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Coupling models to understand the interactions between energy transition and macroeconomic dynamics

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«Ideas of economists and political philosophers [...] are more powerful than is commonly understood. Indeed, the world is ruled by little else.»

John Maynard Keynes

The General Theory of Employment, Interest and Money (1936)

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Abstract

THE global shift towards carbon-neutral energy systems necessitates in-depth, forward-looking analysis and modelling, motivated by the scale and multifaceted nature of the transformations at hand. This thesis examines the coupling of macroeconomic models and energy system models to generate policy-relevant insights into the dynamics of the energy transition. Such integrative approach reveals new dynamics and trajectories that would remain hidden if each model were considered in isolation.

On one hand, macroeconomic models answer the questions which matter to policy makers: what are the implications of the energy transition in terms of inflation, aggregated investment, consumption, public debt and deficit, etc. ? On the other hand, energy system models provide information on the energy technologies to implement and their characteristics. They offer detailed figures for energy system costs and project the trajectory of these costs over the course of the transition to carbon neutrality. By focusing on technical feasibility, these models impose constraints on macroeconomic models, thereby anchoring them within the broader biophysical context. This integration ensures that economic analyses remain aligned with the practical and material limitations of the transformation of the energy system.

The fields of ecological macroeconomics and net energy analysis, to which several of the models used in this thesis belong, are presented. A hard-linking is then performed between a stock-flow consistent (SFC) macroeconomic model calibrated at the global scale and a stylised energy model 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. The resulting coupled model is used to address the following question:

What would be the macroeconomic dynamics of a rapid global energy transition, compatible with the Paris Agreement?

We find that the completion of a global energy transition 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. Potential bottlenecks and supply constraints are a major determinant of the related dynamics.

The second and last coupling focuses on the transition of an individual country. It consists in a bi-directional soft-linking between a macroeconomic model representing a small developing economy with an open financial account and an energy system optimisation model. The coupled model is applied to the case of Colombia to investigate the question:

How can the macroeconomic dynamics of an emerging, fossil fuels exporting economy be affected by its domestic energy transition ?

The simulation results especially highlight the joint dynamics between the energy transition, cross-border financial flows and the national currency exchange rate. Overall, the results suggest that the Colombian domestic energy transition, after a ramp-up during its first decade, can have significant macroeconomic impacts, positive or negative depending on the chosen strategy. Based on this pioneering work, several avenues for future research are put forward, to refine the feedback loops in our model of the economy-finance-energy system.

Keywords
Ecological economics; Energy transition; Model coupling; Stock-flow consistent modelling; Energy system optimization model; EnergyScope; Energy return on investment.

Résumé

La transition mondiale vers des systèmes énergétiques neutres en carbone nécessite un important travail de modélisation et de prospective, du fait de la profondeur et du caractère multidimensionnel des transformations à l'oeuvre. Cette thèse examine le couplage de modèles macroéconomiques et énergétiques afin d'étudier les trajectoires croisées économie-énergie de la transition. Une telle approche intégrative révèle de nouvelles dynamiques qui restent cachées lorsque chaque modèle est considéré individuellement.

D'une part, les modèles macroéconomiques permettent de répondre aux questions qui importent aux décideurs politiques : quelles sont les implications de la transition énergétique en termes d'inflation, d'investissement, de consommation, de dette et de déficit public, etc. ? D'autre part, les modèles énergétiques fournissent des informations sur les technologies à déployer et leurs caractéristiques. Ils permettent de quantifier les coûts du système énergétique et d'anticiper l'évolution de ces coûts sur les multiples décennies que dure la transition. En se concentrant sur la faisabilité technique, ces modèles imposent des contraintes aux modèles macroéconomiques, les ancrant ainsi dans un contexte biophysique plus large. Cette intégration garantit que les analyses économiques restent cohérentes avec les limites physiques et matérielles de la transformation du système énergétique.

Les domaines de la macroéconomie écologique et de l'analyse énergétique nette, dont font partie plusieurs des modèles utilisés dans cette thèse, sont présentés. Un couplage (*hard-linking*) est ensuite réalisé entre un modèle macroéconomique stock-flux cohérent (SFC) calibré à l'échelle mondiale et un modèle énergétique stylisé qui combine des estimations détaillées de la haute intensité capitalistique des énergies renouvelables et du taux

de retour énergétique (TRE) décroissant des énergies fossiles. Le modèle couplé est utilisé pour répondre à la question suivante :

Quelles seraient les dynamiques macroéconomiques engendrées par une transition énergétique mondiale rapide, compatible avec l'accord de Paris ?

Nous constatons que la réalisation d'une transition énergétique mondiale compatible avec l'objectif de 1,5°C de l'Accord de Paris entraîne une diminution du TRE du système énergétique et une augmentation significative de l'investissement agrégé, de l'emploi et de l'inflation. Les goulets d'étranglement potentiels et les contraintes d'offre sont un déterminant majeur des dynamique observées.

Le deuxième et dernier couplage se concentre sur un seul pays. Il consiste en un couplage (*bi-directional soft-linking*) entre un modèle macroéconomique représentant une petite économie en développement avec un compte de capitaux ouvert et un modèle d'optimisation du système énergétique. Le modèle couplé est appliqué au cas de la Colombie pour étudier la question :

Comment la trajectoire macroéconomique d'une économie émergente exportatrice de combustibles fossiles peut-elle être affectée par sa propre transition énergétique ?

Les résultats de simulation mettent particulièrement en évidence les dynamique conjointes entre la transition énergétique, les flux financiers transfrontaliers et le taux de change de la monnaie. Dans l'ensemble, les résultats suggèrent que la transition énergétique nationale colombienne a peu d'impact macroéconomique au cours de la première décennie, mais qu'elle peut avoir des effets significatifs, potentiellement positifs ou négatifs selon la stratégie adoptée, pendant le reste de la transition. Sur base de ce travail pionnier, plusieurs pistes de recherche futures sont proposées pour affiner les boucles de rétroaction dans notre modèle du système économie-finance-énergie.

Mots-clefs
Economie écologique; Transition énergétique; Couplage de modèles; Modèle stock-flux cohérent; Modèle d'optimisation du système énergétique; EnergyScope; Taux de retour énergétique.

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Acronyms and abbreviations

ABM	Agent-Based Modelling (p. 30)
AFD	French Agency for Development (p. 29)
CBAM	Carbon Border Adjustment Mechanism (p. 34)
CCDR	Country Climate and Development Report (p. 89)
CEPCI	Chemical Engineering's Plant Cost Index (p. 78)
CES	Constant Elasticity of Substitution (p. 21)
CGE	Computable General Equilibrium (p. 8)
CMA-ES	Covariance Matrix Adaptation-Evolution Strategy (p. 111)
COP	Colombian Peso (p. 182)
CSP	Concentrated Solar Power (p. 78)
DNP	Departamento Nacional de Planeación (p. 77)
DSGE	Dynamic Stochastic General Equilibrium (p. 8)
DSK	Dystopian Schumpeter meeting Keynes (p. 31)
E3ME	Energy-Environment- Economy Model for Europe (p. 33)
ECB	European Central Bank (p. 8)
EM	Ecological Macroeconomics (p. 3)
eos	elasticity of substitution (p. 21)
EROI	Energy Return On Investment (p. 3)
ESOM	Energy System Optimisation Model (p. 5)
ESTD	EnergyScope Typical Day (p. 77)
EU	European Union (p. 14)
EUD	End-Use Demand (p. 80)

FE — Final Energy (p. 82)

FOF — Flow-of-Funds (p. 137)

GDP — Gross Domestic Product (p. 14)

GEMMES — General Monetary and Multisectoral Macrodynamics for the Ecological Shift (p. 29)

GFC — Global Financial Crisis (p. 12)

GFCF — Gross Fixed Capital Formation (p. 55)

GHG — Greenhouse Gases (p. 43)

GMRIO — Global Multi-Regional Input-Output (p. 54)

HANK — Heterogeneous Agents New Keynesian (p. 20)

IAM — Integrated Assessment Model (p. 22)

ICP — International Comparison Panel (p. 54)

IMF — International Monetary Fund (p. 8)

IO — Input-Output (p. 10)

KLEM — Capital, Labour, Energy and Materials (p. 21)

NDC — Nationally Determined Contribution (p. 79)

NEA — Net Energy Analysis (p. 3)

NK — Neo-Keynesian (p. 9)

NPL — Non-Performing Loans (p. 18)

OECD — Organisation for Economic Co-operation and Development (p. 10)

PD — Probability of Default (p. 18)

PEN — National Energy Plan (p. 79)

PESTD — EnergyScope Pathway using Typical Days (p. 77)

PPP — Purchasing Power Parity (p. 54)

PWT — Penn World Tables (p. 55)

R&D — Research and Development (p. 31)

RBC — Real Business Cycle (p. 8)

SAM — Social Accounting Matrix (p. 10)

SFC — Stock-Fow Consistent (p. 25)

TCFD — Task Force on Climate-Related Financial Disclosures (p. 34)

TEMPLE — Tilting Economic Momentum for Progress to Low-carbon Energies (p. 48)

TFM — Transaction Flow Matrix (p. 137)

URR — Ultimately Recoverable Resource (p. 42)

USD — United States Dollar (p. 78)

VRE — Variable Renewable Energy (p. 77)

WILIAM — Within Limits Integrated Assessment Model (p. 32)

WWII — World War II (p. 62)

List of publications

The introduction of this thesis partly builds on a (forthcoming) working paper:

> Tenreira, L., van Zeben, J., Beckers, A., Laurent, B., Pitteloud, S., Jacques, P., Alayrac, P., Reveillere, V., Mourlon-Druol, E. & Azoulai, L. (2024). *"Unpacking the Green Deal: Redefining approaches, shifting methodologies."* EUI LAW Working Paper (forthcoming).

for which Pierre Jacques is in charge of writing – original draft; writing – review & editing.

Chapter 2 draws on the following working paper:

> Souffron, C. & Jacques, P. (2024). *"A successful assessment of the economic impacts of ecological transition policies in the EU requires the European Commission to broaden the range of its modelling tools."* Available at SSRN: `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4640677`

for which Pierre Jacques was in charge of conceptualisation; writing – original draft; writing – review & editing; project administration.

The first part of Chapter 3 is adapted from an extract of the peer-reviewed journal publication:

> Delannoy, L., Auzanneau, M., Andrieu, B., Vidal, O., Longaretti, P.-Y., Prados, E., Murphy, D. J., Bentley, R. W., Carbajales-Dale, M., Raugei, M., Höök, M., Court, V., King, C. W., Fizaine, F., Jacques, P., Heun, M. K., Jackson, A., Guay-Boutet, C., Aramendia, E., Wang, J., Le Boulzec, H. & Hall, C. A. (2024). *"Emerging consensus on net energy paves the way for improved integrated as-*

sessment modeling." In Energy & Environmental Science (Vol. 17, Pages 11-26). URL: `https://pubs.rsc.org/en/content/articlelanding/2024/ee/d3ee00772c`

for which Pierre Jacques was in charge of writing – review & editing.

Finally, the following peer-reviewed journal publication is reproduced by parts in Section 2.3.1 of Chapter 2, in the second part of Chapter 3 and in Chapter 4:

> Jacques, P., Delannoy, L., Andrieu, B., Yilmaz, D., Jeanmart, H. & Godin, A. (2023). "*Assessing the economic consequences of an energy transition through a biophysical stock-flow consistent model.*" In Ecological Economics (Vol. 209, Page 107832). URL: `https://www.sciencedirect.com/science/article/pii/S0921800923000952`

This research was led by Pierre Jacques, who was in charge of conceptualisation; data curation; methodology; modelling and results; formal analysis; writing – original draft; writing – review & editing; project administration.

Chapter 6 is currently being adapted for publication in a peer-reviewed journal:

> Jacques, P., Augier, S., Barbosa, S., Yilmaz, D., Jeanmart, H. & Godin, A. (2024). "*Coupling a stock-flow consistent macroeconomic model with an energy system optimisation model to study the impacts of the energy transition in Colombia.*" (to be submitted to Energy Economics).

This research is led by Pierre Jacques, who is in charge of conceptualisation; data curation; methodology; modelling and results; formal analysis; writing – original draft; writing – review & editing; project administration.

The following publication is not presented in the thesis.

In a peer-reviewed journal publication, we presented an extension of the EnergyScope TD model incorporating the EROI metric. The impact of the energy transition in Belgium on that metric was analysed in the publication:

> Dumas, J., Dubois, A., Thiran, P., Jacques, P., Contino, F., Cornélusse, B. & Limpens, G. (2022). "*The energy return on investment of whole energy systems: application to Belgium*". In Biophysical Economics and Sustainability, (Vol. 7, 12). URL: `https://doi.org/10.1007/s41247-022-00106-0`

for which Pierre Jacques was in charge of conceptualisation; writing – original draft; writing – review & editing.

1
Introduction

MODELS are central to economics. Some economists even consider that it is the use of models that distinguishes economics from other social sciences and makes it a discipline in its own right (Rodrik, 2015). Models enable economists to propose explanations for observed economic phenomena, to reason as they would in an ordinary discussion, but within the constraints of a mathematical formalism. Such formalism ensures transparency and coherence in the reasoning. In macroeconomics, the use of mathematical models also makes it possible to describe complex systems and to envisage the resultant of multiple contradictory effects, which would sometimes be impossible through a thought experiment alone.

In practice, macroeconomic models are an essential tool for policy design and analysis. While policy makers would ideally dispose of experimental settings to test their policies in lab conditions before enforcing them in the real world, performing such large-scale experiments is generally unfeasible (or unethical). Macroeconomic models are thus used as a second-best choice: they represent in a simplified way, within a computer system, the society or economy under consideration. Disposing of such a tool allows policy makers to perform "what if" analyses: alternative policies are imposed on the model and the economic evolutions which result from them can be observed and analysed (Pollitt, 2018).

Engineers also use models. Like economists, their models are idealisations of the real world. They are linked to a particular purpose or application, as opposed to theories which are more abstract and general (Hansson, 2007). Yet, engineering models differ from economic models in several ways. First, the object of study is typically much simpler and more predictable in engineering. Physical systems tend indeed to present more regular behaviours than human beings and societies. Second, engineering models often build on universal laws from physics (e.g. conservation of mass, the first and second principles of thermodynamics) and their consistency with respect to these laws can be verified. On the contrary, it is hard to define any "universal economic law" which would be applicable to any situation, since human behaviour relies heavily on culture, local context and history. Third, engineering models can be validated by devising appropriate experiments, while it is much less the case for economic models, or at least macroeconomic models which describe an entire society. For these reasons, engineering models prove to be more robust and to provide much higher predictive capabilities than macroeconomic models. Hence, macroeconomic models can sometimes be disconcerting for an engineer and rather look like *"advanced story-telling"* compared to the tools he is accustomed to.

Moreover, by highlighting certain mechanisms in their description of the economy and downplaying others, macroeconomic models carry a particular worldview. Depending on the assumptions made, macroeconomic models will be closer to one political current or another. The choice of macroeconomic model to inform decision-making is therefore non-neutral. This theoretical choice will, from the very start, determine part of the recommendations emanating from the model used. As illustrated by Heimberger et al. (2020), *"economic models can serve as a transmission device between economic paradigms and policy programs, which allow actors drawing on the model to exercise power in decision-making"*, in a way *"mostly concealed from the public discourse"*. Hence, macroeconomic models do not merely act as descriptive or experimental instruments: they provide a normative vision of economic mechanisms and of possible economic policies[1].

[1]Note that engineering models too carry a certain worldview, subjectivity and normativity, but to a much lesser extent than macroeconomic models.

The transition of economies around the world to carbon-neutrality, given the scale and the complexity of the challenge, will require a substantial amount of forward-looking analysis and modelling. Having in mind the role which models play in decision-making, we investigate in this thesis how macroeconomic and engineering models can be integrated to provide useful insights into the dynamics of the energy transition. More specifically, the engineering models used in this work are models of the energy system, which namely provide information on the energy technologies to implement and their characteristics. On one hand, this information allows to feed macroeconomic models with precise figures about the cost of the energy system, and most importantly about how this cost evolves throughout the transition to carbon-neutrality. On the other hand, the energy models, by focusing on technical feasibility, provide constraints to the macroeconomic models and contribute to embedding them into the larger biophysical reality, in the spirit of the landmark modelling work of Meadows et al. (1972). This idea that the economic system is only a sub-set of a larger system governed by biophysical laws is the founding principle of the field known as ecological economics. In this thesis, we are more specifically interested in the sub-field of *ecological macroeconomics* (EM). Although EM have been building experience for decades now, the related models are still under-used for policy making in public institutions. Chapter 2 therefore tries to answer the question:

Do models from ecological macroeconomics have a role to play in policy making ?

To provide an answer to this question, the classes of models currently used for economic policy making in public institutions are presented. Then, the challenges faced by these models are presented and the adequacy of several state-of-the-art EM models to address these challenges is discussed.

Chapter 2 presents the characteristics of EM models mainly in terms of their core economic structure. It leaves out one key particularity of Ecological Macroeconomics: the embedding of the economy into a larger biophysical system, which is explicitly modelled and provides constraints to economic growth. Energy constraints, in particular, can become stringent. The field of Net Energy Analysis (NEA), dedicated to the study of these constraints, has seen an important development since the invention of the Energy Return On Investment (EROI) metric in the 1970s. However, controverses and a lack of standardisation have prevented NEA results to be taken into account in any major report about the low-carbon transition. The first question addressed in Chapter 3 is thus:

Is there a current consensus in Net Energy Analysis, based on which useful insights can be drawn for the low-carbon transition ?

Beyond energy accessibility constraints and the EROI metric, other constraints are also considered in Chapter 3, such as energy availability, materials and waste. These constraints are examined through the lens of the following question:

What is the current state of the art of the integration of biophysical constraints into ecological macroeconomic models ?

After having investigated the potential role for EM models in policy making (Chapter 2) and identified the current literature gaps in the field (Chapter 3), the rest of the thesis adopts a more technical approach. Staying within the paradigm of ecological macroeconomics, couplings between macroeconomic models and models of the energy system are performed. Such couplings help to address blind spots present in each category of models. Besides, the coupled models allow to represent in one single framework the intertwined dynamics between the energy system, the economy and the financial system. By doing so, new dynamics and trajectories emerge, which would not be visible through the lens of one or another model taken individually. Identifying these intricate dynamics is key to the successful planning of the energy transition and constitutes the main objective of Chapters 4 and 6.

A coupling between a macroeconomic and an energy model can be performed in many different ways. They are classified in the literature between two broad categories: hard-linking and soft-linking. In hard-linking, the two models are merged into one single set of equations while in soft-linking, the models are kept apart but exchange and process information from each other. Both types of coupling present their own advantage. On one hand, hard-linking favours analytical coherence but often requires to profoundly change the original models. On the other hand, soft-linking allows to preserve all details and richness of the coupled models. Overall, both types of coupling require a significant amount of work. They are both employed in this thesis, but for two different applications.

The two macroeconomic models used in this thesis are top-down models which share a very similar structure. First, the world model presented in Augier (2019) is used, which draws on the structure of Bovari et al. (2018a). The second model to be coupled is the GEMMES model described in Godin and Yilmaz (2020). This model presents the same core equations as the one from Augier (2019), but represents a single country instead of the global economy. This multiplies the number of equations and hence greatly increases the model complexity, since all cross-border flows are explicitly accounted for. The two energy models used in the thesis, in turn, are bottom-up models which come from two distinct categories: models from the field of net energy analysis (NEA) and Energy System Optimisation Models (ESOMs).

