case, we apply the consumer price indexes to the 255 sub-sectors of the ICP sectors (some of the 200 EXIOBASE sectors are disaggregated between several ICP sectors). We then look for correlations between sub sectors' share of expenditures and energy intensities as a function of GDP.

ENERGY ASSOCIATED WITH ECONOMIC GROWTH

Energy per capita (E_{cap}) is obtained by combining the regressions of E_{hh} and I_{fc}^{K} as a function of affluence multiplied by final consumption expenditures per capita:

$$E_{\text{cap}} = \exp\left(a \log \frac{Y}{\text{pop}} + b\right) + \frac{Y_{\text{fc}}}{\text{pop}} \left(c \frac{Y}{\text{pop}} + d\right) \quad (4.20)$$

With a , b , c and d , the coefficients obtained from the regressions. To calculate the impact of economic growth, we modify the intercepts of the regressions of the previous equation for each region. Otherwise, the results would not account for the dispersion of the data around the regression line. For each given region, we define b' and d' the modified intercepts of the regressions of E_{hh} and I_{fc}^{K} so that the lines with slopes a and c pass by that region's data point. Solving for the increase of E_{cap} due to 1% increase of Y and Y_{fc} gives:

$$\Delta E_{\text{cap}} = (1.01^a - 1)e^{b'} \left(\frac{Y}{\text{pop}}\right)^a + 0.01 \frac{Y_{\text{fc}}}{\text{pop}} \left(2.01c \frac{Y}{\text{pop}} + d'\right) \quad (4.21)$$

DATA

Our calculations are based on EXIOBASE v3.8.2 (Stadler et al., 2018), an open-access MRIO database which represents the world economy divided between 200 products in 44 countries and 5 rest of the world regions. It contains many environmental extensions, including primary energy and energy loss, which allows to calculate a final energy environmental extension. As of this version, the energy data for year 2017 is a nowcast based on 2015 International Energy Agency (IEA) world energy balances (IEA, 2022). The trade and macroeconomic data for year 2017 has been estimated by EXIOBASE authors based on the original EXIOBASE3 data series for year 2011 and United Nations macroeconomic data for year 2017 (Stadler et al., 2018). The data for capital endogenization is based on matrixes built by Södersten and colleagues (Södersten et al., 2018) for year 2015 and was nowcasted to year 2017 using World Bank data (World Bank, 2022). The sectoral PPPs come from the International Comparison Panel (ICP) 2017 cycle (World Bank, 2020c).

LIMITATIONS

The main limitations to this study are those inherent to input-output calculation (Rodrigues et al., 2018). We chose EXIOBASE3 for this study in order to endogenize capital using existing matrixes. Existing input-output databases have been extensively compared and differ in their methodology, thus yielding differences in the results (Owen, 2017). However, these differences are limited—1-3% of difference for most regions and up to 20% for outlier countries—when comparing carbon emission accounts for the same base year (Wood et al., 2019). Uncertainties are also associated with the year of reference of our data. ICP data is compiled for year 2017 but EXIOBASE tables were compiled for year 2011 and updated using macro-economic data for year 2017. The reference year for the inter-industry capital requirement matrix is 2015 (Södersten,

2020) and we updated it using World Bank and EXIOBASE data for year 2017. Important differences existed between EXIOBASE and World Bank CFC data (β values). Energy data is a now-cast from 2015 IEA data (IEA, 2022). Uncertainties are also associated with sector aggregation in input-output (Steen-Olsen et al., 2014; de Koning et al., 2015). However, we aggregate sectors only after calculating the footprint so matrix L is not impacted. Uncertainties do exist due to the conversion of EXIOBASE sectors to COICOP sectors as it is not possible to have an exact correspondence.