Chapter 4 presents a hard-linking between a stylised energy model building on NEA metrics (Dupont et al., 2018, 2020) and the macroeconomic model of Augier (2019). The goal of this work is to answer the following question:

What would be the macroeconomic dynamics of a rapid global energy transition, compatible with the Paris Agreement?

Then, Chapter 5 presents the adaptation of the ESOM EnergyScope to the specific cases of Colombia and Turkey. Additions are made to the model and preliminary insights into the energy transition in these two countries are drawn. The impact of macroeconomic parameters on the model's results are also discussed, to pave the way for the coupling of EnergyScope with a macroeconomic model.

Such coupling comes in Chapter 6, where a bi-directional soft-linking is performed between GEMMES and EnergyScope. The modifications applied to both models in the context of the coupling are presented, together with the coupling methodology. The resulting model is then used to address the following question, via the case study of Colombia:

How can the macroeconomic dynamics of an emerging, fossil fuels exporting economy be affected by its domestic energy transition ?

Finally, Chapter 7 recapitulates the main outcomes of the thesis and paves the way for future research.

To complement Chapters 4, 5 and 6, Appendices A, B and C, respectively, present the details of the models used. The structure of the codes used in Chapters 5 and 6 is further described in Appendix D.

2

Do models from Ecological Macroeconomics have a role to play in policy making ?

CONTEMPORARY societies are marked by a major environmental, social, economic, geopolitical polycrisis, which requires a profound transformation of the global economy (Lawrence et al., 2024). Pledges towards such transformation have been taken by the vast majority of governments through the process of the climate and biodiversity COPs. Yet, reaching those goals will require a substantial amount of forward-looking analysis and modelling. For decades, the perspective of the ecological transition has specifically fostered the development of a field known as Ecological Economics. Several macroeconomic models of the field (i.e. Ecological Macroeconomics (EM) models) have now reached a sufficient level of maturity to be used directly for policy making. However, EM models are currently little used by governments and international organisations for macroeconomic analysis in the light of the ecological transition. In particular, the discussion developed below is built based on the scrutiniy of macroeconomic modelling in European institutions. We observe that in this context, macroeconomic analysis is overwhelmingly conducted using models rooted in general equilibrium theory, especially Dynamic Stochastic

General Equilibrium (DSGE) and Computable General Equilibrium (CGE) models. One can therefore ask whether EM models have anything to bring to (European) policy making. In this chapter, we argue that EM models have an important role to play. Not only do they avoid common pitfalls faced by general equilibrium models, they are also becoming increasingly relevant as the ecological transition is gathering steam and the economy is being destabilised by climate change impacts. Section 2.1 provides a brief overview of DSGE and CGE models currently dominant in policy making. Section 2.2 highlights a list of challenges encountered by these models classes and points how the ecological transition and environmental degradation are further exacerbating these shortcomings. Section 2.3 then presents the field of EM, as well of a list of advanced models which could directly be used in policy making. The robustness of these models to the challenges outlined in Section 2.2 is also discussed.

2.1 A brief theoretical description of DSGE and CGE models

DSGE and CGE models have emerged from the academic literature of recent decades to become widely used by international and national public institutions (e.g. IMF, World Bank, ECB, US Federal Reserve). Let us start by pointing out that there is no "standard" DSGE or CGE, even though these model classes can be found in stylized forms in advanced textbooks for graduates. Each institution generally develops its own variants of these models. We will therefore attempt to refer both to the historically "canonical" models and to the models currently in use. While DSGEs and CGEs are both based on General Equilibrium modelling[1] (following the seminal work of Frisch, Johansen, Leontief, Chenery, Von Neumann and Scarf in the 1950s and 1960s), they have their differences and do not respond to the same needs and issues.

DSGEs are a more recent category of economic models, used to analyse economic fluctuations and economic policies. They were developed in the wake of the RBC (Real Business Cycle) models and in response to Lucas' critique. This critique can be summarised by the idea that macroeconomic models can be relevant for policy making only if they incorporate the rational expectations of agents and their resulting behaviour in response to these policies (Lucas, 1976). DSGEs are thus characterised by the use of "microfoundations". That is, they are based on the optimal microeconomic behaviour

[1]Meaning that general equilibrium is included in these models as a (core) assumption.

(i.e. rational maximisation under constraints) of representative economic agents such as households and companies. In a DSGE model, agents make decisions based on their expectations about the future, and these decisions influence macroeconomic variables such as output, employment, consumption, investment and inflation. DSGE models also incorporate exogenous random shocks (hence the stochastic character) that can affect the economy, such as technology, productivity, demand or monetary policy shocks. These shocks are modelled as stochastic perturbations of the model equations, and may have persistent effects on the economy due to the model dynamics. DSGE models are solved numerically and calibrated or estimated using economic data, often in a Bayesian fashion. This is for example the case for the model of Smets and Wouters (2007), published as an ECB working paper and often regarded as canonical.

Nowadays, DSGE models are increasingly coming with a New Keynesian (NK) coloration. It consists in the addition of frictions, rigidities and sticky prices and wages, asymmetric access to financial markets, market imperfections and agent heterogeneity. Such additions lead to different transitory and long-term results. They can notably imply a short-term non-neutrality of money. They also leave room in the model for expansionary public policies. This NK coloration has become widespread since Christiano et al. (2005), for example through heterogeneous agent models (see e.g. Galí and Gertler, 1999; Galí, 2018). For a recent review of DSGEs with numerous references, see Lindé et al. (2016).

CGE models are economic models used to simulate the impact of changes in economic policy, technology or other external factors, either on the economy as a whole or on specific sectors. Mainly developed since the 1970s at the World Bank, these models examine how supply and demand interact in different markets to determine prices and quantities of goods and services. CGE models are characterised by a detailed representation of the economy, including a disaggregation into several sectors, agents and markets. They take into account the interactions between these, whether in terms of flows of goods between sectors or in terms of elasticities of substitution. In a CGE model, the economy is represented by a set of equations describing production, consumption, exchange and price formation. Economic agents, such as households, firms and government, are modelled as optimisers who make decisions based on prices, income and technological constraints, again based on the theory of rational behaviour. CGE models are solved by finding the set of prices and quantities that balance supply and demand in all markets, taking into account government policies and external shocks. They are generally calibrated on a "base year", on which everything is assumed to be in equilibrium. A CGE model is first benchmarked with disaggregated data from the Input-Output (IO) tables of the national accounts through Social Accounting Matrices (SAM). Technical and behavioural relationships linked to the general equilibrium theory are then added to the model[2]. Unlike DSGEs, CGE models usually are recursive and do not include forward-looking intertemporal optimisation; if they do, they cannot always be solved intertemporally. CGEs were originally static, but are becoming increasingly dynamic (Babatunde et al., 2017). For an example of a canonical dynamic recursive environmental CGE model, see namely ENV-Linkages of the OECD (Château et al., 2014).

2.1.1 Uses and purposes of DSGEs and CGEs

DSGE models offer a very high level of aggregation and stylization of economic agents, variables and phenomena. They are mainly used to study economic fluctuations, as well as monetary and fiscal policies and their impact on the former. They serve to make macroeconomic forecasts on economic aggregates such as unemployment, general inflation, economic growth or the rate of change of wages. Based on an intertemporal optimisation framework on the part of representative agents, DSGEs also aim to derive "optimal" trajectories for public policies. They are widely used by central banks, financial institutions and public Treasuries to formulate monetary and budgetary policies, as well as for forecasting. In the context of the ecological transition, DSGEs are either used to study the impact on growth, consumption, production and investment of environmental policies, including taxes, subsidies and regulation (e.g. Coenen et al., 2024; Zhao and Tang, 2024), or to deduce "optimal" emission and carbon cost trajectories (Golosov et al., 2014; Hambel et al., 2021). Macroeconomic fluctuations in those models are triggered (only) by "exogenous shocks" and the optimal reactions of agents under constraints to these shocks.

CGE models, on the other hand, are disaggregated, multi-sector models, designed to study the production and trade of each sector and the interdependencies within the economy. Often very broad, they are used to assess

[2]Actually, one can think of a CGE as a traditional IO model, onto which is grafted general equilibrium à la Walras / Arrow-Debreu with price rather than quantity adjustment, optimisation behaviours, and elasticities representing preferences and technologies.

the impacts of changes in economic, fiscal (especially taxes and subsidies), commercial, environmental and technological policies. Those impacts are studied on each sector and on the economy as a whole, together with the potential distortions and direct and indirect effects arising from them. By using national accounting data through Social Accounting Matrices (SAM), CGEs can study the allocative and redistributive effects of policies on households and businesses. They can also endogenize technology, to study its determinants, or to study how technology itself is a determinant of growth and structural change. Contrary to DSGEs, their aim is not to deduce optimal dynamic policies, but to study the impact of *ad hoc* policies on the economy. In the context of increased environmental regulation, CGEs have been applied since the 1990s to study the specific impacts of tax-type policies. They were namely used to compute the social cost of complying with the Kyoto Protocol (externality CGEs, e.g. Böhringer and Rutherford, 2010). The modeled impacts can be on the concerned sector or, through substitution elasticities, on other sectors, as well as on endogenous technological evolution or on the consumption of different resources (e.g. Gao et al., 2024).

The two classes of models thus rely on different methodologies to answer different but complementary questions, with distinct temporalities and different levels of aggregation.

2.2 Challenges faced by CGE and DSGE models in the light of the ecological transition

Although useful for the design of economic and environmental policies, CGE and DSGE models face certain theoretical, methodological and practical challenges. Such limitations are non-trivial, especially in the context of the ecological transformation. The aim of this section is therefore to present a constructive summary of these challenges, which have been underlined by regular users and designers of these model classes. Section 2.3 subsequently presents diverse solutions in the form of existing modelling tools from the field of Ecological Macroeconomics.

A large number of criticisms, well documented, have long been levelled at both DSGE and CGE models, including by leading researchers, practitioners, users and developers, among others for their failure to forecast and predict financial and economic crises like the Global Financial Crisis (GFC) of 2008. With regard to the DSGEs, Vines and Wills (2018) conducted a survey in the framework of the Rebuilding Macroeconomic Theory Project, asking leading macroeconomists to describe how the canonical NK DSGE models could be rebuilt following the 2008 crisis. Their findings confirmed the need for a change in macroeconomic theory, implying a more pluralistic discipline. By way of significant examples, Blanchard (2016), former IMF chief economist, in an article entitled "Do DSGE Models Have a Future?" considers them to be *"seriously flawed"*, due to (i) assumptions that are not only unrealistic but also in conflict with empirical knowledge about firms and consumers, whether for the Euler equation or Calvo pricing (in the aggregate demand and forward-looking price adjustment equations); (ii) major problems of calibration and (now mostly Bayesian) estimation; (iii) problems of use for normative purposes, particularly in terms of welfare functions and the optimality of trajectories and policies; and (iv) the inability to communicate to the reader the results of policies and distortions introduced on a really heavy algebraic structure, and the proper causality. He concludes by recommending that DSGEs become less *"insular"* and less *"imperialist"* and need to be integrated into a much broader and complementary ecosystem of economic models. In his view, *ad hoc* aggregate equation models and structural equation models (e.g. Blanchard and Bernanke, 2023) have an important role to play, both upstream and downstream.

Kocherlakota (2016, 2018), former President of the Minneapolis Fed, argues that in an institutional and public policy design framework, macroeconomic evaluation, to be of any practical value, should be based on a regression-based approach with past macroeconomic data rather than on putative structural models. Mankiw (2006); Solow (2010); Romer (2015, 2016); Stiglitz (2018) make similar and complementary criticisms. They identify problems caused by rational expectations (making those models to be estimated sometimes more *ad hoc* than previous macroeconometric equation models). These classes of models, they claim, favour analytical coherence of a specific and chosen theory, generally at the detriment of their relevance for studying reality and recommending policies.

Similarly, CGE models are better suited for applying economic theory than for testing it - what is referred to as the *"bridge perspective"* by Bergman (2005). They are based on strong, normative theoretical choices, such as the general equilibrium framework, where perfect flexibility of prices and quantities ensures the existence of an equilibrium. Thus, CGEs tend to provide a normative vision of economic mechanisms and even of possible economic policies, instead of testing them. This is all the more important since, as the literature review by Ji et al. (2022) shows, *"reflections on environmental policy instruments have shifted from command-based to market-based"* and *CGE model promotes the shift*. Nevertheless, it should be noted that recent CGEs gradually include the possibility of imperfect competition, disequilibria and involuntary unemployment.

It is important to emphasise that macroeconomic research, like any scientific discipline, is constantly evolving. It is clear that the models involved are also moving forward. More and more frictions and rigidities (nominal, real, financial) are added; the frameworks of pure and perfect competition are relaxed, and heterogeneity among agents is introduced (such as with HANK models (Alves et al., 2022) and Galí-Gertler-type models); the assumptions of perfect rationality are gradually replaced by bounded rationality (Beqiraj et al., 2018); and financial markets and market beliefs are sometimes added (e.g. Annicchiarico et al., 2022). Although positive, these transformations and additions are only partial and thus insufficient, especially in light of the current economic and environmental situation. In the following pages, we therefore attempt to review the challenges faced by CGEs and DSGEs.

2.2.1 Output gap framework

In standard DSGE and CGE models, economic variables converge by design towards structural ("natural") rates. This is typically the case for output and employment. Generally speaking, variations outside these structural values are only temporary (zero or very short time for original RBC type models, short or medium time for NK-type models à la Galí and Gertler, 1999). In this case, the temporary rise in production, the "output gap", is caused solely by the misinterpretation of inflation by producing agents, which is understood not as general but idiosyncratic (specific to the producers' asset). Producers will perceive a decrease in the relative price of their output, and will therefore invest and hire less, decreasing output and employment and thus closing this output gap. Thus, the output gap is defined as the difference between the real gross domestic product (GDP) of a country and the potential GDP that would be attainable if all production factors were used at "normal" capacity utilisation, i.e. at non-inflationary levels. Once firms have liquidated the overcapacity, equilibrium values are restored - the only difference being a higher general price level (the *"Island parable"* Phelps, 1969). Thus, economic policies tend to have no effect at all on real variables for RBCs, and no effect in the long term for NK DSGEs, except on price level. There is virtually no room for expansionary economic policies, or only temporary and for monetarist reasons (Sargent and Wallace, 1975). The fiscal policy has as its sole aim to stabilise the debt-to-GDP ratio towards the target and limit fluctuation of fiscal deficit. Thus, fiscal consolidation is generally deduced from the output gap, a policy that has already led to weak domestic demand in the European Union (EU) and weak output (Fatás and Summers, 2018; Fatás, 2019)[3]. The transition towards a carbon-neutral economy nonetheless implies profound changes, which can only be achieved with the support of proactive green economic policies on the part of governments (Stern, 2022). It is essential for modelling tools to be able to represent and assess such active policies.

[3]In the EU, the European Commission uses an output gap model as the core of its fiscal surveillance of member states. However, there is a self-prophetic effect of pessimistic estimates of potential outputs, particularly after crises, for example that of 2008, following which estimates were very pessimistic and which, through negative loops, led to fiscal consolidation and austerity policies, partially confirming the pessimistic estimates and leading to increasing public debt-to-GDP ratios through the negative impact on output, instead of reducing public debt (Fatás and Summers, 2018; Fatás, 2019). This confirms the pro-cyclical and self-defeating nature of fiscal consolidations (DeLong and Summers, 2012).

Despite being a theoretical construct which is not observable (or, at least, whose structural parameters identification remains questionable), the output gap is generally still at the core of macroeconomic modelling. However, NK models, which are more and more widespread, introduce a set of more realistic assumptions: price viscosity, nominal and real rigidities, imperfect information and markets, liquidity constraints (e.g. Galí et al., 2007), as well as a Taylor rule for monetary policies. These adaptations restore the possibility for expansionary policies to have an impact in the models, at least in the short term.

2.2.2 Equilibrium framework and Say's Law

Standard macroeconomic modelling, including CGEs and DSGEs, is based on an equilibrium framework, not as a result but as an assumption. Blanchard (2018) puts forward as a *"widely believed proposition"* with *"a wide agreement"* that *"Macroeconomics is about general equilibrium"*. This framework, in addition to eliminating numerous real dynamics, prevents the modelling of a central and fundamental empirical fact: fluctuations that are endogenous to the economic system, in the absence of exogenous shocks. Indeed, macroeconomic variations in those models are not endogenous but caused by exogenous shocks, real or monetary. DSGEs then focus on equilibria that are stationary linear fluctuations from those shocks. Therefore, macroeconomic fluctuations can be seen as the optimal response of the private sector to those shocks under constraints. This approach, beyond its lack of realism and the *ad hoc*, *ex-post* nature of the assumed shocks also prevents the modelling of persistent financial crises and economic recessions (e.g. massive and long-term unemployment). Eventually, DSGEs postulate from the outset (or adopt assumptions that necessarily lead to the built-in property) that there is a unique equilibrium, which is moreover locally stable – so that small exogenous shocks do not prevent the economy, after a small deviation, from returning back to the original steady state. By contrast, most of the specialised literature on General Equilibrium Theory from the 1990s' has shown these postulates to be only exceptionally valid (Ackerman, 2002). All these remarks are nonetheless widely documented empirically. It is therefore not excessive to require a model, especially within an institutional framework, that allows for (i) crises (with persistence and hysteresis) and (ii) endogenous, out-of-equilibrium fluctuations, even without exogenous "productivity shocks".

Even if some recent CGEs allow for imperfect competition and involuntary unemployment, most CGEs assume perfect price and quantity flexibility, which guarantees full utilisation of production factors at all times since the base year. Prices are market-derived and ensure the existence of an equilibrium. Assuming equilibrium and market clearing in those CGE models amounts to postulating Say's Law i.e. that demand always adjusts to match exactly the level of output in the economy. Such an assumption has been broadly questioned (Shaikh, 2016) and empirically contested, namely in the aftermath of the 2008 crisis (Yellen, 2016), and in terms of relevance (Kornai, 1971). Moreover, Say's Law implies that the economy always operates at full capacity (CGEs assume capital is fully utilised in the baseline scenario). Investments related to the green transition can only displace or "crowd-out" other economic activity in the model, making it deviate from the optimal path and thus resulting in economic costs or losses. The claim that the economy would be operating at full capacity is highly contested. On the contrary, several works point at the potential economic benefits brought by additional green spending, since they could allow to employ previously idle resources (Dwesar et al., 2022). Models should therefore allow imbalances between supply and demand, with dynamic fluctuations, including the empirical role of demand on business cycle fluctuations (Andrle et al., 2017).

2.2.3 Neutrality and exogeneity of money

Money is not just a medium of exchange (Keynes, 1936); it also serves as a store of value linked to expectations, beliefs and precaution, a unit of account, and, most importantly, a driver of economic activity through its impact on liquidity, debt, and investment decisions (see Arestis and Sawyer (2006) for a survey). This has led to the idea of non-neutrality of money (Bernanke and Gertler, 1995; Christiano et al., 2005). This hypothesis has been empirically studied following Friedman and Schwartz (1963). While classical RBC and CGE models are models without money or only as a numeraire for relative prices and a proxy for the general price level, more recent CGEs and the current NK DSGEs are monetarist (since a monetary shock is always assumed to be inflationary and to lead to an idiosyncratic short-term increase by agents in the goods they produce, hence to a temporary rise in output). While money is neutral in the short and long term for classical RBC models, it is neutral only in the long run for NK DSGE models, in which money can have real short-term effects on output and employment due to price and wage rigidities, stickiness and adjustment times (see Mankiw and Romer (1991) for a standard illustration).

Moreover, considering money as exogenous overlooks the critical role that financial institutions play in money creation, allocation of credit, and thus in influencing economic cycles. A vast literature shows the endogeneity of money, including based on empirical demonstrations (e.g. McLeay et al., 2014; Myatt, 1986; Werner, 2014, 2016, by Granger's causality). Banks do not need to collect savings in order to lend them out, and the literature tends to show that their ability to issue credit is not constrained by the central bank's money supply through a "money multiplier". In fact, commercial banks obtain money from the central bank on demand, at the rate set by monetary policy. A tradition of models have been integrating money-creating banks where they pre-finance investments (e.g. Jakab and Kumhof, 2015). Such models often integrate short and even long term non-neutrality of money, and can be seen as monetary extensions of Solow's growth model (Van der Ploeg, 1985; Gertler and Kiyotaki, 2011).

2.2.4 Private debt and financial instability

The economic role of private debt, credit emission and financial markets, both in investment and in financial crises, has been widely documented (cf. work by Fisher, 1933; Minsky, 1977, 1986; Kindleberger and Aliber, 1978), from the Japanese stagnation to the 2008 GFC (Koo, 2009). High levels of private debt in the non-financial sector and rapid credit expansion can lead to financial instability and are good predictors for it (cf. *inter alia* Claessens et al., 2012; Drehmann et al., 2012; Gourinchas and Obstfeld, 2012; BIS, 2014; IMF, 2017; Gertler and Gilchrist, 2018; BIS, 2022). They reinforce macroeconomic cyclicality, especially from the moment when real income is insufficient to repay the leveraged loan (the so-called *"Minsky moment"*), for example during asset bubbles (Grasselli and Costa-Lima, 2012). Thus, models that integrate private debt can better analyse the implications of debt accumulation and deleveraging processes on economic stability.

However, including private debt is not sufficient when such inclusion is performed in a general equilibrium framework where, by construction and assumption, stabilisers lead to market clearing, capital readjustment and therefore to the drastic reduction in the possibilities of modelling financial crisis results. There is a need to include reinforcing feedbacks in the financial sector and amplification mechanisms which lead to out-of-equilibrium dynamics and therefore to massive financial crises and recessions (e.g. Krugman, 2009). Such additions are necessary if one wishes to simulate the post-2008 recession. Thus, a few NK models were modified to encompass not only private debt, but also further additions like a debt-limit and the deleveraging effect of shocks (Eggertsson and Krugman, 2012). Others were adapted to include monetary transactions and the possibility for default, so that monetary policy could affect the real output even with fully flexible prices (Giraud and Pottier, 2016). By doing so, they show the risk of the impact of rapid deleveraging on the emergence of Fisherian debt deflation (Fisher, 1933), a liquidity trap and a savings paradox. This calls for models to take into account financial assets and their counterparts, not just real assets. These assets must be modelled as stocks, and not only flows. This requires an integration of the financial mechanisms and drivers of these imbalances, notably banks probability of default (PD), non-performing loans (NPL), investors' balance sheets, pure speculative assets and a distinction between real resources and financial assets, as there is sometimes a confusion between them (cf. *infra*).

The integration of private debt is particularly justified in the context of the environmental crisis and ecological transition, as *"climate change can increase defaults with adverse effects on bank leverage ... can cause an asset price deflation process. Climate-induced financial instability reinforces the growth-reducing effects of climate change."* (Dafermos et al., 2018). On the one hand, the financial risk in the event of non-rapid-enough transition must be taken into account, in relation to the necessary investments for repairing the environmental damage undergone by the economy (Dietz and Stern, 2015; Bovari et al., 2018a). On the other hand, the risk of debt overhang in the event of investments with low returns in the ecological transition need also to be accounted for (cf. Carney (2016) on the dual risk of non-transition and transition). Besides, the management of asset stranding and capital stranding is today a brake on the ecological transition (Giraud et al., 2021) and will tomorrow be a major prudential and financial risk. This further justifies the integration of financial assets in macroeconomic models, also to be able to analyse green prudential policies such as *public bad banks* (Daumas, 2023a).

Finally, integrating money and private debt would also prevent confusion in the interpretation of the *"savings equal investments"* equation as pertaining to financing whereas it actually tracks resource flows (Borio and Disyatat, 2015; Taylor, 2004). Indeed, traditional interpretation of the equation often fails to distinguish between financial savings (gross financial flows) and real savings (deferred consumption for future investment in real assets, implying the existence of inventories and stocks). It overlooks the role of the financial sector in creating credit, which can influence investment independently of real savings. Incorporating financial flows and private debt into economic models thus clarifies the distinction between savings and investment (Lindner, 2015; Taylor, 2016). It emphasises that investment can be financed through credit creation, which does not depend on prior savings (Jakab and Kumhof, 2015). Such issuance of bank credit and therefore money to fill the savings/debt imbalance amounts to relaxing Say's Law.

2.2.5 Representative agents

Another important feature of DSGE and CGE models is their optimisation behaviour. Indeed, they are based on constrained optimisation by an agent representative of the economy (in the sense of Lucas, 1977; Kydland and Prescott, 1982). The aim of this construction is to have a model that is robust to structural change in the economy, when macro-econometric models estimated on past time series may not be valid after such a change. It follows that, in the case of optimisation, whatever the shock, agents will always optimise their situation, maximising the use of resources at any period. Beyond the fact that this assumption may be questionable in terms of realism, it does not seem appropriate to consider that any model other than those using optimisation would be *ad hoc* and therefore *"inferior"* or *"useless"*. Macro-econometric models may not robust be to structural changes indeed (such as the Phillips curve of recent decades, cf. Ratner and Sim, 2022), but this can be decided, analysed and adapted on a case-by-case basis.

Moreover, the nature of the agent in the models where there is only one, so-called representative, agent, is based on an ergodicity assumption, bypassing the problems of emergence and aggregation widely addressed in general equilibrium theory (Sonnenschein (1972); Mantel (1974); Debreu (1974), forming the "SMD" Theorem, generalised by Chiappori and Ekeland (2004)). Such assumption also prevents complexity phenomena from being taken into account (cf. Kirman's work). The Lucasian representative agent is not in fact a consistent, stylized representation of the sum of economic agents behaviours (Kirman, 1992). Howitt (2006) calls it a fallacy of composition. Even if preferences are under Gorman form, the representative agent hypothesis skews the analysis of economic dynamics (Summers, 1986), ignores non-normal distributions, and is itself not robust to Lucas (1976)'s critique (Haldane and Turrell, 2018).

2.2.6 Rational expectations

Generally, representative agents have been attributed rational expectations, i.e. perfect foresight in mean (except for stochastic unexpected shocks), ever since the rational expectation "revolution" (Muth, 1961; Lucas, 1977). However, in addition to the vast empirical, psychological and econometric literature contributing to show that agents do not have rational expectations (cf. *inter alia* Lovell, 1986; Pesaran, 1987; Manski, 2004; Guesnerie, 2005; Evans et al., 2018; Kirman, 2021; D'Haultfœuille et al., 2021), the theory illustrates the fundamentally unstable nature of the latter in the presence of non-linear dynamics à la Solow (Cass and Stiglitz (1969)[4]; Guesnerie (2005) on eductive instability and coordination failures). Moreover, the coupling of rational expectations with the Ricardian hypothesis implies a neutralisation of fiscal policies – agents reduce their consumption by the same amount in intergenerational anticipation of future taxes to pay it back. Such hypothesis is empirically contested (Stanley, 1998; Wroblowsky, 2007) or at least nuanced (Nickel and Vansteenkiste, 2008). This hypothesis holds mainly thanks to (or because of) the *ad hoc* optimisation framework (Ricciuti, 2001), together with the added problem of publication bias (D'Andrea, 2022). Finally, rational expectations may be seen as eliminating the dynamic character of even a multi-period model in discrete time, since backward induction may just double the number of equations in a single period.

Some models now integrate bounded rationality, as well as suboptimal and heterogenous forecasting power of agents, with heuristics (e.g. Deak et al., 2017). Nevertheless, the intertemporal optimisation goal of agents, even in a framework of bounded rationality, leads to a smoothing of the impact of economic shocks, through a modification of the capital stock seen as extremely flexible and able to be reallocated intertemporally to achieve the desired return, which can underestimate the impact of negative economic shocks (for example, underestimating the impact of capital stranding in the case of ecological transition). To overcome this problem, Heterogeneous Agents New Keynesian (HANK) models aim to replace the aggregate Euler's Equation (IS curve) with more modern theories of consumption and saving (e.g. *"buffer stock"* model), with a diversity of households (and sometimes firms), which are heterogeneous ex-ante and ex-post, with incomplete financial markets and imperfect risk sharing among them. It allows to

[4] It shows that a rational expectation inflation path is not locally stable, as any mistake by any agent in the formation of expectations will lead to another path, leading to a generic failure of agent coordination on this path.

relax the Ricardian hypothesis and intertemporal optimising behaviour hypothesis through hand-to-mouth agents, as empirical work tends to show that consumption has a weak sensitivity to real rate changes and strong, very heterogeneous responses to transitory income changes. See Alves et al. (2022) for a review of HANKs and Kaplan et al. (2018) for the importance of heterogeneous agents' responses in the transmission mechanism of monetary policy[5]. However, the complexity of HANKs added onto the NK DSGE structure leads to important computational issues, as *"solving for the equilibria requires the use of nontrivial computational techniques, given the need to keep track of the distribution of wealth, and the hurdles arising from the presence of occasionally binding borrowing constraints. The reliance on numerical techniques for the analysis of those models often presents a challenge when it comes to understanding the mechanisms underlying some of the findings, and may thus limit their use in the classroom or as an input in policy institutions"* (Debortoli and Galí, 2017).

2.2.7 Substitutability of inputs in production functions

Economic models generally build on production functions, which take production factors as inputs (mostly capital and labour) and give production level as output. If standard models generally do not include energy into production factors, energy plays a fundamental role in the economy, which can also be conceptualised as a dissipative structure requiring energy and material flows to sustain itself (Herbert et al., 2023). If energy is rarely mentioned as a factor of production, often hidden as a residue of capital, it is included in current economic-energy-environment models, usually through a nested KLEM (Capital, Labour, Energy and Materials) production function. Yet, a problem emerges regarding the degree of substitutability between inputs in the production functions (i.e. the ability to compensate for one factor of production with another while maintaining the same level of production). Those functions are generally of the Cobb-Douglas type or CES (Constant Elasticity of Substitution) type, with different elasticities of substitution (eos) between production factors. The value of substitutability between energy and other inputs in nested CES production functions has a critical impact on the transition trajectories obtained from the models. Trivially, the higher the eos, the easier it is to transition and the less costly it is. Indeed,

[5] The heterogeneity of agents and their behaviour, beyond realism, is an important element as it can undermine policy model analyses, for example of standard NK DSGE results, as optimal monetary policies and distributional effects are affected by this heterogeneity and differences in expectations (e.g. Gasteiger, 2014; Di Bartolomeo et al., 2016).

high eos indicates an ease to replace the productive apparatus with a "clean" one, thus implying a low degree of path dependency for the system. This is in line with one of the common criticisms against large scale CGEs: the fact that, from a certain scale, we no longer know what determines the trajectory, whether public policy or the choice of certain parameters' values. It also ties in with Pindyck (2017)'s criticism of the arbitrary calibration within Integrated Assessment models (IAMs) of parameters that are nonetheless crucial to the model dynamics and results. Besides, the possibility itself to estimate production functions and the values of the substitution elasticities is questioned, and may not be robust (Shaikh, 1974; Felipe and McCombie, 2005, 2010; Csereklyei et al., 2016). This estimation is derived more from tautological accounting identities and statistical artefacts than from technological relationships (Felipe and McCombie, 2010).

2.2.8 International trade, finance and flows

When DSGE and CGE models encompass an open economy framework with cross-border flows, they generally do so based on a simplification that confuses financial flows and real resources through the accounting equation: "Current Account = Savings – Investments" (Borio and Disyatat, 2015). Such equation entails a confusion between current account and net financial flows. Imports and exports represent real flows, different from net financial flows. Thus, *"contrary to a common view, current account patterns are largely silent about the role a country plays in international borrowing, lending and financial intermediation - aspects that must be at the core of the understanding of any financial crisis."* (*Ibid.*). For example, the private productive sector of a country with a trade deficit can theoretically finance itself through its banking system, by issuing credit *ex nihilo* (even though such money creation has an effect on inflation, exchange rates, and creates other challenges). Thus, in DSGEs and CGEs, the borrowing/lending is in real terms simply the balance of trade, preventing a realistic and analytical representation of international financing mechanisms.

Conclusion

In conclusion, we attempted to draw up a list of challenges faced by economic modellers working on the ecological transition. Recent new features and improvements of DSGE and CGE models bring some innovations, adaptations, and partial answers to those challenges. We argue that diversifying the classes of models used can lead to more comprehensive and systematic responses to the challenges presented in this section. This is also due to the fact that, as Dow (2021); Storm (2021); Blanchard (2016) show, New Keynesian extensions and additions to DSGEs and CGEs are applied on an already existing structure, leading to limits in the scope of additions, complexity and tractability. Models with a different core structure therefore seem to have all their place to complement the macroeconomic models currently used for policy making. The following section aims to present such complementary modelling tools and their added-value.

2.3 Insights and solutions brought by models from Ecological Macroeconomics

It was underlined in the previous section that there are many challenges and limitations, widely documented in the literature, to the macroeconomic modelling of the ecological transition by CGE and DSGE models. These challenges can be summarised as follows:

1. Output gap framework;
2. Equilibrium framework and Say's Law;
3. Neutrality and exogeneity of money;
4. Private debt and financial instability;
5. Representative agents;
6. Rational expectations;
7. Substitutability of inputs in production functions;
8. International trade, finance and flows.

Table 2.1 presents a list of advanced models from Ecological Macroeconomics (EM), assessing for each model its robustness to the critiques from Section 2.2. Those models present an important variety of sizes and scopes. They were selected for their empirical character and because they could be rapidly adapted to be used by European institutions for macroeconomic policy design and analysis. The following paragraphs further describe these models in terms of features, aim and scope.

Model	1	2	3	4	5	6	7	8
DEFINE	✓	✓	✓	✓				
DSK	✓	✓	✓	✓	✓	✓		
E3ME	✓	✓			(✓)	(✓)	✓	(✓)
EIRIN	✓	✓	✓	✓	(✓)	(✓)	✓	(✓)
EUROGREEN	✓	✓	✓	✓				
GEMMES	✓	✓	✓	✓			(✓)	✓
WILIAM	✓	✓	✓	✓	(✓)	(✓)	✓	

Table 2.1 List of advanced EM models. A check mark indicates that the model is robust to the corresponding critique from Section 2.2. A check with brackets indicates that the model is partially robust to the critique. The listed models present an important variety of sizes and scopes.

2.3.1 Stock-Flow Consistent modelling

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 models have their roots in the development of the flow of funds analysis by Copeland (1952). They emerged as a structured theory following the work of Nobel prize James Tobin (Backus et al., 1980). Since the financial crisis of 2008 especially, SFC modelling has grown into a blossoming literature. More interestingly, SFC models have for several years now been widely used as a tool of macroeconomic analysis for the ecological transition (Svartzman et al., 2019; Carnevali et al., 2019). SFC macromodels are characterised by two main features: a distinct accounting framework and behavioural 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. The behavioural equations in turn model all the transactions that are not directly determined by the accounting structure of the economy. One main advantage of SFC models is that they ensure the overall consistency of the modelled economy[6]: the outflows of one sector are always the inflows of another sector and simi-

[6]Social Accounting Matrices (SAMs, the usual accounting frameworks of CGEs) are in theory also capable of representing financial assets and flow of funds, even though such mapping is not carried out systematically like in SFC models. The main novelty in the SFC approach is the continuous retroaction on flows of the accumulation of financial stocks, hence introducing a static (for SAM) versus dynamic (for SFC, with historical time) difference.

larly, the liabilities of one sector are always the assets of another sector[7]. 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 (2017) for recent literature reviews.

The two first points of criticism detailed in Section 2.2 (output gap framework; equilibrium framework and Say's Law) are intrinsic to the optimisation equilibrium framework of DSGEs and CGEs. As explained, the related challenges, although understood and tentatively dealt with, cannot be fully addressed while staying in such a framework. On the contrary, SFC models adopt a rather positivist approach to the economy. Their behavioural equations describe macro-trends in the economy or dynamic behaviours of economic agents. They do not rely on any equilibrium assumption or on systematic optimisation. They can represent fluctuations endogenous to the economic system instead of being triggered by exogenous shocks. This allows SFC models to be robust to our two first points of criticism. Then, the two following critiques made in Section 2.2 (real economy model, neutrality and exogeneity of money; absence of private debt and financial instability) stem from the limited treatment of the monetary and financial systems in most DSGEs and CGEs. SFC models, on their part, were developed with the specific aim to allow finance, the real economy and the interactions between the two to be represented in a single framework, and thus to overcome such challenges (Godley and Lavoie, 2007).

An advanced, empirical SFC model is the EIRIN model (Monasterolo and Raberto, 2018, 2019). It was specifically developed to analyse the direct and indirect impacts of climate risks, green fiscal and finance policies on the real economy and on finance. EIRIN is an open economy model composed of a limited number of heterogeneous agents and sectors of the real economy,

[7] In addition, some SFC models (e.g. Dafermos et al., 2017) also introduce Georgescu-Roegen's flow/fund distinction (Georgescu-Roegen, 1971, 1979, 1984) which is a core principle of ecological economics. *"The stock-flow resources (non-renewable energy and material resources) are transformed into what they produce (including by-products), can theoretically be used at any rate desired and can be stockpiled for future use. The fund-service resources (labour, capital and Ricardian land) are not embodied in the output produced, can be used only at specific rates and cannot be stockpiled for future use. Crucially, these types of resources are not substitutable: they are both necessary for the production process."* (Dafermos et al., 2017; Mayumi, 2001; Daly and Farley, 2011). This helps to refine the understanding of the role of each physical element in the productive process - and also to differentiate their destruction in the context of climate damage functions and negative feedback from the environment on these resources.

public and private finance. Agents are heterogeneous in terms of sources of income and wealth, access to financial markets, access to capital, skills and GHG emission intensity. Thanks to this, the distributive effects of green policies are assessed in terms of income inequality and wealth concentration (Monasterolo and Raberto, 2018). Agents are endowed with behavioural decisions based on empirical information and heuristics. They formulate decisions based on adaptive expectations. Agents and sectors interact through a set of real and financial markets, thus allowing to assess the impact of both endogenous and exogenous climate related shocks. The way how productive firms progressively shift their investments from brown to green assets, in reaction and in anticipation of several types of public policies, is explicitly modelled. Besides being robust to the first four points of criticism of Section 2.2 and to integrate the role of agents' expectations in economic phenomena, EIRIN also addresses the modelling issues related to substitutability of inputs in production functions. The EIRIN model includes a Leontief production function with no substitution between labour, capital and raw materials (encompassing fossil fuels). This allows to better account for path dependency and to incorporate the importance of the firms' investment decisions on the short- and medium-term. Having raw materials and energy sources (fossil fuels and renewables) that enter the production function further allows the model to assess how resource and carbon- intensive production and consumption affects the performance of the economy. EIRIN has already been applied by several central banks and international financial institutions to complement standard macroeconomic approaches in the assessment of the impacts of climate risks in the economy and finance. These include the analysis of the double materiality of climate risks in the euro area in collaboration with the European Central Bank (Gourdel et al., 2022); the assessment of compounding COVID and climate physical risks in emerging markets and developing economies with the World Bank (Ranger et al., 2022; Dunz et al., 2023); the impact of cross-border climate risks on sovereign fiscal and financial stability (Gourdel and Monasterolo, 2022; Gourdel et al., 2022) within the G24-V20- Task Force on Climate Development and the IMF; the dynamic balance sheet assessment of the NGFS scenarios (Gourdel et al., 2024).