RESULTS AND DISCUSSION

CHOOSING THE RIGHT INDICATOR

Differences in energy intensities calculation methods are illustrated in Figure 4.2 for the two EXIOBASE regions with extreme levels of affluence: Luxembourg and “Rest of Africa” (Africa excluding Egypt and South Africa). I_{pba} (Fig. 4.2 a), I_{cba} (Fig. 4.2 b) and I_{fc}^K (Fig. 4.2 c) have respective values of 2.3, 2.4 and 4.4 MJ/US\$ppp in Luxembourg and 4.3, 4.9 and 1.4 MJ/US\$ppp in “Rest of Africa”. For these regions, the consumption-based and production-based approaches yield similar results, with the energy intensity of “Rest of Africa” being twice higher than that of Luxembourg. However, I_{fc}^K is two times higher than I_{cba} in Luxembourg and three times lower than I_{cba} in “Rest of Africa”. This difference is mostly due to E_{hh} which is accounted for in I_{cba} but not in I_{fc}^K —another difference being the share of final consumption in GDP—. E_{hh} represents 65% of I_{cba} in “Rest of Africa” but only 17% in Luxembourg, although E_{hh} per capita is four times lower in “Rest of Africa” than in Luxembourg.

This finding can be generalized to all EXIOBASE regions. Even though E_{hh} increases with affluence (Fig. 4.3 a), its share in the total footprint of regions decreases with affluence (Fig. 4.3 b). This change is due to the fact that even at very low levels of affluence (thus very low levels of final consumption energy footprint), direct energy is still used by individuals for survival or every day needs.

We argue that E_{hh} must be calculated separately from the energy intensity of GDP because it has a different dynamic. Oswald and colleagues (Oswald et al., 2020) also found that “Heat and electricity”, the direct energy sector with the highest energy intensity, behaved fundamentally differently from others. Including E_{hh} in energy intensity calculation biases the results by inflating the energy intensity of poor regions more than that of wealthy ones. Energy intensities should therefore be analysed using I_{fc}^K and not I_{cba} . Using I_{cba} instead of I_{fc}^K could lead to major misinterpretations, such as concluding that Luxembourg is two times more efficient than “Rest of Africa” (Fig. 4.2 b) whereas it is actually 3 times less efficient (Fig. 4.2 c).

INTERNATIONAL ENERGY INTENSITY DISPARITIES

Regional values of I_{pba} are scattered but no trend is observed as a function of affluence ($R^2 < 0.2$) (Figure 4.4 a, d). In contrast, I_{fc}^K is higher in wealthier regions, with an elasticity of 0.27 (I_{fc}^K increases by 0.27% for every 1% increase of affluence) (Figure 4.4 c, e). I_{pba} and I_{fc}^K are disaggregated for regions with extreme levels of affluence on Figure 4.4 b. I_{pba} is made of household direct energy use (in orange) and domestic production energy (in blue), whereas I_{fc}^K is only made of the footprint of final consumption (in gray).

Our results show that when calculating the energy intensity with capital endogenized, the energy intensity is higher in richer regions, while Oswald and colleagues (Oswald et al., 2020) found that it decreases slightly in richer regions. Three factors explain these differences: we con-

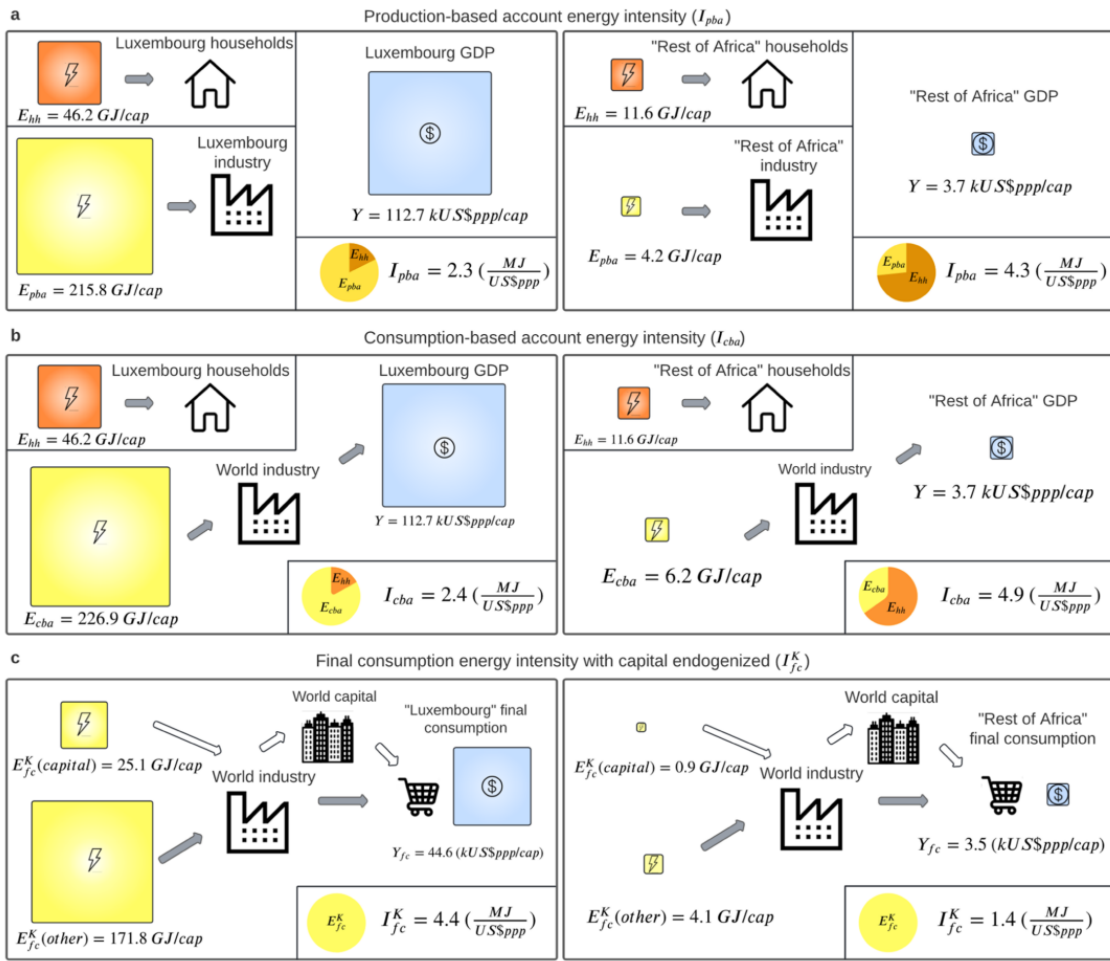


FIGURE 4.2: Energy intensity scopes. (a) Production-based energy intensity (I_{pba}). (b) Consumption-based energy intensity (I_{cba}). (c) Final consumption energy intensity with capital endogenized (I_{fc}^K). (a-c), Comparisons between richest and poorest EXIOBASE regions. "Rest of Africa" is the African continent less South Africa and Egypt. Open access pictograms from svgrepo.com.