Another prominent SFC model is EUROGREEN (D'Alessandro et al., 2020; Cieplinski et al., 2021). This model is especially focused on inequalities and was designed to assess the impacts of alternative packages of climate policies in terms of employment and wealth distribution between various population groups. The model was developed in the wake of the *"Gilets jaunes" (Yellow Vests)* movement and was focused on the case of France, partly due to the availability of extensive national data on welfare accounting, which allowed a thorough country-specific calibration of the model. The EUROGREEN model comprises 13 heterogeneous population groups, defined in terms of skills and working status. It gives a detailed description of the French welfare system and of the various income sources of each population group. The policy packages studied in the model include incentives for different types of technological innovation, carbon border adjustment mechanism, working time reduction, job guarantee program and a wealth tax. Next to income distribution and unemployment, the model also studies the impacts of different policy mixes on economic growth, energy demand, GHG emissions and government budget. The respect of the Maastricht criteria are discussed in each scenario and the simulation results are compared with the forecasts from the EU's official reports. Besides, a distinctive feature of the EUROGREEN model is its endogenous determination of technological progress. Production in the model is defined by an input-output matrix including multiple industries. Endogenous investment decisions determine innovation and the emergence of various new industry-specific technologies, which are then adopted or not by the agents based on a cost-minimisation (D'Alessandro et al., 2020).

A model particularly rooted in the thermodynamics perspective at the origin of ecological economics is the DEFINE model (Dafermos et al., 2017, 2018; Dafermos and Nikolaidi, 2019, 2021, 2022). DEFINE encompasses economic, monetary and financial stocks and flows on the one hand, and physical stocks and flows on the other hand, based on the laws of thermodynamics. The production functions are Leontief-type (imperfect substitutability). In addition to capital and labour, inputs to the production function include extracted materials, recycled materials and energy, with distinctive intensities depending on the type of capital (i.e. green capital vs. conventional capital). The environmental feedback loops on the economy are incorporated through different channels. First, a climate damage function is included, similar to the ones of standard IAMs. The difference here is that climate change does not impact production directly, but rather the resources used as factors of production. Second, the climate damage function does not only impact production, but also the different components of aggregate demand. Third, the exhaustion of natural resources (fossil fuels, minerals) used as factors of production in the model can result in supply constraints. The impacts of environmental degradation are therefore included both from a supply and demand perspective (Dafermos et al., 2017). The DEFINE model is then used to study the environmental, economic and financial impacts of numerous green policies, be it carbon taxes, green subsidies, green public investment (Dafermos and Nikolaidi, 2019), financial regulation tools for climate-related financial risks (Dafermos and Nikolaidi, 2021), a green quantitative easing programme (Dafermos et al., 2018) or sufficiency policies (Dafermos and Nikolaidi, 2022). Such policies are not analysed in a cost-benefit or optimisation perspective and no social discount rate is used. Instead, *"policies are evaluated based on their ability to achieve high well-being in a way that does not cause a collapse of the highly interconnected macroeconomic, financial and ecological systems (in both the short run and the long run)"* (Dafermos and Nikolaidi, 2019). The scope of DEFINE is currently global, but a national version of the model (calibrated to the UK) is also under development (George and Dafermos, 2023).

Moreover, the French Agency for Development (AFD) developed an advanced and highly detailed SFC model: the GEMMES model. GEMMES (General Monetary and Multisectoral Macrodynamics for the Ecological Shift) is an SFC macromodel in continuous time. It represents a small developing economy with an open financial account, explicitly accounting for all gross financial flows (and not just net flows). This model exhibits disequilibrium dynamics with both prices and quantities adjustment. Such dynamics apply namely to the supply-demand relationship for consumption goods and to the determination of the exchange rate. The accumulation of foreign exchange reserves are included in a robust way in the model, with clearly identified causal mechanisms, encompassing the role of agents' expectations. Real and financial flows are distinguished from each other and the interdependence between both is modelled. The GEMMES model therefore adequately answers the international trade, finance and flows critique from Section 2.2. The canonical GEMMES model (Godin and Yilmaz, 2020) was developed to study how fluctuations in major financial centres could induce boom and bust episodes in such an open economy, via portfolio flows and cross-border lending (Rey, 2015). It then led to the development of various country-specific versions, for example for the case of Vietnam (Woillez and Espagne, 2022; Truong et al., 2023), Tunisia (Yilmaz et al., 2023) or Colombia (Godin et al., 2024; Moreno et al., 2024). GEMMES was also coupled with several biophysical models, namely crop production models under different climate scenarios (Yilmaz et al., 2023) and energy models (LEAP for Morocco & Vietnam – ongoing work). Moreover, (Woillez and Espagne, 2022) added to GEMMES, under different climate scenarios, various sectoral climate damages which were interconnected and could lead to an aggregate damage which was higher than the sum of its parts. Thus, GEMMES has been extensively used to study how climate change and/or decarbonisation policies impacted trade, resource, energy and financial flows. Importantly, GEMMES not only assesses the impacts of adaptation/decarbonisation policies, but also the impacts of the alternative ways to finance these. The GEMMES model considers transitions as processes of structural change, leading to disequilibrium dynamics (stranded assets, creative destruction, etc.). Thus, it uses procedural rationality and asymmetric information. The model also includes explicit aspects of tensions between economic actors, leading to temporary or permanent imbalances. Furthermore, GEMMES incorporates investment functions à la Bhaduri and Marglin (1990), which allow to model economies that can be driven by both supply and demand (profit rate and productive capacity utilisation rate, cf. Blecker and Setterfield, 2019).

2.3.2 Agent-based modelling

A drawback of SFC models is that they stay at the aggregate level and do not model intra-sectoral flows (Caiani et al., 2016). In particular, the focus of SFC models on macro-tendencies renders them especially vulnerable to the Lucas critique. With this in view and thanks to the new perspectives opened up by advanced computing capabilities, another form of modelling has developed: agent-based modelling (ABM). It uses an entirely different language of autonomous agents, objects and environments rather than variables, functions and equations (Boulanger and Bréchet, 2005). As explained by Caiani et al. (2016), ABM *"conceives the economy as a complex adaptive system populated by heterogeneous locally interacting agents"*. ABMs are bottom-up macroeconomic models in the sense that the behaviour of actors at the micro-level, relative to the opportunities and thresholds fixed by the broader environment, brings about emergence of aggregate properties. They illustrate a major new development in both economic and behavioural modelling, allowing better ways to model non-equilibrium evolutionary economic phenomena based on empirical grounds. As noted by Caiani et al.

(2016): *"empirically, agent based macroeconomic models have proven to be capable of reproducing a significant number of micro and macroeconomic stylized facts ... often outperforming DSGE models"*. Besides, Colander et al. (2008) highlight how such empirical reconstruction of macroeconomics with agent-based computational modelling improves robustness of models to the issue of aggregation.

In recent years, a blossoming literature on ABM has developed, namely in the context of ecological economics (Lamperti et al., 2018). Although many agent-based models are not stock-flow consistent, the ABM and SFC approaches are complementary and can be very successfully combined (Caiani et al., 2016). An agent-based stock-flow consistent (AB-SFC) model of particular interest is the Dystopian Schumpeter meeting Keynes (DSK) model of (Lamperti et al., 2018, 2019, 2020, 2021). This model is especially relevant when considering the challenges related to representative agent and climate damage functions. The DSK model is populated with heterogeneous firms (i.e. agents) belonging to the capital-good, consumption-good and energy sectors. The use of fossil fuels in the energy sector exacerbates climate change, which feedbacks on economic activity in a stochastic fashion. Climate damages are indeed modelled as a multitude of random shocks hitting workers labour productivity, energy efficiency, capital stock and individual firms' inventories. Markets are modelled as imperfect and climate shocks generate turbulence and inefficiencies in the firms competition process (Lamperti et al., 2018). By modelling stochastic climate damages of various types at the micro level, Lamperti et al. (2018) find that the nature of the economic channels affected by the shocks greatly determine their impact on business cycles and endogenous technical-change trajectories. The results from the DSK model also point towards the *"emergence of tipping points (i.e. regime shifts) in the growth process of the economy"* (Lamperti et al., 2018). Very importantly, those results also highlight how using climate damage functions at the aggregate level leads to the over-simplification and under-estimation of those damages in most IAMs. The DSK model, encompassing endogenous R&D investments with given probabilities of success, is further used in various Monte Carlo analyses for studying climate-induced crises in the financial system (Lamperti et al., 2019), the likelihood of green transitions under different scenarios (Lamperti et al., 2020) and the impacts of green policy mixes (Lamperti et al., 2021; Lamperti and Roventini, 2022).

2.3.3 Multi-sector disaggregated models

The six alternative models presented so far are all suitable complements to DSGEs, since their level of detail, scope and applications are similar in nature. However, none of these models focuses on representing a multi-sector, disaggregated economy with its interdependencies, in the way that CGEs do[8]. The goal of the MEDEAS, then LOCOMOTION projects was to fill this gap[9]. Those two research projects were funded by the European Union's Horizon 2020 research and innovation program and led to the development of the MEDEAS IAM, followed by WILIAM. MEDEAS is a system dynamics model, in the fashion of the pioneering WORLD3 model of Meadows et al. (1972). The main goal of MEDEAS is to provide a detailed, multi-sectoral model which endogenously accounts for biophysical constraints (energy and resources, namely). The economic module (one of the 9 main modules composing the model) is based on a dynamic Input-Output (IO) framework, with a sectoral disaggregation into 35 industries. MEDEAS has been developed at three different scales: global (Nieto et al., 2020b; Capellán-Pérez et al., 2020), EU (de Blas Sanz et al., 2018; Nieto et al., 2020a) and country-level (Álvarez Antelo et al., 2018). Those three models are nested into each other, with a one-way integration: the parent models (World, EU) provide the child models (EU, country) with the constraints in terms of energy and materials availability deriving from regional or global dynamics. In the same way, CO2 concentration and global temperature increase are determined by running MEDEAS-World. They are then taken as inputs by the EU and country models, based on which these models compute heterogeneous climate damages (Nieto et al., 2020b; Capellán-Pérez et al., 2020)[10].

The LOCOMOTION project departed from the legacy of MEDEAS to develop WILIAM (Within Limits Integrated Assessment Model). In WILIAM, the economic model of MEDEAS was replaced by a dynamic econometric multi-regional Input-Output (IO) model[11]. WILIAM comprises a high level of disaggregation of economic sectors (62 industries), households (60 types)

[8]Except maybe GEMMES, when coupled with physical multi-sectoral models.

[9]More information on these two projects can be found on their respective websites: `https://medeas.eu/` and `https://www.locomotion-h2020.eu/`

[10]Given that MEDEAS is a model essentially focused on biophysical constraints and less on macroeconomic aspects, it was not included in Table 2.1, unlike WILIAM.

[11]The full WILIAM model, together with its documentation, is available here: `https://github.com/LOCOMOTION-h2020/WILIAM_model_VENSIM/wiki`. See also Lifi et al. (2023); Samsó et al. (2023)

and regions (35) and captures the mutual feedbacks between quantities and prices, and the interplay between consumer demand, induced investment, government and exports demand, on the one side, and production and income generation and distribution on the other. The different regions are linked through trade flows, with trade shares defined through Armington elasticities, which enables the analysis of different configurations of supply chains (e.g. globalisation, near-shoring, or back-shoring) (Lifi et al., 2023; Samsó et al., 2023).

A model sharing several similarities with WILIAM is E3ME (Energy - Environment - Economy Model for Europe). E3ME is a global, multi-country, non-equilibrium model including detailed econometric equations. It was developed by Cambridge Econometrics, originally through a European Commission's research framework programme. E3ME models the close integration of the economy, the energy systems and the environment, with two-way linkages between the economy and energy system. It combines microfounded technological choices and innovations in a bottom-up way with a macroeconomic structure, allowing true multi-sectoral disaggregation, sector-specific energy intensities and intersectoral spillovers. The econometric specification of E3ME gives the model a strong empirical grounding. In particular, its harmonious bottom-up and top-down integration makes the model robust to the Lucas critique (or at least as much as possible, since there exists no macroeconomic model whose entire set of calibrated parameters are perfectly immune to that critique). E3ME uses a system of error correction, allowing short-term dynamic (or transition) outcomes, moving towards a long-term trend. The dynamic specification is important when considering short and medium-term analysis and rebound effects, which are included as standard in the model's results. E3ME represents 71 countries, 70 industrial sectors and 43 categories of household expenditure (Dwesar et al., 2022). Furthermore, as E3ME is a simulation model without optimisation behaviour, it allows for the representation of the unused resources and productive capacities in the economy, reducing the risk of crowding out effects, while still representing potential constraints in the scenarios studied such as the total available workforce. The model is widely used in Europe and beyond for policy assessment, for forecasting and for research purposes.

Finally, the ESTEEM model developed by the AFD is complementary to the other models listed above[12]. This model relies on a multi-regional IO framework to analyse the exposure of multiple countries to sunset industries according to three dimensions: external (sunset industries being a source of foreign exchange), fiscal (government revenues) and socioeconomic (job losses). The carbon-intensive industries are identified and each country's dependence on these industries, both direct and indirect, is analysed. Such dependency is unique for each country and depends on the structure of its economy and on its trade relations with other countries. Magacho et al. (2023) performed such analysis for 189 countries, assessing their level of exposure and how transition risks could be addressed in each case to ensure an adequate transition path. The impacts of CBAM (Carbon Border Adjustment Mechanism) on EU trade partners was also analysed with ESTEEM (Magacho et al., 2024). Thus, this model provides an insightful tool to study the intertwine between cross-sectoral dependencies and international flows' interdependence.

2.3.4 On the use of macroeconomic models

The 9 models presented above are part of the blossoming research field of Ecological Macroeconomics (Delannoy, 2023). Most of them were developed with the specific aim of overcoming one or several of the challenges listed in Section 2.2. Yet, as can be seen from Table 2.1, none of these models is robust to all points of criticism. This is not an aim *per se*. As Blanchard (2018) puts it: *"We need different types of macroeconomic models for different purposes ... No model can be all things to all people"*. A model is developed to answer one or several specific policy questions. Given the complexity and variety of domains affected by the ecological shift, one cannot hope to dispose of a single, exhaustive tool to guide policy making in the green transition. Instead, a variety of models must be used, reflecting a plurality of views and methodologies.

Having a co-existence of DSGEs and CGEs with alternative models is therefore key for policy discussion. Existing examples of models diversification include the World bank, which jointly used E3ME and MANAGE (a CGE model) for producing the Country Climate and Development Report for China (World Bank Group, 2022a) or the Task Force on Climate-Related Financial Disclosures (TCFD), IMF and European Central Bank which released a series of technical papers using the EIRIN model (see *supra*).

[12] Note that ESTEEM, given its very different structure from the other models presented in this Section, was not included in Table 2.1 to avoid confusion.

3

Net energy analysis and biophysical constraints to economic activity

Chapter 2 showed how, by relying on a different core economic structure, Ecological Macroeconomics (EM) models avoided a number of pitfalls faced by DSGE and CGE models. Yet, this aspect does not fully characterise the field of EM. As already stated in the previous chapter, this field holds its roots in the view that 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 constrained both by input and output flows.

One such flow potentially limiting economic activity is the energy supply. The study of energy flows and how they relate to economic activity is an integral part of the field known as Net Energy Analysis (NEA). The first part of this chapter reproduces an extract from Delannoy et al. (2024). This article, which we co-authored together with 21 leading NEA researchers, presents the state of the art and highlights 8 points of consensus which have progressively emerged.

The second part of this chapter lists additional biophysical constraints to economic growth. It presents a literature review of EM models which integrate both a subset of these biophysical constraints and a Stock-Flow Consistent (SFC) description of the economy. A literature gap is identified and paves the way for the presentation of the TEMPLE model in Chapter 4.

3.1 The Net Energy Analysis approach

Net energy analysis consists in tracking the input (E_{in}) and output flows (E_{out}) of energy in technical systems and human societies. Net energy is defined as 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. Net energy is thus a fundamental prerequisite for the production and exchange of goods and services: $E_{net} = E_{out} - E_{in}$.

For a given amount of net energy, a key metric of the energy system is the Energy Return On Investment or EROI – defined as the ratio between the total energy output and the total energy invested to accomplish the conversion over the entire life cycle of the system under study, i.e. $EROI = E_{out}/E_{in}$[1].

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 1 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 3.1, $EROI_2 = E_{returned,2}/E_{invested,2}$ with $E_{invested,2}$ 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, 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, 2011; Raugei, 2019).

[1]Two alternative EROI definitions are already possible at this point, called gross EROI and net EROI: $EROI_{gross} = E_{out}/E_{in}$ and $EROI_{net} = (E_{out} - E_{in})/E_{in} = EROI_{gross} - 1$. In this thesis, the EROI mentioned are always gross EROI.

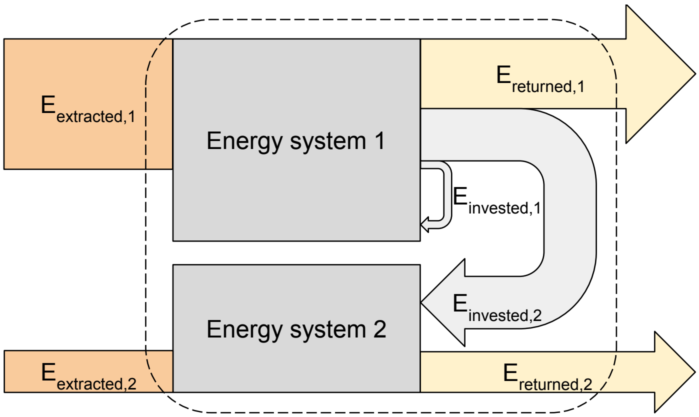


Fig. 3.1 Returned energy as a function of the extracted and the invested energy for two systems. EROI (global) = ($E_{returned,1}$ + $E_{returned,2}$ + $E_{invested,1}$ + $E_{invested,2}$)/($E_{invested,1}$ + $E_{invested,2}$). EROI (energy system 2) = ($E_{returned,2}$)/($E_{invested,2}$). Energy losses 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 considers 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 and losses are considered. Focusing on the point of use is gaining in importance, as: (i) the energy requirements and losses of the processing, refining and other downstream processes for fossil fuels may be larger than those 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 the energy consumption of this energy system 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 Emerging consensus on net energy

In Delannoy et al. (2024), we summarise our position on 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., 2021b,a).
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) storage[2] technologies (Raugei et al., 2020; Murphy et al., 2022). However,

[2] The 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.

average EROI values hide strong regional variability, particularly for solar and wind technologies (Dupont et al., 2018, 2020).