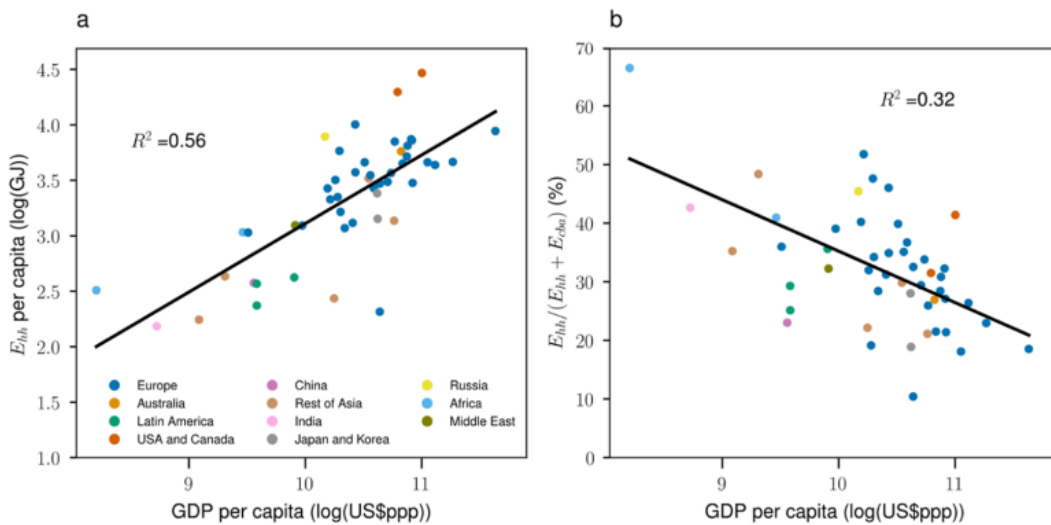


FIGURE 4.3: Households direct energy use (E_{hh}). (a) Households direct energy use per capita (E_{hh} per capita). (b) Share of households' direct energy use in consumption-based footprint ($E_{hh}/(E_{hh} + E_{cba})$). (a-b) Richer regions have higher per capita E_{hh} but the share of E_{hh} in the footprint decreases with affluence.

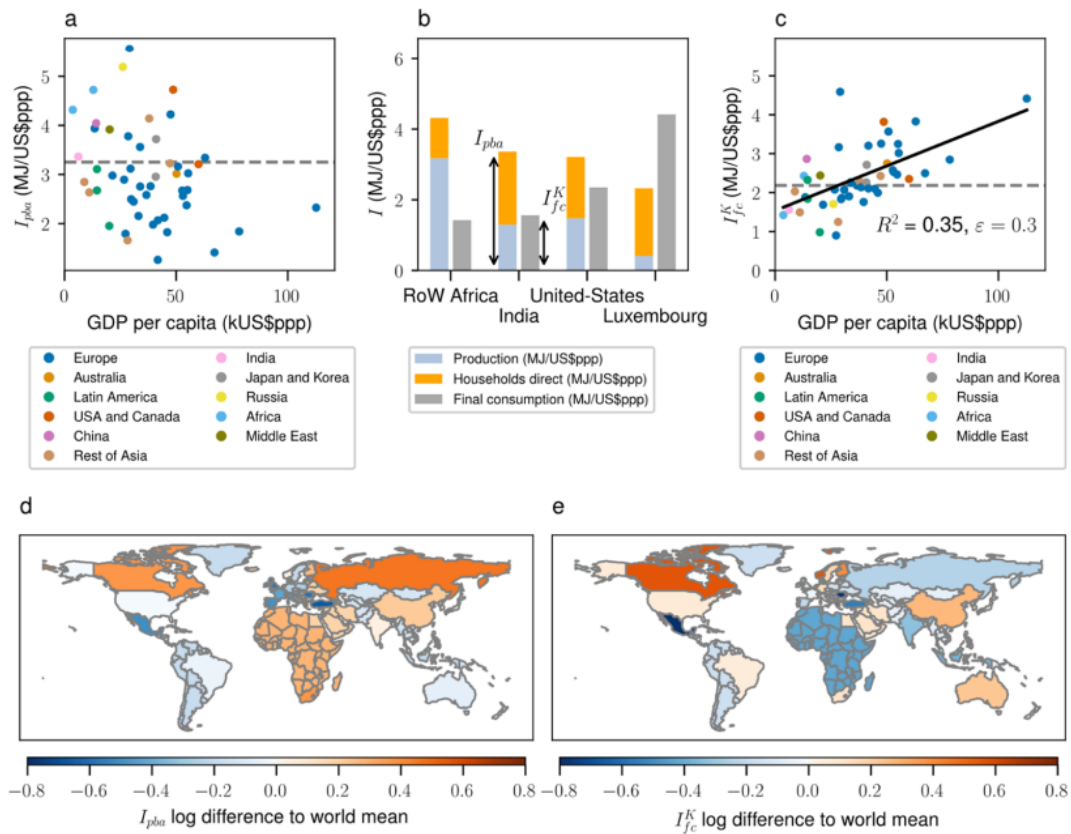


FIGURE 4.4: Energy intensity disparities. (a) Production-based account energy intensity (I_{pba}) as a function of affluence. The dashed gray line represents the world value. Regional data (scattered dots) do not fit affluence ($R^2 < 0.2$). (b) Energy intensity examples (I_{pba} and I_{fc}^K). (c) Final consumption energy intensity with capital endogenized (I_{fc}^K) as a function of affluence. The dashed gray line represents the world value and the black line the linear fit. An elasticity (ϵ) of 0.27 is calculated. (d) Log difference of I_{pba} to the world mean. (e) Log difference of I_{fc}^K to the world mean. 20 of the 49 regions switch colors between the two maps.

	World value	I_{sect}^K R^2	$\varepsilon_{\text{sect}}^I$	η_{sect}^I	World value	θ_{sect} R^2	$\varepsilon_{\text{sect}}^I$	η_{sect}^I
CPI: 01 - Food and non-Alcoholic beverages	4	0.02	0.14	0.02	0.07	0.02	-0.16	-0.01
CPI: 02 - Alcoholic beverages, tobacco and narcotics	6.4	0.05	-0.15	0	0.01	0.01	-0.19	0
CPI: 03 - Clothing and footwear	5.2	0.08	0.19	0.01	0.02	0	-0.19	-0.01
CPI: 04 - Housing, water, electricity, gas and other fuels	1.8	0.46	0.48	0.08	0.19	0.17	-0.17	0.01
CPI: 05 - Furnishings, household equipment and routine household maintenance	4.6	0.18	0.17	0.01	0.02	0.04	-0.01	0
CPI: 06 - Health	1.5	0.25	0.3	0.02	0.07	0.07	0.15	0
CPI: 07 - Transport	4.6	0.02	0.27	0.04	0.07	0.36	0.34	0.02
CPI: 08 - Communication	1.4	0.01	-0.02	0	0.04	0.08	0.41	-0.01
CPI: 09 - Recreation and culture	3.1	0.04	0.09	0.01	0.06	0.01	0.1	0
CPI: 10 - Education	0.7	0.26	0.47	0.02	0.15	0.11	-0.12	0.01
CPI: 11 - Restaurants and hotels	1.3	0.02	0.15	0.01	0.06	0	-0.53	0.01
CPI: 12 - Miscellaneous goods and services	2	0.04	0.15	0.03	0.25	0.04	0.14	0

TABLE 4.1: Elasticities. R^2 refers to the coefficient of regression of I_{sect}^K and θ_{sect} as a function of affluence. The associated ε and η are used in the paper only if $R^2 > 0.2$ (colored lines).

sider the footprint of capital goods and of government final consumption expenditures, we do not consider households direct energy use, and we study year 2017 and not 2011. Our results challenge the belief that richer regions are more efficient. One explanation is that economy-wide rebound effects can cut half of the gains from improved energy efficiency (Brockway et al., 2021). Another explanation could be that the energy efficiency gains in a region affects other regions in a globalized world economy. Indeed, if technologies are transferred, they can improve energy intensity of all regions at the same time and not only that of the wealthy ones. This is consistent with the fact that absolute decoupling of energy consumption and GDP (growth of GDP and degrowth of energy consumption) though experienced in a limited number of regions has been observed in regions with extremely low human development index and not only in high-income regions (Akizu-Gardoki et al., 2018). Vita et al. (2021) also found that over the period 1995–2011, energy efficiency was observed in 47 out of 49 studied regions with very different affluence levels.

SECTOR-LEVEL ENERGY INTENSITIES

The fact that I_{fc}^K scales with affluence can either be explained by increases of sector-level energy intensities I_{sect}^K with affluence or by a change of composition of final consumption across regions. Only the housing, education, and health sectors representing, respectively, 19, 15 and 7% of world final consumption show a correlation between I_{sect}^K and affluence ($R^2 > 0.2$) (Table 4.1, Figure 4.5). Their elasticities, $\varepsilon_{\text{sect}}^I$, defined as the percentage change of I_{fc}^K due to a change of I_{sect}^K resulting from an increase of affluence by 1%, are 0.08, 0.02, and 0.02%. The increase in the energy intensity of these three sectors thus explains 45% of the total elasticity of I_{fc}^K , equal to 0.27% (Figure 4.4 c).