6. The EROI of nuclear and hydropower have historically been high, but 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; Colla et al., 2024).
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; Slameršak et al., 2022a; Fabre, 2019).

In parallel to this emerging consensus, an 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 3.2) 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.

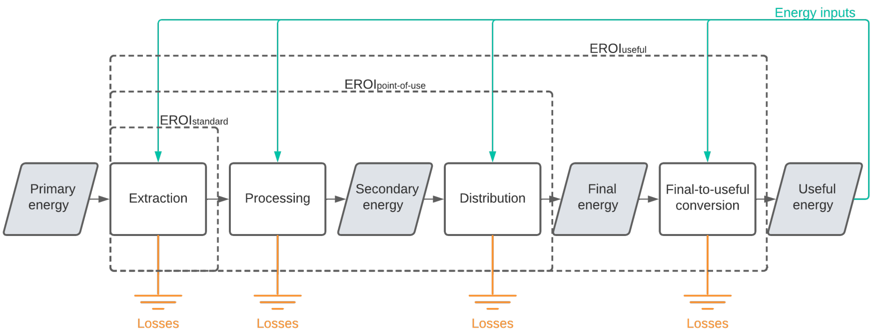


Fig. 3.2 Standard, or primary stage EROI (EROI$_{standard}$), point-of-use or final stage EROI (EROI$_{point-of-use}$) and useful EROI (EROI$_{useful}$).

3.3 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 adverse economic effects, which raise questions of socio-political acceptance.

As illustrated on Figure 3.3, 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. 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 lower curve moves over time to become stiffer as the carbon budget corresponding to the climate target is used up. The upper constraint is also likely to worsen due to 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 (Shukla et al., 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., 2011a; Millward-Hopkins et al., 2020; Kikstra et al., 2021).

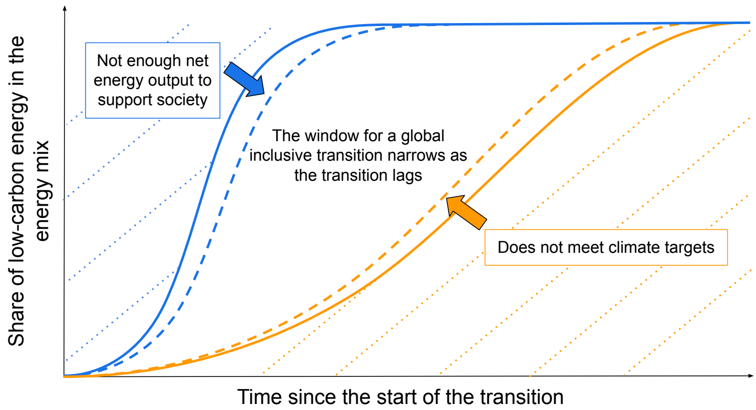


Fig. 3.3 Sketch of principle of an evolving window of opportunity for the global inclusive transition to low-carbon energy as a function of normalized time at the start of the transition. The solid lines delineate the current window of opportunity. The dashed lines represent a future window in which action has not been taken quickly enough such that climate and net energy increasingly constrain the window of opportunity.

3.4 Integrating biophysical constraints to economic growth in SFC macromodels

Recent developments in the Net Energy Analysis (NEA) research community have highlighted EROI implications for socio-economic scenarios (King and van den Bergh, 2018; Delannoy et al., 2021a; Slameršak et al., 2022a). Nonetheless, 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, net energy has been addressed only marginally in reference works on mitigation pathways. The latest IPCC report (Shukla et al., 2022), for instance, mentions EROI issues in only one paragraph (ch. 6, p. 44) and leaves out the evolution of the related literature.

However, namely thanks to the emergence of the 8 key points developed above, the inclusion of NEA metrics in macroeconomic models has gained momentum in recent years, especially in Ecological Macroeconomics (EM). Here below, we recapitulate a set of 9 biophysical constraints to economic growth, including the accessibility of energy measured through the EROI metric. We then review in the following section the literature of ecological SFC macromodels incorporating such biophysical constraints.

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)[3]. 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. As thoroughly discussed above, this accessibility is measured by the EROI metric.

Materials

Minerals are finite resources too. They differ from energy resources though, in the sense that – among other things – they can be recycled and do not deplete after initial production[4] (Prior et al., 2012). There are still availability risks for mineral types with low remaining reserves, poor geographical distribution, limited adequate substitutes[5] or subject to economic, social or environmental constraints (Meinert et al., 2016). The accessibility of these minerals could be affected 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., 2022). The potential impact of mining energy intensity on the transition of the energy system has been investigated in the NEA literature. After early warnings that the EROI of wind and solar PV might be negatively affected by the increase in mining energy requirements (Fizaine and Court, 2015), recent research has shown that these effects were in fact marginal and the related concerns unfounded (Aramendia et al., 2024).

[3]Coal 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).

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

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

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). Waste is one driver, among many others, of this collapse. The economic value provided 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 chapter as we focus on the energy-matter-economy nexus.

3.5 Biophysical-based ecological SFC macromodels

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 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 (biodiversity loss and to some extent, pollutants directly affecting human health e.g. fine particles). Second, 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 Chapter 4 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.

		Biophysical constraints								Model of the economy				
		Energy			Materials		Waste			Eq. mechanism	Sectors included			
Model	Authors	Av. NRE	Av. RE	EROI	Av.	Biodiv.	Poll.	GHG	CD	Demand-driven	Gov.	CB	RoW	Multi-sect.
n/a	Barth and Richters (2019)	×	×	✓	×	×	×	✓	×	✓	✓	×	×	×
n/a	Berg et al. (2015)	×	×	✓	×	×	×	✓	✓	×	✓	×	×	×
COPING	Bovari et al. (2018a)	×	×	×	×	×	×	✓	✓	×	×	×	×	×
COPING	Bovari et al. (2018b)	×	×	×	×	×	×	✓	✓	×	×	×	×	×
COPING	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	Chapter 4 of this thesis	×	✓	✓	×	×	×	×	×	✓	✓	✓	×	✓

Table 3.1 Major ecological SFC macromodels. 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.

4

Assessing the economic consequences of a global energy transition through a biophysical stock-flow consistent model

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 (Masson-Delmotte et al., 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, as already discussed in Section 3.4, 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 here 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 EROI for fossil fuels and renewable energy technologies. We then analyse 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 chapter is structured as follows. Section 4.1 presents the TEMPLE model. Section 4.2 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 4.3 evaluates the robustness of the results, underlines the limitations of the model and suggests perspectives for future research. Section 4.4 concludes.

4.1 Materials and methods

4.1.1 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 4.1 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

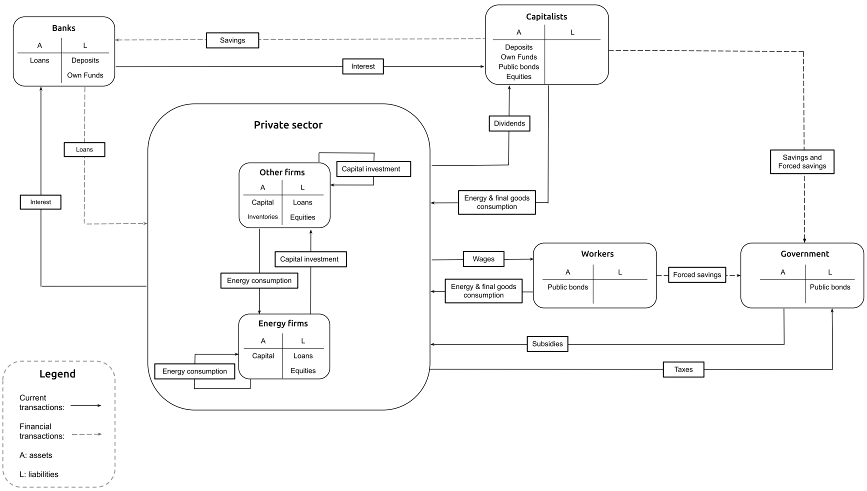


Fig. 4.1 Overall structure of the *TEMPLE* model - economic and financial flows

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 4.1, are given in Appendix A.1. The equations of the model are detailed in Appendix A.3.

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: energy[1], 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 4.1.3. Production decision determines the utilisation 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

[1]As made clear by Keen et al. (2019), energy is a fundamental factor of production.

TEMPLE model, presented in Appendix A.4, where the economy is always at full capacity, our demand-driven model allows the utilisation 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 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 realised profits. These expected profits (or the realised 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 utilisation rate of capital[2]. The difference between the firms' investment and their retained earnings is financed by issuing new debt[3] (if it is positive) 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 A.1.

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 4.1.3) determines the global employment rate[4]. 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

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

[3]We 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.

[4]Note 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 4.2 appear to be so low.

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 chapter, 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 A.3.5, into a reduced form model. This reduced form model comprises 12 differential equations and is presented in Appendix A.3.6.

Calibration

We choose to calibrate the *TEMPLE* model on an intial 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 A.5.

4.1.2 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 scenarios are built on top of it, as described in Section 4.1.3. 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 (Jackson and Jackson, 2021; Sers and Victor, 2018; Capellán-Pérez et al., 2020). 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)[5]. 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:

$$\text{EROI} = \frac{E_{out}\left(1 - \eta_{op}\right)}{E_{in,cap}} \tag{4.1}$$

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 4.1.3). 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

[5]The code used to generate these EROI curves is open-source and available at https://github.com/EliseDup/WorldEROI.

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)[6] 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. (2021a,b). 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 (2020) 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 A.6.

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., 2011b). 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, 2020) and Eurostat to distinguish between the dynamics of goods and services. Energy intensities for goods, services and energy are then calculated (and expressed in MJ / 2017 US$) to account for the final energy required

[6] This 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., 2018) also estimates the point-of-use EROI of fossil fuels, but does so for China only.

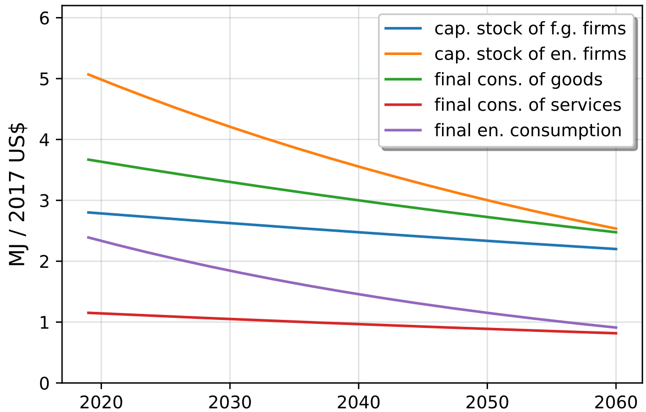


Fig. 4.2 Energy intensities of final goods production and consumption. Computed values for the year 2019 and projected evolution until 2060.

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. For a full description of the methodology and a justification for the chosen assumptions, see Andrieu et al. (2022).

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 2011-2017[7]. 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 4.3.2. 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

[7]The 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.

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 4.2 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 4.2). The corresponding values are given in Table A.5 in Appendix A.6.

World population

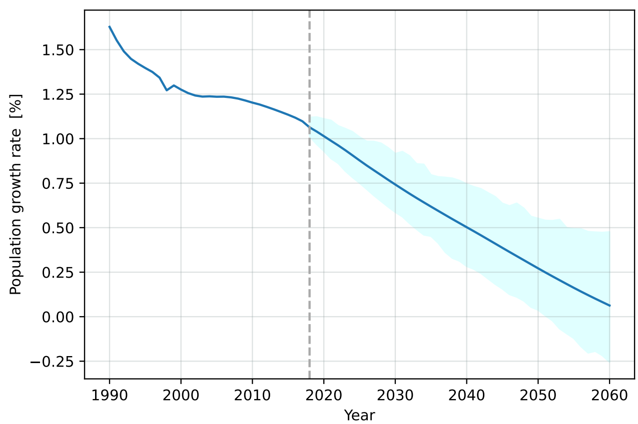


Fig. 4.3 Projection of the global population growth rate in the reference scenario with 95% UI, adapted from Vollset et al. (2020)

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 of global population growth rate from the reference scenario of Vollset et al. (2020), adapted in Figure 4.3, is used. In this study, 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 – and unlike in the population projections from the UN or IIASA – completed cohort fertility at age 50 is used rather than total fertility rate (Adam, 2021). Yet, the effects of climate change and pessimism about the future on fertility and mortality rates are not considered by the authors. According to Figure 4.3, the world population will thus *"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"* (Vollset et al., 2020).

4.1.3 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 chapter 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 4.2 and the population growth from Figure 4.3. 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, 2020; Moriarty and Honnery, 2020; IEA, 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[8]. This sigmoid profile is represented in Figure 4.4 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 renewables by 2050[9,10]. 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 materialises through the evolution of the capital and energy intensities of the energy sub-sector. Indeed,

[8] A sigmoid is used since it is a common profile for the adoption trajectory of a new technology (Perez, 2010). Other profiles are of course possible for the evolution of χ, as discussed in Section 4.3.

[9] To be precise, in our scenario the transition is only 100% completed in 2060

[10] Note that in this chapter, 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.

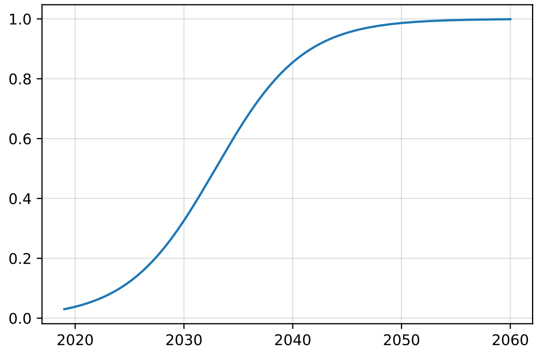


Fig. 4.4 Degree of progress of the energy transition, i.e. χ, as a function of time in the second and third scenarios.

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 A.6. 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 energy intensity of final goods production is also modeled in detail, as explained in Section 4.1.2. 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 4.1.2.
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 price[11]. 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 4.2, 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 4.7)(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 A.6 for the equations' details).

[11] Other threshold values are of course possible for this cap.

4.2 Results and discussion

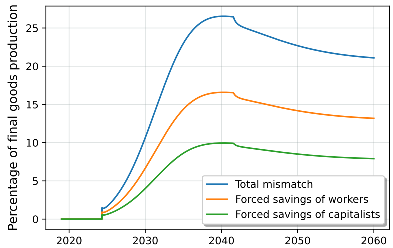
Figure 4.5 presents the macroeconomic dynamics obtained in the energy transition scenario[12]. Figure 4.6 complements them by showing the biophysical dynamics of the energy system under that same scenario. Finally, Figure 4.7 underlines the most relevant differences between the energy transition scenario 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 the present work, which focuses on the energy transition.

4.2.1 A large imbalance on the final goods market

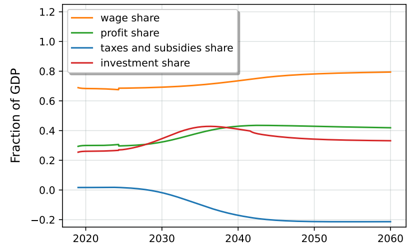
When analysing the simulations, the first thing to notice is that due to the high capital intensity of renewable energy production (as outlined in Appendix A.6, the capital intensity of renewable energy production is one order of magnitude higher than for non-renewable energy production), the demand for final goods quickly exceeds supply. Indeed, as explained in Section 4.1, 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 4.5(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 infrastructure[13]. The savings of workers and capitalists correspond to the buying of public bonds. Those new funds

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

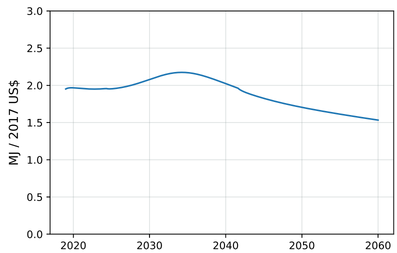
[13]Thus, the TEMPLE model becomes supply-constrained as a result of the transition. This explains why the alternative, supply-driven version of the model gives similar simulation results, see Appendix A.7.



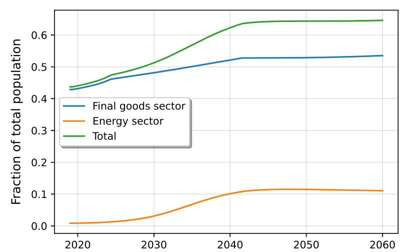
(a) Mismatch between demand and supply



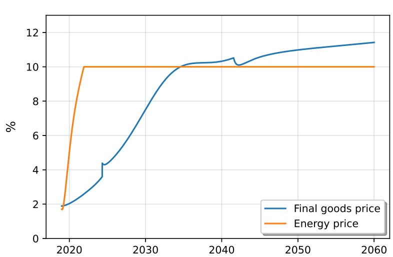
(b) GDP shares



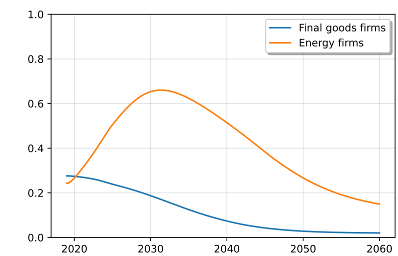
(c) Mean energy intensity of final goods production



(d) Employment level



(e) Inflation



(f) Debt ratios

Fig. 4.5 Simulated macroeconomic dynamics of the energy transition under the second scenario: "energy transition scenario".

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 4.5. 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 utilisation rate of the capital stock of final goods firms. This utilisation rate progressively increases until hitting the ceiling value of 1, which causes the kink in 2041.

4.2.2 Towards a war economy ?

Figure 4.5(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 A.3.6. In addition, Figure 4.5(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 government 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 World War II (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.

4.2.3 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 4.5(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 4.2), 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.

4.2.4 High employment, high inflation

The evolution of employment during the transition, shown in Figure 4.5(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 4.3).

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 4.1.3 and as made clear in Figure 4.5(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.