The transport sector's share in the final consumption ($\theta_{\text{transport}}$) is the only one correlated with affluence ($R^2 > 0.2$) (Extended Data Table 4.1, Figure 4.6). For each 1% increase of affluence, $\theta_{\text{transport}}$ increases by 0.34%. As the energy intensity of the transport sector is higher than that of the world mean (Table 4.1, Figure 4.4 e), an increase in $\theta_{\text{transport}}$ translates by an increase of I_{fc}^K . The increase of I_{fc}^K due to an increase of $\theta_{\text{transport}}$ resulting from an increase of 1% of affluence is of 0.02%. This value represents 8% of the total elasticity of I_{fc}^K . The four dynamics above-mentioned are significant as they explain 53% of the total elasticity, the 20 other dynamics (Table 4.1) explaining the other 47% but with R^2 under 0.2. Four sectors play a specific role in this energy intensity evolution. The first contribution comes from the transport sector, whose share in final consumption expenditures increases with affluence. As the energy intensity of this sector is twice higher than that of total final consumption, a higher share of transport sector implies a higher energy intensity. The energy intensity elasticities of housing, education,

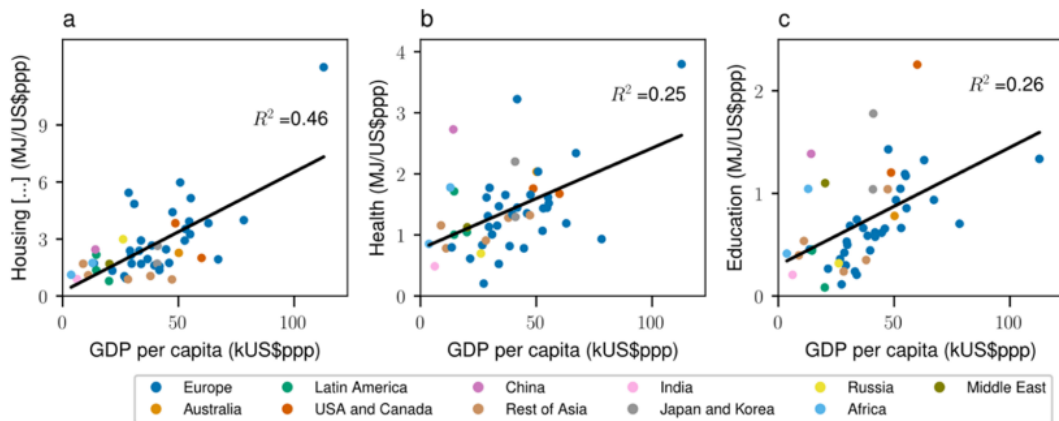


FIGURE 4.5: Sector-level energy intensities. (a) Housing, water, electricity, gas, and other fuel sectors. (b) Health sector. (c) Education sector. (a–c) The black lines represent linear fits. The nine other sectors are not displayed as we obtained $R^2 < 0.2$.

and health sectors are positive, meaning that richer regions use more energy per dollar of final consumption. However, the contribution to the increase of I_{fc}^K due to the housing sector is 4 times higher than that of the education and health sectors.

These sectors can be further disaggregated into EXIOBASE subsectors. Out of 255 possible EXIOBASE subsectors, only 12 had their expenditure shares of the CPI sector total which fitted as a function of GDP with $R^2 > 0.2$. Among these, none represented more than 4% of a CPI sector's total expenditures. Moreover, 40 subsectors had their energy intensity which fitted as a function of GDP with $R^2 > 0.2$. Among these, only 7 represented more than 4% of a CPI sector's total expenditures, all fitting positively as a function of GDP. These included vegetables, fruit, nuts (14% of CPI 01), wearing apparel, furs (18% of CPI 03 total), real estate services (55% of CPI 04 total), public administration and defense services, compulsory social security services (15% of CPI 06 total), air transport services (7% of CPI 07 total), education services (65% of CPI 10 total), and retail trade services, except of motor vehicles and motorcycles and repair services of personal and household goods (15% of CPI 10 total).

TOTAL ENERGY FOOTPRINT

The total footprint energy per capita (Figure 4.7) is obtained by combining the regression of E_{hh} per capita (Figure 4.3 a) and the regression of I_{fc}^K (Figure 4.4 c), multiplied by final consumption per capita. The black line of Figure 4.7 is not linear because regions have a different share of final consumption in their GDP. Together, these two dynamics explain the differences in the total footprint per capita between regions with a R^2 of 0.88 (Figure 4.7).