4.2.5 An energy sector strongly supported by the government

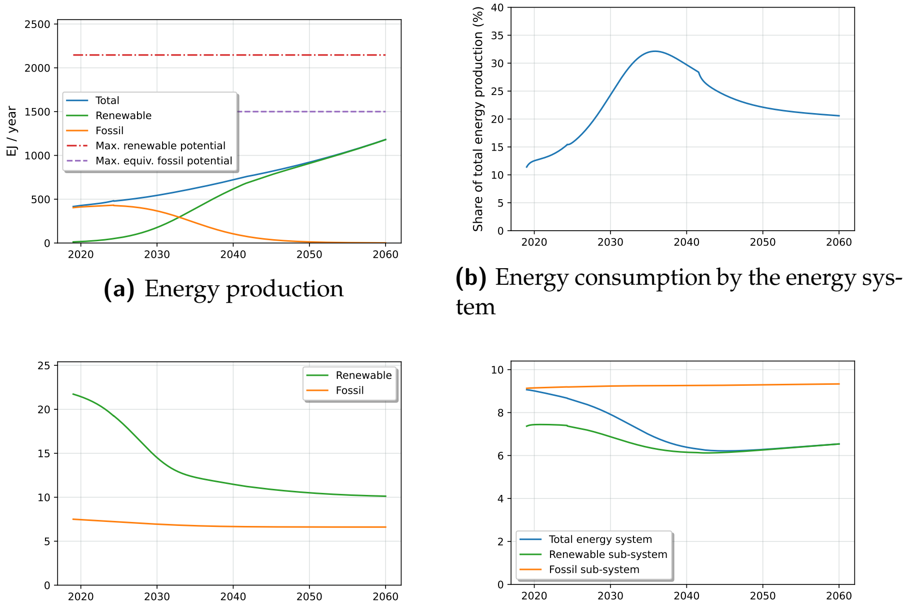
As explained in our scenario definition, the public sector provides large subsidies to the energy firms to ensure their profitability despite the cap on the energy price. The subsidies given are of the order of magnitude of the forced savings shown in Figure 4.5(a). In addition, the debt of energy firms is guaranteed by the government, so that the interest rate on their debt never exceeds 1%. Figure 4.5(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. 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.

4.2.6 An EROI perspective on the transition

Coming back to the biophysical constraints, Figure 4.6 displays the evolution of several characteristics of the energy system along the energy transition scenario. The first thing to notice is that on the medium term, such transition is not constrained by the availability of energy (as defined in Section 3.4). Indeed, Figure 4.6(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 4.6(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 4.6(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 4.6(c), and the EROI of the energy system[14], Figure 4.6(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

[14]To 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 A.6.



(a) Energy production

(b) Energy consumption by the energy system

(c) Final EROI of technologies

(d) EROI of the energy system

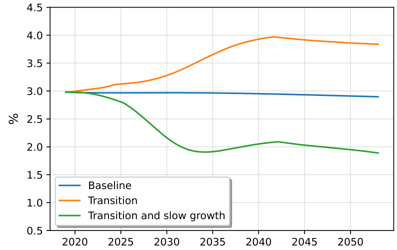
Fig. 4.6 Simulated biophysical dynamics of the energy system under the second scenario: "energy transition scenario".

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. (2022b). 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).

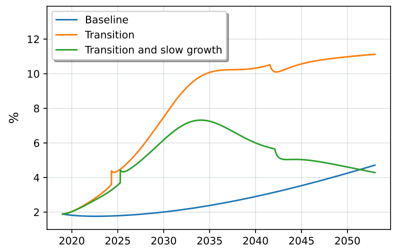
An important insight is that the main stumbling block of the transition does not lie in the required quantity of energy for building and operating the energy system, but rather in the form which these required energy inputs must take and how this interacts with the rest of the economy. The transition 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 4.3.3.

4.2.7 What if the economy grows more slowly?

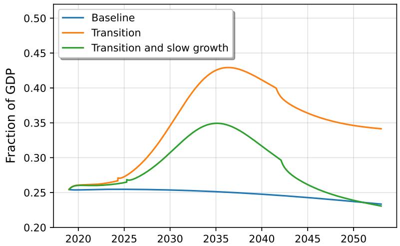
The previous subsections have described the results of the energy transition scenario. Figure 4.7 contrasts the main results of this scenario with the two other scenarios outlined in Section 4.1.3. The only difference between the energy transition scenario and the slower growth scenario is that the growth rate of the capital stock of final goods firms is lower in the latter case. As shown in Figure 4.7(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 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 4.6(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 4.7(b)). Similarly, Figure 4.7(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.



(a) Growth rate of capital stock of final goods firms



(b) Inflation in final goods price



(c) investment share

Fig. 4.7 Major differences in the macroeconomic dynamics of the three scenarios modeled with TEMPLE

4.3 Robustness, limitations and further work

4.3.1 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 Dupont et al. (2021b); Režný and Bureš (2019); Dale et al. (2012) 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 assumptions[15,16]: (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 grows, to give a growth rate of over 3%[17]; (ii) 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

[15]There 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.

[16]Note than we consider higher capital needs than Jackson and Jackson (2021) for renewable energies: in TranSim, the capital intensity of renewable energies is between 3 and 5 times higher than the one of fossil fuels; in TEMPLE, it is 10 times higher at the beginning of the transition. In the initial steady-state in TranSim, the capital costs make up 50% of the total costs for fossil fuels and 70% for renewables. In TEMPLE, it is 50% for fossil fuels and 90% for renewables. However, this difference is compensated by the assumption in TranSim that fossil capital stock has a lifetime twice longer than renewables, while both lifetimes are equal in TEMPLE.

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

reasons, the 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 TEMPLE[18].

4.3.2 Sensitivity analysis

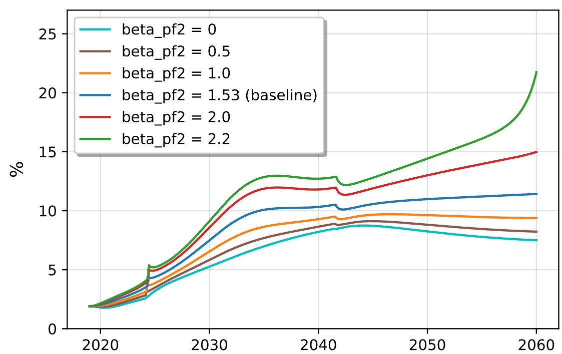


Fig. 4.8 Impact on inflation of varying jointly the adjustment speeds for cost-push and demand-pull inflation in the final goods' price

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

[18]The 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%.

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 4.3. 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 4.4, this alternative specification follows a linear increase up to the value of 1 in 2050.

The results of these sensitivity analyses are plotted in Appendix A.8. 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 4.8. Since the main driver of inflation in the price of final 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 Appendix A.7. Finally, increasing the adjustment speed of expected demand to actual demand in the final goods sector also adds inflationary pressure on the economy (see graph in Appendix A.8), 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 Appendix A.8.

4.3.3 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, 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 assume that our scenario does not require carbon capture and storage technologies, overlooking their potential energy, economic and human requirements (Sgouridis et al., 2019). On the contrary, our assumption to neglect technological and industrial improvements and the reliance on renewable EROI data from Dupont et al. (2018, 2020) which are now (at the time of completion of this PhD thesis) more than 7 years old might make our estimations too pessimistic, given the stronger-than-expected fall of renewable energy costs in recent years. Addressing these limitations and updating the model based on more recent data could change the simulation results. Nonetheless, while the peaking values of the different curves would be affected, the key outcomes and dynamics described above would still be valid.

In parallel to EROI considerations, 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). Finally, it has to be noted that the parallel drawn between the simulations results given above and a war economy faces several limitations. Indeed, a war economy is always associated with the short-term (Monnet, 2022). Exceptional efforts are accepted by the population against the promise of a return to normality and forced savings become spent after the end of the war. In TEMPLE, most changes are permanent and the savings remain blocked indefinitely. Besides, in a war economy, capital becomes destroyed and needs to be replaced at a fast pace, which fuels technological improvements which are absent from TEMPLE.

4.4 Conclusion

The transition to renewable energy sources represents a dual economic and energy challenge. In order to integrate this double perspective, we propose in this chapter 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 subsectors.

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 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 privatisation 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.

5

Modelling the energy transition of emerging economies with an ESOM

This chapter relies on the use of the EnergyScope model. As the focus of this thesis is not on the development of EnergyScope but rather on model coupling, the internal structure of EnergyScope is not covered in detail. For a full description of EnergyScope, see Limpens et al. (2019) (EnergyScope Typical Day) and Limpens et al. (2024) (EnergyScope Pathway). The online documentation of the model (Jacques and Limpens, 2024) details the input data, data sources and asumptions used for the case studies described in this chapter.

5 | Modelling the energy transition of emerging economies with an ESOM

In the previous chapter, an SFC model was coupled with an energy model based on world EROI curves. Such an approach allows to adopt a global perspective, where the burden of the transition cannot be outsourced to other countries or continents. However, it misses the diversity of realities of the energy transition in different countries, and does not allow to have a detailed vision of the energy system. Thus, we present in this chapter an Energy System Optimisation Model (ESOM), which gives a technology-rich description of the whole energy system of a given country. This model, *EnergyScope*, is applied to study the decarbonisation of Colombia and Turkey: first by representing a single target year with the version *EnergyScope Typical Day*, then by representing an entire transition pathway with the version *EnergyScope Pathway*. In both cases, the modifications made to the model to adapt to the local context are presented and the impact of some parameters are discussed. Some of these modifications are also ment to prepare EnergyScope for its coupling with an SFC model, which will be performed in Chapter 6.

The case studies of Colombia and Turkey were chosen for two main reasons. First, we required countries for which a GEMMES version was already available or was currently under construction, to open up the possibility of a GEMMES-EnergyScope coupling. Chapter 6 presents the coupled model applied to the case of Colombia, while the adaptation of the coupling to Turkey will be the object of future research. Second, Colombia and Turkey are especially relevant: the energy transition is expected to have significant economic impacts for both countries, but in different ways. On one hand, the Colombian economy relies massively on fossil fuel exports and is expected to suffer from the global energy transition. On the other hand, Turkey imports virtually all the fossil energy it consumes. A rapid domestic energy transition would be a real relief for its economy.

5.1 The EnergyScope Model

A family of models widely used for energy transition planning are the energy system optimisation models (ESOMs). These bottom-up models represent in detail multiple subsectors of a national energy system into a single, consistent framework. They then rely on an optimisation algorithm to navigate the large array of possible energy futures and put forward one transition pathway, which is computed as optimal regarding one or several criteria (DeCarolis et al., 2017).

EnergyScope is an ESOM which computes a least-cost design and operation of the entire energy system of a given country or region, including the electricity, heat and mobility sectors as well as non-energy demand. It is a linear model with a single-node spatial resolution. This model presents several advantages:

- a fine time granularity (i.e. hourly resolution), which is important for assessing the adequacy between demand and variable renewable energy (VRE) supply, as well as dimensioning the required energy storage capacities;
- a light, transparent formulation and a high computing efficiency;
- its open-source character. Working open-source naturally leads to transparency and reproducibility of results. Furthermore, it allows rapid improvement and extensions of the model through effective decentralised collaborations. Having open-source tools is also valuable when collaborating with public institutions of emerging economies. Governements can indeed have tight resources and might be reluctant to buy a new, unknown model for public policy purposes. This criterion was given to us as a decisive one by Departamento Nacional de Planeación (DNP - Colombia's National Planning Department) in their decision to adopt the model and collaborate with us.

Two main versions of EnergyScope exist. EnergyScope Typical Day (EnergyScope TD or ESTD) simulates the energy system for a target year in the future, regardless of currently installed capacities. Its computational time is typically less than a minute on a personal laptop (Limpens et al., 2019). Then, EnergyScope Pathway (PESTD) models the transition from the existing energy system to a long-term target. The transition path is segmented into five-year intervals, with instances of ESTD representing the state of the energy system every five years. The different instances of ESTD are linked to make one, large linear programming problem thanks to constraints which account for decommissioning of assets, new investments and societal inertia. The resulting optimisation problem generally assumes perfect foresight, although a myopic version is also available. Finally, the computational time remains low, typically around 15 minutes on a personal laptop (Limpens et al., 2024). In this chapter, Energy Scope TD is used in Section 5.2. The focus then shifts to EnergyScope Pathway in Section 5.3. The modifications made to EnergyScope TD and EnergyScope Pathway are respectively presented in Subsections 5.2.1 and 5.3.1.

5.2 Application of EnergyScope TD to the case of Colombia and Turkey

5.2.1 Additions to EnergyScope TD

EnergyScope was originally developed for analysing the Swiss energy system (Moret, 2017). It was then improved to become EnergyScope TD (Limpens et al., 2019), via an application to Belgium (Limpens et al., 2020). Overall, the different versions of EnergyScope have been mostly applied to European countries (e.g. Borasio and Moret, 2022; Dumas et al., 2022; Rixhon, 2024; Thiran, 2024).

The version of ESTD used in this thesis builds on the version from Limpens et al. (2019). The modelling of the cooling demand and technologies from Borasio and Moret (2022) is added onto it. Several novel technologies developed in Thiran (2024) are also added, like hydroelectric dam, electrofuels or concentrated solar power (CSP). Moreover, other technologies need to be added to reflect the specificities of emerging economies. First, the considered economies produce part of their fossil fuels domestically. A distinction is therefore made between local and imported coal, as well as local and imported gas. Gas technologies are assumed to be able to operate with both types of gas. For coal however, technologies running on local vs. imported coal are distinguished in terms of cost and efficiency (this is especially relevant for Turkey, where domestic coal is low-quality lignite, unlike imported coal). Second, coal stoves are added to the set of modelled technologies, as well as fossil-powered and electric motorcycles.

The costs of technologies are taken from Rixhon (2024), except when a value has been updated in Thiran (2024): in this case, the latter value is used (e.g. for wind and solar technologies). In all previous versions of EnergyScope, the costs were expressed in constant euros for the year 2015. Using such currency for a Latin American country makes little sense. Thus, as described in Appendix B, all costs are converted into constant United States Dollars (USD) for the year 2021. The evolution of technology costs between 2015 and 2021 is captured via the CEPCI (Chemical Engineering's Plant Cost Index). The costs of resources are recomputed based on specific data from each country (i.e. using data from the Colombian national energy plan for the case of Colombia and IEA data for Cyprus (as a proxi) for the case of Turkey – Minenergía-UPME, 2020; UPME, 2023; IEA, 2024b).

The exhaustive list of equations for the version of ESTD used in this thesis can be found in the online documentation (Jacques and Limpens, 2024).

5.2.2 Modelling the Colombian energy system: previous works

At the United Nations 2019 Climate Action Summit, Colombia committed to the goal of reaching carbon neutrality by 2050. Planning towards this goal has, to date, resulted in the Country's Nationally Determined Contribution (NDC) and its *E2050 Vision*. The biggest climate mitigation effort is expected to come from the forestry, land-use and agriculture sectors, which are responsible together for 55% of the country GHG emissions, as opposed to 35% for the energy sector (IEA, 2023).

In parallel to the *E2050 Vision*, the National Energy Plan (PEN, Minenergía-UPME, 2020) and its latest update (UPME, 2023) present an analysis of the energy system, assessing the effects of different scenarios and green policy mixes. To do so, the PEN relies on the use of the LEAP model (Low Emissions Analysis Platform), an energy system model based on simulation rather than optimisation. While providing useful scenario analyses, neither the PEN, nor the E2050 Vision explicitly take into account the economic impacts of the loss of fossil fuel exports when planning the transition of the Colombian energy system. The intertwine between the energy system, cross-border financial flows and the national currency's exchange rate are not considered.

To our best knowledge, the only ESOM having been applied so far to study deep decarbonisation pathways of the Colombian whole energy system is the Open Source Energy Modelling System (OSeMOSYS) model. Plazas-Niño et al. (2023) calibrated this model to Colombia, computed a cost-optimal trajectory to reduce the energy sector's emissions by 90% and computed the associated investment costs. Plazas-Niño et al. (2024) further expanded this work by modelling a potential supply-demand hydrogen chain in Colombia and simulating a set of 10 scenarios regarding the development of the hydrogen economy. The authors then suggested modifications to the National Hydrogen Roadmap (Minenergía, 2021) based on their simulation results. Among promising avenues for future research, Plazas-Niño et al. (2023) highlighted the interest of assessing the fiscal and macroeconomic impacts of the energy system decarbonisation.

5.2.3 Modelling the Colombian energy system with EnergyScope TD

We first model the year 2021. Indeed, starting with a past year allows us to verify that ESTD is able to accurately reproduce the Colombian energy system. 2021 is the last year for which all required data are fully available. The calibration of ESTD to the 2021 Colombian system is described in Jacques and Limpens (2024), including all input data, data sources and assumptions. Namely, coal, oil, diesel and all types of bioenergy are assumed to be fully local in Colombia. We also model the Colombian energy system in 2036, half-way between 2021 and the target year for carbon neutrality of 2051. Three scenarios are investigated with EnergyScope for the year 2036: one where the design of the energy system is guided only by cost-minimisation, without any constraint on GHG emissions; one where they are limited to 40% of their value in 2021; and one where carbon neutrality is imposed.
Table 5.1 shows the resource use in each case, together with the corresponding GHG emissions. Note that the emissions indicated, expressed in million tons of carbon dioxide equivalent, cover both the direct and indirect emissions related to the combustion and the entire lifecycle of resources. The emissions related to combustion only are also computed and used to validate the calibration of EnergyScope to the year 2021 (see Jacques and Limpens (2024) for more details). Figures 5.1-5.4 represent Sankey diagrams for each case study, showing the conversion chain from resources to end-use. Figure 5.5 shows the cost of the energy system in each of the four cases.

The information conveyed by Table 5.1 tells us that in 2021, 73% of final energy consumption in Colombia consisted in fossil fuels. The electricity sector was decarbonised to a large extent though, with 75% of electricity generated by hydro power plants. Biomass was mostly used for domestic heat generation, especially for cooking and heating. 70% of passenger transport was provided by public mobility (i.e. buses and coaches), while private transport consisted in motorcycles (52%), gasoline cars (33%) and cars running on natural gas (15%).

To model the energy system in 2036, we multiply all End-Use Demands (EUDs) from 2021 by a factor 1.4, which reflect the increased energy use due to economic growth, drawing on projections from the PEN (Minenergía-UPME, 2020; UPME, 2023). The costs of all technologies also evolve. For example, the CAPEX of utility-scale PV decreases by 40% between 2021 and 2036, while the CAPEX of gasoline cars increases by 5%. The cost of

	2021		2036 – no constraint		2036 – 60% emissions reduction		2036 – net zero emissions	
	Resources [TWh/year]	Emissions [$MtCO_2$-eq./year]	Resources [TWh/year]	Emissions [$MtCO_2$-eq./year]	Resources [TWh/year]	Emissions [$MtCO_2$-eq./year]	Resources [TWh/year]	Emissions [$MtCO_2$-eq./year]
Coal	41.0	16.5	120.9	48.5	0	0	0	0
Natural gas	79.7	21.2	13.0	3.5	13.0	3.5	0	0
Gasoline	63.4	21.9	3.0	1.0	3.0	1.0	0	0
Diesel	70.9	22.3	114.3	36.0	43.1	13.6	0	0
Bioethanol	6.2	0	0	0	0	0	45.0	0
Biodiesel	2.5	0	0	0	50.0	0	50.0	0
Light fuel oil	40.8	12.7	57.1	17.8	57.1	17.8	2.8	0.9
Woody biomass	38.9	0.5	24.6	0.3	24.6	0.3	24.6	0.3
Wet biomass	0	0	29.9	0.4	29.9	0.4	29.9	0.4
Non-renewable waste	0	0	10.3	1.6	10.3	1.6	0	0
Hydro-electricity	60.7	0	62.7	0	109.4	0	109.4	0
Solar electricity	0.4	0	34.4	0	44.0	0	42.3	0
Wind electricity	0	0	0	0	12.9	0	117.6	0
Electricity imports	0.1	0	3.3	0.7	0	0	0	0
Total	**400.3**	**95.1**	**463.5**	**109.7**	**397.2**	**38.0**	**421.7**	**1.5**

Table 5.1 Resource use and GHG emissions of the Colombian energy system in each of the four case studies modelled with EnergyScope TD.

most resources is assumed to increase during that period (e.g. +40% for gasoline, +55% for local gas, +30% for local coal), drawing on analyses from Minenergía-UPME (2020); UPME (2023).