Economic growth is sometimes considered useful to reduce energy use as it could drive technological progress, thereby reducing overall energy use (Bogmans et al., 2020). However, the first consequence of economic growth is to produce more goods and services. We quantify the regional increase in energy footprint per capita due to 1% of economic growth for the year 2017, independently of technological progress (Figure 4.8). In 2017, 9.2% of global population still lived in extreme poverty (World Bank, 2020b). We show that the energy associated with 1% of economic growth is 27 times higher in the richest region studied than in the poorest, meaning that supplementary energy use would have much more impact if used for the Global South than for the Global North. This corroborates similar work on carbon emissions which has shown that eradicating world poverty would increase global carbon emissions by less than 2.1% (Bruck-

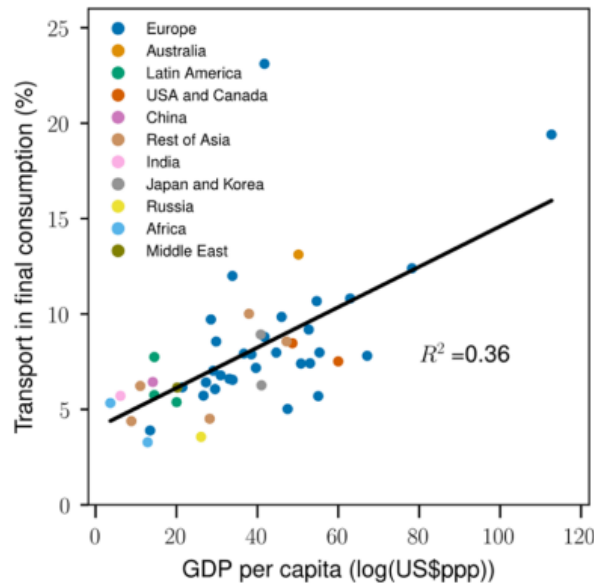


FIGURE 4.6: Share of transport sector in final consumption expenditures versus affluence. The black line represents the linear fit. The 11 other sectors are not displayed as we obtained $R^2 < 0.2$.

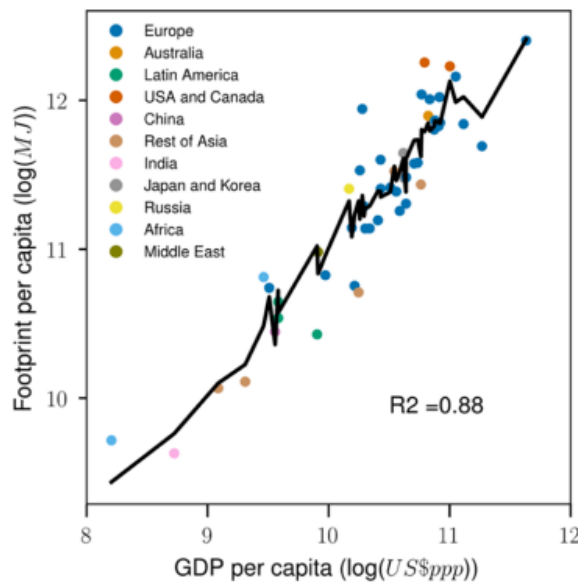


FIGURE 4.7: Total footprint energy per capita. Total footprint energy per capita scales with affluence ($R^2 = 0.88$). The black line is obtained by summing E_{hh} per capita from the regression of Figure 4.4 a and E_{fc}^K from the regression of Figure 4.4 e multiplied by the final consumption expenditure per capita. Inspired by Csereklyei et al. (2016).