We observe with Table 5.1 and Figure 5.2 that without imposing a constraint on GHG emissions in 2036 and by relying only on the cost-minimisation of the energy system, the GHG emissions increase by 15% compared to 2021. We can further express these emissions as:

$$\text{GHG} = \text{EUD} \times \frac{\text{FE}}{\text{EUD}} \times \frac{\text{GHG}}{\text{FE}} \tag{5.1}$$

where FE stands for Final Energy. When looking at the evolution of the intensities $\frac{\text{FE}}{\text{EUD}}$ and $\frac{\text{GHG}}{\text{FE}}$, we see that between 2021 and 2036, the final energy intensity of the economy decreases by 5% and the emissions intensity of final energy decreases by 13%. Yet, this is not enough to compensate for the 40% increase in EUD. The reason why the intensities do not decrease more is the larger reliance on domestic coal, which is very emitting and energy inefficient. Domestic coal is indeed extremely cheap in Colombia. Moreover, the use of natural gas shrinks compared to 2021 due to diminishing local resources (the modelling assumption therefor is taken from Willis Towers Watson, 2023) and high cost of gas imports, while natural gas was a good substitute for coal. Gasoline nearly disappears in the simulation: it is replaced by diesel for freight and public mobility, and electric cars replace gasoline cars for private mobility. Besides, hydro-electricity production remains equal to its 2021 value whereas 18.6 GW of new PV is installed.

When imposing a 60% reduction in GHG emissions compared to 2021, Table 5.1 and Figure 5.3 tell us that the design of the 2036 energy system drastically changes. 5.5 GW of additional PV is installed compared to the previous case study, as well as 3 GW of offshore wind. The total capacity of hydro-electric dam nearly doubles thanks to 10.7 GW of new capacity. The mobility system is essentially the same as in the previous case study, except that 50 TWh of fossil diesel becomes replaced by locally grown biodiesel. In this case study, the increased electrification of the energy system due to the integration of renewable energies allows to reduce the final energy intensity $\frac{\text{FE}}{\text{EUD}}$ by 30% compared to 2021.

Finally, going from -60% emissions to carbon neutrality for the 2036 energy system is achieved by installing 24 GW of additional offshore wind turbines and by cultivating 45 TWh of bioethanol (see Figure 5.4), on top of the 50 TWh of biodiesel already present in the previous case study. Such domestic culture of bioethanol and biodiesel amounts to covering 2.5% of Colombia's surface with biomass for biofuel production. In 2021, 40% of Colombia's surface was dedicated to agriculture[1]. Part of the electricity produced by the new wind turbines is converted into green hydrogen (using 6.1 GW of electrolysers) then into methanol, to provide a substitute for the light fuel oil previously fulfilling the non-energy demand.

[1]Note that developing the cultivation of biofuels can create pressure on other activities and on ecosystems, which might result in increased GHG emissions due to land use change. These aspects are not considered in the model.

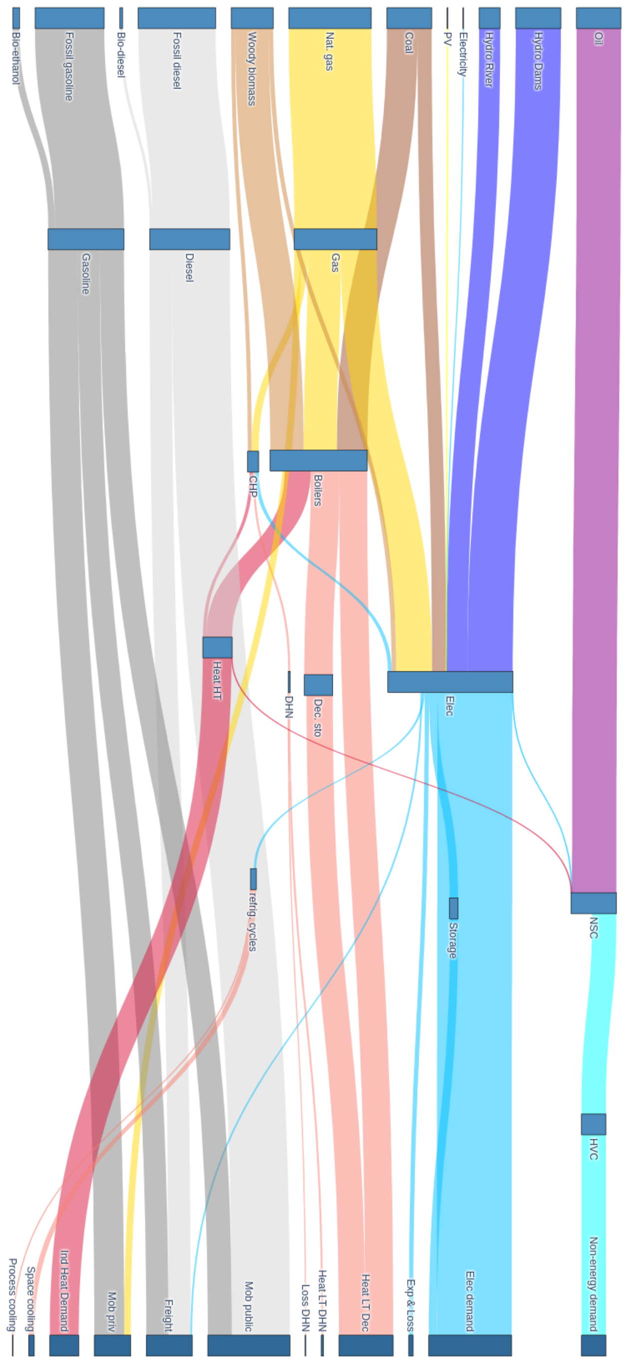


Fig. 5.1 Calibration of EnergyScope TD to the year 2021 for Colombia. The sum of all resources on the left-hand side of the Sankey diagram amounts to 400.3 TWh/year

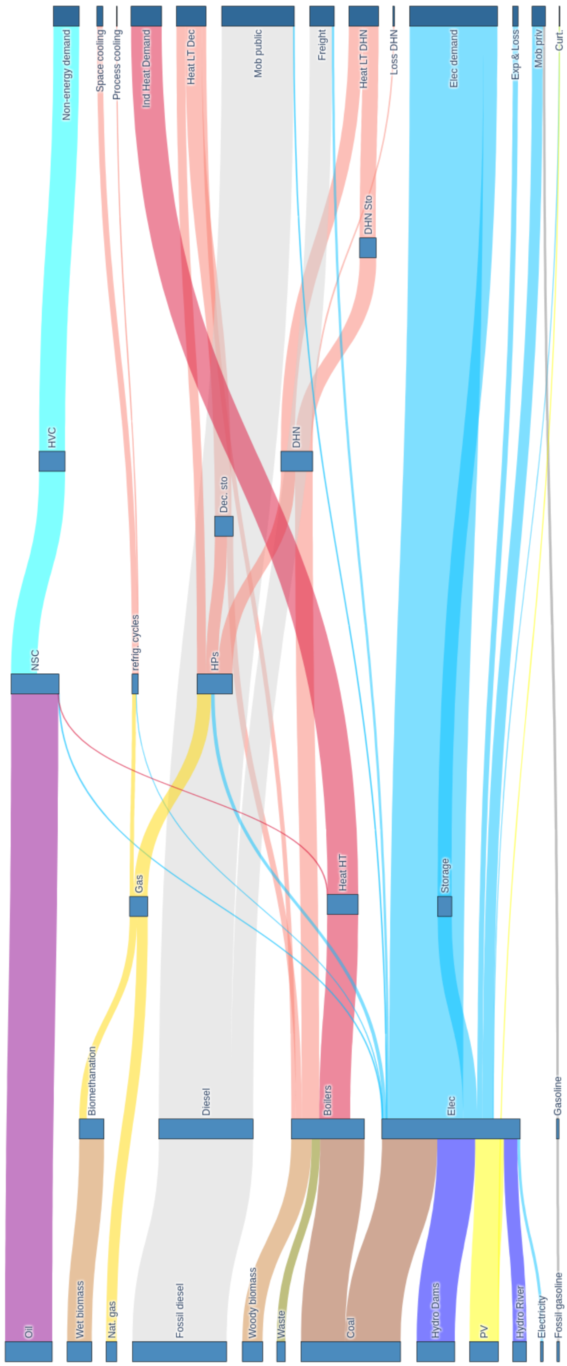


Fig. 5.2 Cost-optimal Colombian energy system in 2036 with no constraint on GHG emissions. The sum of all resources on the left-hand side of the Sankey diagram amounts to 463.5 TWh/year

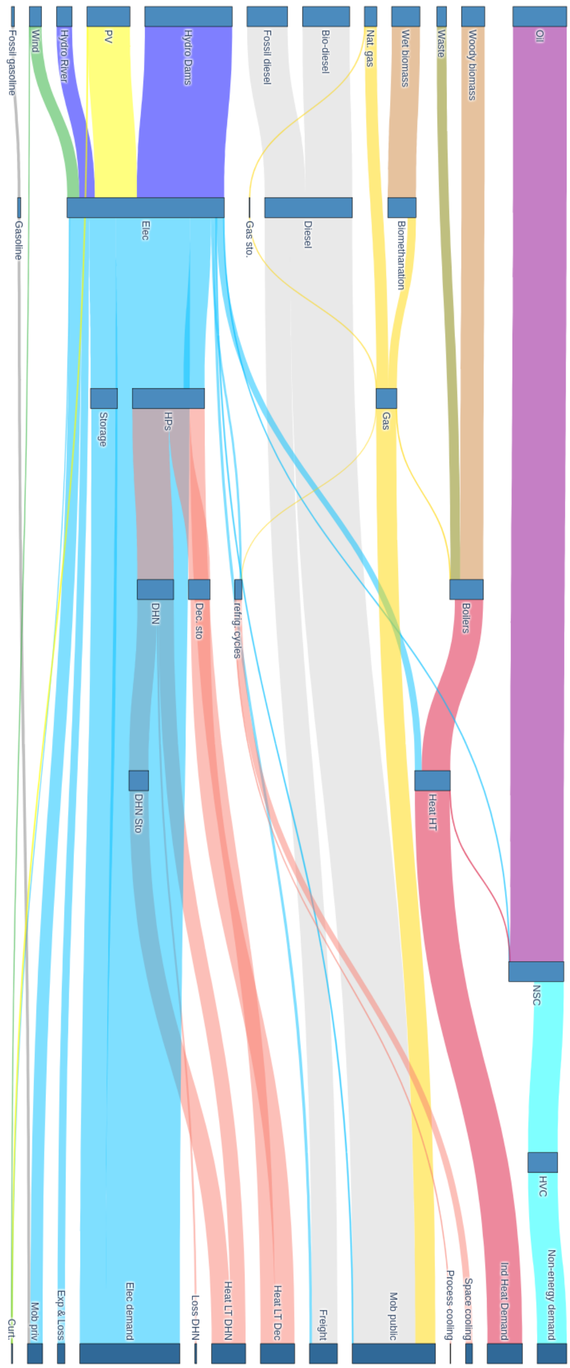


Fig. 5.3 Cost-optimal Colombian energy system in 2036 with an imposed 60% reduction in emissions compared to 2021. The sum of all resources on the left-hand side of the Sankey diagram amounts to 397.2 TWh/year

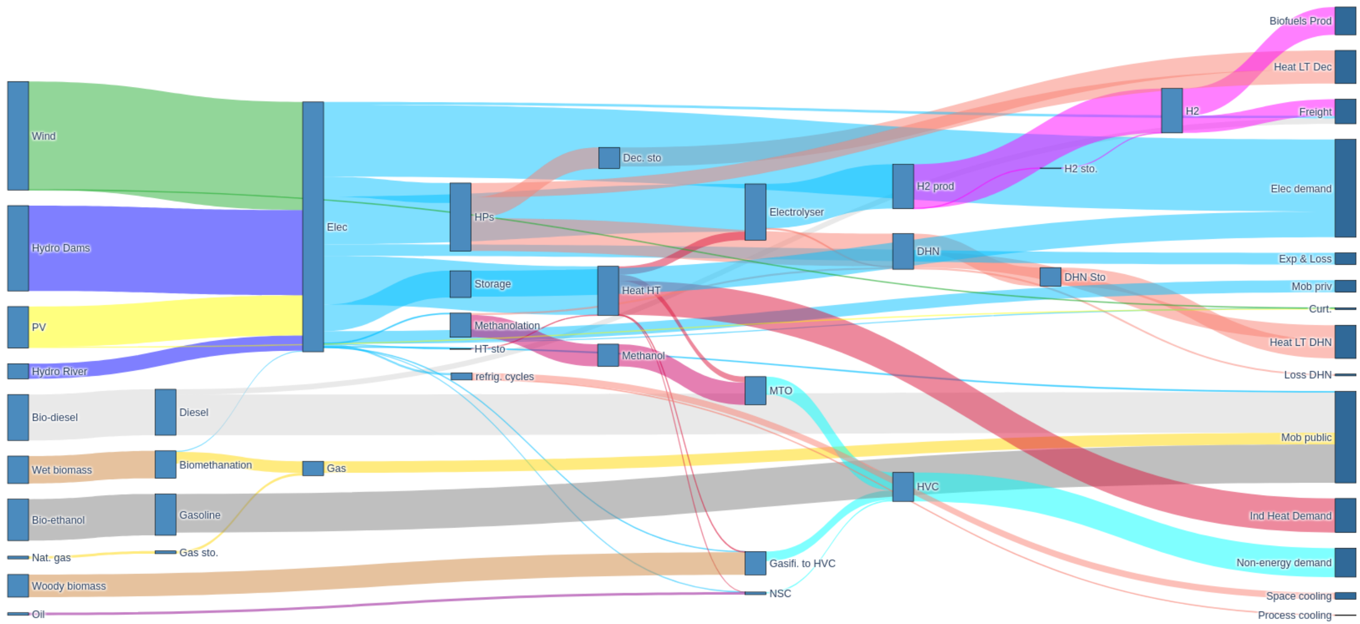


Fig. 5.4 Cost-optimal Colombian energy system in 2036 with imposed net zero emissions. The sum of all resources on the left-hand side of the Sankey amounts to 421.7 TWh/year

Regarding the cost of the energy system in each case study, Figure 5.5 indicates that its composition does not vary significantly with decarbonisation. In 2021, the cost of resources represented only 13% of the Colombian energy system's total cost, despite its high reliance on fossil fuels. Indeed, as a producer of coal, oil and gas, Colombia had access to these resources at a low cost. In 2036, the cost of resources represents a similar share of the total cost for all three scenarios: the cost of fossil fuels in the high emitting energy system is replaced by the cost of biofuels in the decarbonised one, biofuels being between 2 and 10 times more expensive than locally produced hydrocarbons (depending on the pair of fuels compared). The net-zero energy system is 21% more expensive than the uncontrained energy system in 2036, while the energy system with 60% emissions reduction is only 4% more expensive.

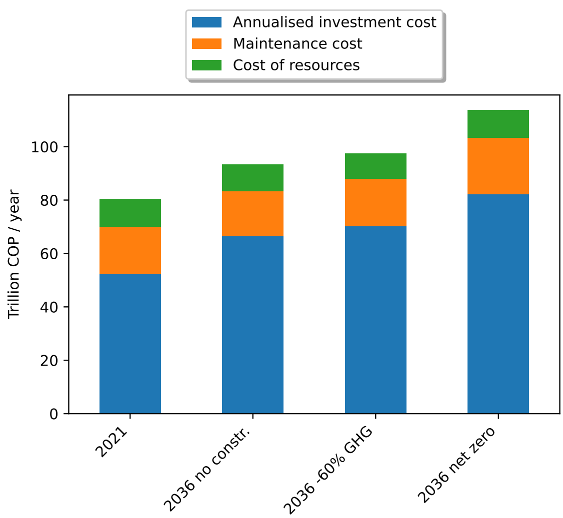


Fig. 5.5 Cost of the energy system in the different case studies. The cost composition does not vary significantly with decarbonisation because of the specific situation of Colombia being a fossil fuels producer.

5.2.4 Modelling the Turkish energy system: previous works

Turkey announced its NDC as a declaration of intent before the Paris Agreement in 2015. It consisted in reducing its GHG emissions *"by up to 21% from a business-as-usual level by 2030"* (IEA, 2021b). However, Turkey only signed the Paris Agreement in 2021, making it the last G20 country to ratify the text

(Sahin et al., 2022). This ratification led to an updated NDC aiming for net zero emissions by the year 2053, and came together with several initiatives for planning the road to carbon neutrality. The most authoritative one is Turkey's National Energy Plan (Ministry of Energy and Natural Resources, 2022). This plan maps out the route to 2035, using an ESOM derived from the PRIMES model of the EU Commission. It has a relatively similar scope as EnergyScope, but relies on market equilibrium rather than cost minimisation. The World Bank also performed a modelling exercise (the Country Climate and Development Report or CCDR) for planning decarbonisation in Turkey (World Bank Group, 2022b). The energy module of the Turkish CCDR uses the World Bank's Electricity Planning Model (EPM), which cost-optimises the design and operation of the electricity system. This model focuses exclusively on the power system and is thus complemented by other models, such as the Transport, Energy and GHG emissions model (D-SEG). The results of these models are then fed to a CGE model (MANAGE) and a macro-structural model (MFMod) to analyse the macroeconomic impacts of the sectoral policies. Another notable report is Turkey's Decarbonisation Roadmap, which was produced by Istanbul Policy Center and the Sabancı University (Sahin et al., 2022). This report depends on simulations from independent models for the electricity, transport, buildings and industry sectors. The electricity model used is the TR-Power optimisation model (see Kat (2023) for a recent version).

Thus, a number of analyses have already been produced for the decarbonisation of the Turkish energy system, all relying on ESOMs. The application of EnergyScope TD, then Pathway to Turkey relies on several data and assumptions of these ESOMs. The main advantage of using EnergyScope is that it is fully open-source, unlike all three ESOMs mentioned above. Moreover, EnergyScope combines electricity, transport, buildings and industry in one single, light modelling structure, instead of running separate models and then iterating to harmonise their results. In the context of this thesis, applying EnergyScope Pathway to Turkey allows to compare and discuss the sensitivity of the model in its applications to Turkey and Colombia (see Section 5.3). Unlike for Colombia in Chapter 6, no coupling between GEMMES and EnergyScope is carried out for Turkey in this thesis. It will however be the object of future research.