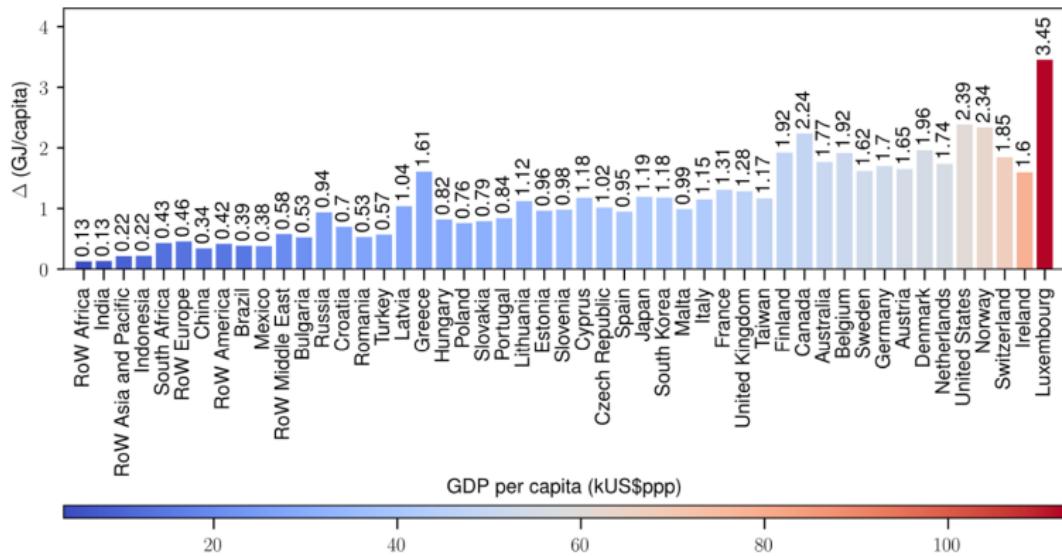


FIGURE 4.8: Energy per capita associated with 1% of economic growth. Bars represent the increase of energy footprint per capita if a region's GDP increases by 1% for year 2017, that is, without technological progress associated with time.

ner et al., 2022) or that a recomposition of consumption could reduce by 16% overall emissions while allowing a rise in consumption for those earning the less (Millward-Hopkins et al., 2020). Equity in energy use would reduce poverty and shift energy use from luxury and transport to subsistence and necessities (Oswald et al., 2021).

IMPLICATIONS FOR ENERGY TRANSITION SCENARIOS

Conceptually, the energy intensity of final consumption calculated by using sectoral PPPs and considering capital goods is the most interesting definition of energy intensity as it is the closest to the thermodynamic meaning of embodied energy. This indicator increases with GDP per capita, meaning that richer regions are less efficient than poorer ones. This contradicts the common belief that a higher GDP is correlated with a better efficiency and corroborates the existing research questioning the plausibility of a break in the historical energy intensity trend (Brockway et al., 2021; Semieniuk et al., 2021; Andrieu et al., 2022a). Though the potential of improvement is still considerable (Nakićenović et al., 1996; Cullen et al., 2011), economy-wide rebound effects (Sorrell and Dimitropoulos, 2008; Brockway et al., 2021), costly investments (Fowlie et al., 2018; Gillingham and Stock, 2018), and adaptation to climate change (van Ruijven et al., 2019) may limit our ability to reduce energy intensity as fast as it is planned in reference scenarios (Semieniuk et al., 2021).

We call for the authoritative scenario makers to stop speculating on energy intensity reduction and to produce prudential scenarios in which environmental and social targets are met, no matter the energy intensity. Mathematically, it means that some regions must be prepared to limit their economic growth. Energy scenarios must focus on sufficiency (Millward-Hopkins et al., 2020) in order to meet everyone's basic needs (Grubler et al., 2016; Rao et al., 2019), even if this implies limiting the luxury consumption of a rich minority (Oswald et al., 2020). The choice of the regions whose economic growth must be limited should take place in the context of common but differentiated responsibilities to tackle climate change (UNFCCC, 1992) and within a specific framework of energy justice (Sovacool et al., 2016). A solution could be to

achieve absolute convergence between Global South and Global North energy use per capita (Hickel et al., 2022a). We go even further and argue that the Global South must temporarily have more access to energy per capita to build the infrastructure already built in the Global North (Vidal et al., 2021). If there is a break in the historical data due to breakthrough technologies, then growth in every region could become an option again but climate action would not have been jeopardized by exogenously fixed economic growth.

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