5.2.5 Modelling the Turkish energy system with EnergyScope TD

We first model the Turkish energy system in 2019, since it is the last year for which all required data are fully available. The calibration of ESTD to accurately reproduce the 2019 Turkish energy system is described in Jacques and Limpens (2024). Namely, oil and natural gas are assumed, as a simplification, to be fully imported in Turkey (according to IEA (2021b), around 10% of Turkish oil consumption and 1% of gas consumption were in fact covered by domestic supply in 2019). The only domestic fossil fuel resource considered in EnergyScope is therefore coal. Local Turkish coal is typically low-quality lignite. Machines using domestic coal are differentiated from machines using imported coal in the model, in terms of cost and efficiency. We also model the Turkish energy system in 2034, halfway through the transition. All fossil fuels are again assumed to be imported except domestic coal, thus neglecting the recently discovered gas fields which might enter in operation in the coming decade. For the sake of brevity and since unlike Colombia, Turkey will not be further studied in Chapter 6, only one scenario is investigated for the year 2034, where GHG emissions are imposed to be 60% lower than in 2019. Table 5.2 shows the resource use for each year, together with the corresponding GHG emissions. Figures 5.6 and 5.7 display the Sankey diagrams of the energy system in 2019 and 2034, respectively.

Table 5.2 and Figure 5.6 inform us that in 2019, 87% of final energy consumption in Turkey consisted in fossil fuels. Indeed, as highlighted by IEA (2021b), such share of fossil fuels in the energy supply positioned Turkey as having the ninth-highest reliance on fossil fuels among IEA member countries. Yet, renewable energy capacity was non-negiligible with 28.5 GW of hydropower plant, 7.6 GW of onshore wind, 6 GW of PV and 1.2 GW of geothermal plant installed. 37% of passenger transport was provided by public mobility (mainly buses and coaches) while private transport consisted in diesel cars (50%), cars running on natural gas (38%) and gasoline cars (12%).

To model the energy system in 2034, all End-Use Demands (EUDs) from 2019 are multiplied by a factor 1.42, based on a projection from the Ministry of Energy and Natural Resources (2022) that reflects the increased energy use due to economic growth. We observe in Table 5.2 and Figure 5.7 that the enforcement of the 60% decrease in GHG emissions leads to the phasing out of local coal and gasoline. Natural gas, which is less emissive, is still abundantly used. To compensate for the reduction in fossil fuels use, important additional renewable energy capacities are installed: 104.6 GW of PV, 40.4 GW of onshore wind, 45.1 GW of offshore wind (including 35.9 GW of floating offshore), 7.8 GW of hydro power and 3 GW of geothermal plants. 4.8 GW of nuclear energy is also deployed, corresponding to the planned commissioning of the Akuyu power plant (World Bank Group, 2022b). The 40 GW of gas turbines which were present in 2021 are decommissioned. Instead, the natural gas supply is used for refrigeration and freight (using trucks running on natural gas). Although rational from an abstract cost-optimisation perspective, such use of natural gas would still need to be confronted with other considerations that the model does take sufficiently into account, such as the costs of developing different types of gas networks and safety concerns.

	2019		2034 – 60% emissions reduction	
	Resources [TWh/year]	Emissions [MtCO_2-eq./year]	Resources [TWh/year]	Emissions [MtCO_2-eq./year]
Local coal	281.5	122.2	0	0
Imported coal	144.9	53.4	8.7	3.2
Natural gas	440.9	117.6	422.1	112.5
Gasoline	13.0	4.5	0	0
Diesel	214.9	67.7	65.4	20.6
Bioethanol	0	0	0	0
Biodiesel	0	0	0	0
Light fuel oil	220.2	68.6	107.1	33.4
Woody biomass	40.0	0.5	66.7	0.8
Wet biomass	0	0	250.0	3.0
Non-renewable waste	0.1	0	0	0
Geothermal energy	31.5	0	31.6	0
Hydro-electricity	88.9	0	123.0	0
Solar electricity	19.2	0	178.1	0
Wind electricity	22.3	0	301.0	0
Electricity imports	0.6	0.2	0.4	0
Uranium	0	0	104.4	0.4
Total	**1518.0**	**434.6**	**1734.1**	**173.9**

Table 5.2 Resource use and GHG emissions of the Turkish energy system in the two case studies modelled with EnergyScope.

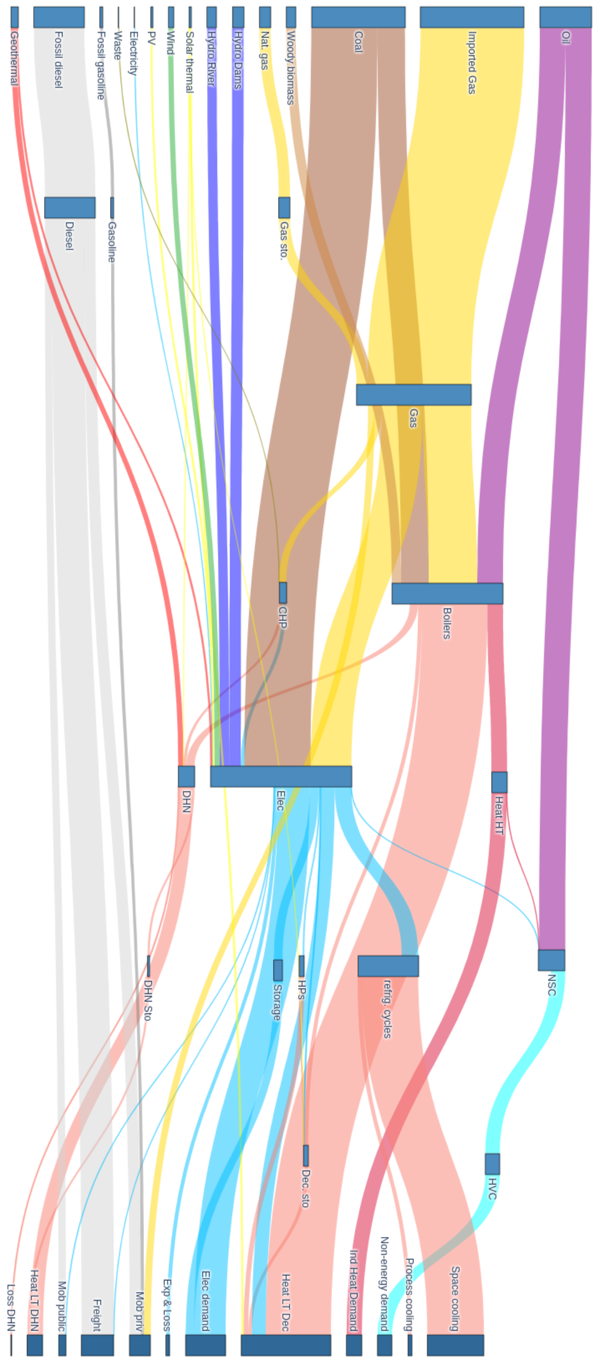


Fig. 5.6 Calibration of EnergyScope TD to the year 2019 for Turkey

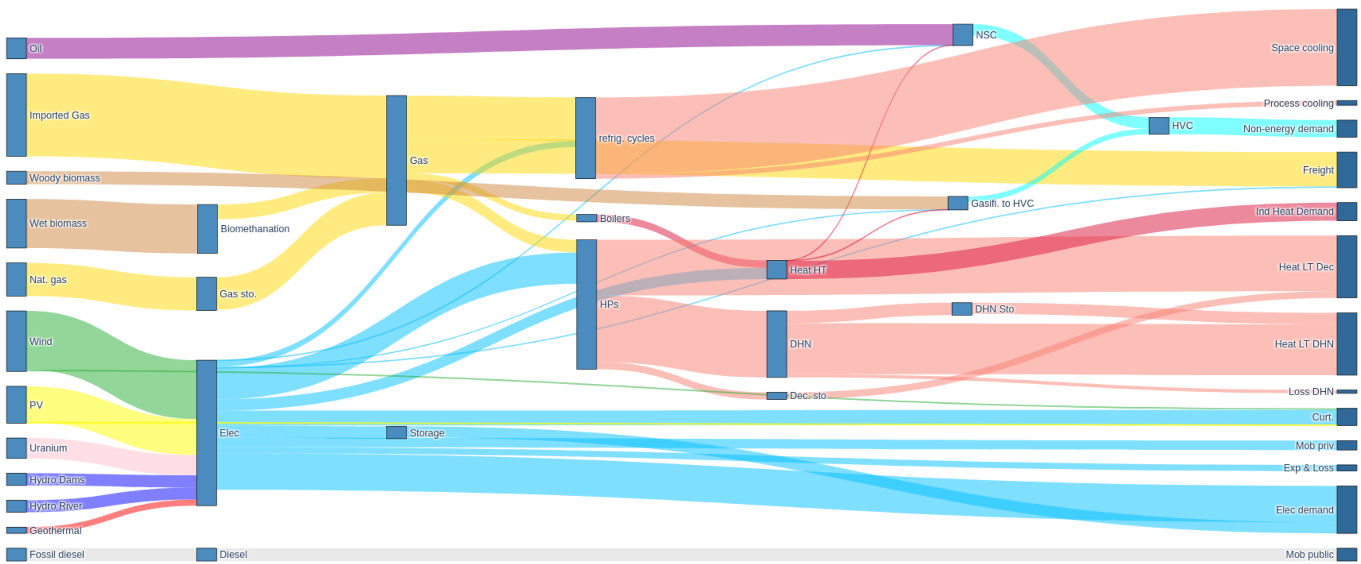


Fig. 5.7 Cost-optimal Turkish energy system in 2034 with an imposed 60% reduction in emissions compared to 2019

5.3 Application of EnergyScope Pathway to the case of Colombia and Turkey

5.3.1 Improving the macroeconomic features of EnergyScope Pathway

EnergyScope Pathway is primarily an engineering model, focused on the technical description of the energy system. Yet, since the optimisation criterion is the total energy system cost, macroeconomic aspects also play a role in the model. We further develop the economic aspects of EnergyScope Pathway in this thesis, for two main reasons. First, such improvements allow to gain new insights in the evolution of the energy system, as discussed in the following sections. Second, these modifications are a pre-condition for meaningfully coupling EnergyScope with the GEMMES macroeconomic model, as will be carried out in Chapter 6. Hence, we present in Appendix B a set of modifications to allow EnergyScope to better take into account the fluctuating character of the economic environment in which it operates. More specifically: (i) we allow the discount rate to change value every five years; (ii) we explicitly model the imported components in the energy system and how their price is affected by the international exchange rate; (iii) we allow EnergyScope to be fed by energy demand projections coming from a macroeconomic model.

The new input data related to these modifications are given to EnergyScope as CSV files:

- *r_discount.csv*;
- *Technos_information.csv*;
- *exchange_rate.csv*;
- *EUD_YEAR.csv*.

The files can either be produced by a macroeconomic model in the frame of a coupling or be edited by hand. Further details about the open-source codes and programmation languages used are given in Appendix D.

Besides, we also allow for the possibility to replace the hard constraint on GHG emissions by a carbon tax embodied in EnergyScope (see Appendix B.3). This option is not used in this chapter, but is activated in Chapter 6.

5.3.2 Modelling a decarbonisation path for the Colombian energy system with EnergyScope Pathway

As explained in Section 5.1, EnergyScope Pathway is composed of several instances of ESTD separated by five-year intervals. The first instance is set to year 2021. The other instances of ESTD then correspond to the years 2026, 2031, etc. until the final year 2051. The calibration of ESTD to the year 2021 for Colombia was already described in Section 5.2.3. The input data used for modelling the year 2036 with ESTD are given in Jacques and Limpens (2024). The data for years 2021 and 2036 are then extrapolated into trajectories to give input data for the years 2026, 2031, 2041, etc[2].

To compute the import content of energy technologies, we rely on the Supply Use Tables from DANE (National Administrative Department of Statistics). These tables allow us to accurately pinpoint the contributions of local production versus imports for individual technologies[3]. Godin et al. (2024) already highlighted that manufactured goods were largely imported in Colombia. Energy technologies are no exception: our import content data indicate that 60% of the value of the Colombian energy system in 2021 was imported. Green technologies (e.g. solar panels, wind turbines, electric vehicles) have even greater import contents.

The possibility to export electrofuels (i.e. hydrogen, methane, methanol or ammonia produced with renewable electricity and hence labelled as "green") is also introduced in EnergyScope Pathway (see Appendix B.4). The choice to export electrofuels or not is left to the cost-optimisation algorithm.

The value of the imposed upper bound for GHG emissions decreases linearly until carbon neutrality is enforced in 2051. We prefer here to use a ceiling for GHG emissions rather than a carbon cost (see Appendix B.3) to prevent changes in the value of the discount rate, which directly modify the intertemporal time preferences, from interfering with the impact of the carbon cost trajectory.

[2]The entire set of input data for EnergyScope Pathway is given in the following github repository: `https://github.com/energyscope/EnergyScope_coupling_GEMMES/tree/eec22143ff7f8bbf37aa764ed2b6aec911df78a7/EnergyScope_Pathway/ESMY/STEP_2_Pathway_Model`

[3]The resulting matrix giving the import content of each energy technology can be found at the following link: `https://github.com/energyscope/EnergyScope_coupling_GEMMES/blob/eec22143ff7f8bbf37aa764ed2b6aec911df78a7/EnergyScope_Pathway/run/Technos_information_CO.csv`

Three cases are thus studied with EnergyScope Pathway, in order to discuss the impact on the simulations of the variation in the new input data listed in Section 5.3.1:

1. A constant exchange rate and a constant discount rate of 6% (i.e. the value used by Plazas-Niño et al., 2023) are kept throughout the transition;
2. The exchange rate is kept as is but the discount rate is set to a constant value of 10%, in line with the Colombian Central Bank's interest rate values observed during the last two years;
3. The discount rate is reset to its previous value of 6% but an increasing trend is taken for the exchange rate, which doubles between 2021 and 2051. This exchange rate trajectory is taken from the GEMMES simulation outputs of the scenario *"Loss of fossil fuel exports with no export diversification – Global Transition"* from Chapter 3 of Godin et al. (2024). It is very close to the projections from Ministerio de Hacienda y Crédito Público (2022).

Case study	Technology	2021	2031	2041	2051
	Hydro	11.9	16.8	20.8	25.0
	PV	0.1	18.4	46.0	76.8
1.	Onshore wind	0	2.2	7.3	7.3
	Offshore wind	0	5.9	12.3	42.4
	Electrolyser	0	0	0.1	14.3
	Hydro	11.9	16.8	20.8	25.0
	PV	0.1	15.4	37.9	67.5
2.	Onshore wind	0	2.2	7.3	7.3
	Offshore wind	0	3.1	10.8	28.6
	Electrolyser	0	0	0	7.1
	Hydro	11.9	16.8	20.8	25.0
	PV	0.1	14.8	62.0	102.0
3.	Onshore wind	0	2.2	7.3	7.3
	Offshore wind	0	31.0	48.8	48.8
	Electrolyser	0	9.0	18.0	18.4

Table 5.3 Total installed capacities (in GW) of selected renewable energy technologies and electrolysers in the three case studies for Colombia.

Table 5.3 presents the installed capacities of key renewable energy technologies in each of the three case studies. We observe that the variation of the discount rate and exchange rate have a significant impact on the design of the energy system, particularly regarding the export of e-fuels on international energy markets. In the first case study, the cost-optimisation algorithm chooses to export up to 100 TWh of green hydrogen. However, these exports completely cease in the second case study: the higher discount rate diminishes the weight of the export revenues in comparison with the required upfront investment in the wind turbines, PV and electrolysers for producing the green hydrogen. The 7.1 GW of electrolysers installed are used to produce hydrogen solely for domestic consumption. In the third case study, on the contrary, the depreciation of the currency boosts the e-fuels exports, which reach 175 TWh at their peak year.

Given the proximity of EnergyScope with OSeMOSYS and the use of many similar data (see Jacques and Limpens, 2024), it would be tempting to compare our results with the ones from Plazas-Niño et al. (2023, 2024). Unfortunately, such comparison is hampered by the important difference in the growth rate of end-use demands between the two models, as well as by the important difference in time granularity.

5.3.3 Modelling a decarbonisation path for the Turkish energy system with EnergyScope Pathway

As already recalled above, EnergyScope Pathway is made up of several instances of ESTD separated by five-year intervals. The first instance for Turkey is set to year 2019. The other instances of ESTD then correspond to the years 2024, 2029, etc. until the final year 2049. The calibration of ESTD to the year 2019 for Turkey was already described in Section 5.2.5. The input data used for modelling the year 2034 with ESTD are given in Jacques and Limpens (2024). The data for years 2019 and 2034 are then extrapolated into trajectories to give input data for the years 2024, 2029, 2039, etc[4].

[4] The entire set of input data for EnergyScope Pathway is given in the following github repository: `https://github.com/energyscope/EnergyScope_coupling_GEMMES/tree/eec22143ff7f8bbf37aa764ed2b6aec911df78a7/EnergyScope_Pathway/ESMY/STEP_2_Pathway_Model`

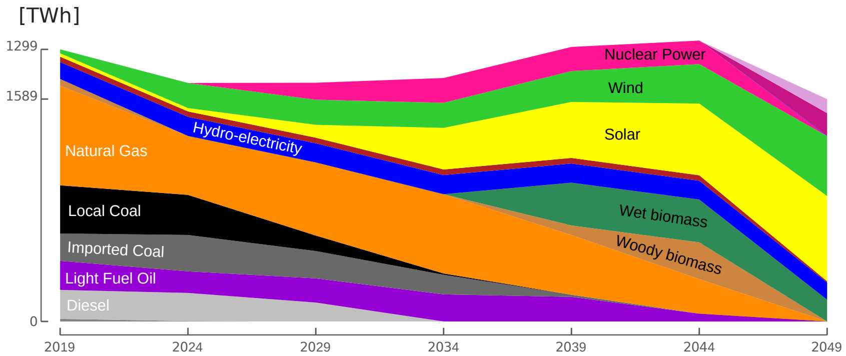
Since we do not dispose of official data for the import content of energy technologies, we re-use the data for Colombia and adapt them based on our knowledge of the Turkish economy[5]. We do not explore the possibility of Turkey exporting electrofuels and we block this option in EnergyScope, in order to focus on changes in energy technologies that meet domestic energy needs. The value of the imposed upper bound for GHG emissions decreases linearly until carbon neutrality is enforced in 2049.

Like for Colombia, three cases are studied with EnergyScope Pathway:

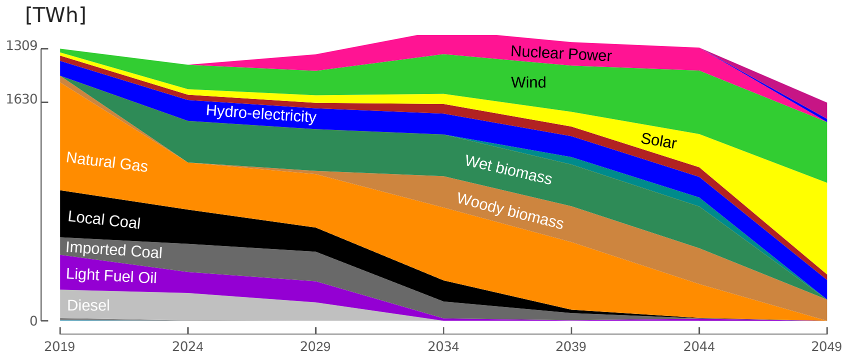
1. A constant exchange rate and a constant discount rate of 6%;
2. The exchange rate is kept as is but the discount rate is set to a constant value of 50% during the first 5-year phase, then 10% for the following phases (in 2024, the Turkish Central Bank rose its interest rate to 50% to try to halt the ongoing currency crisis);
3. The discount rate is taken back at its constant value of 6% but an increasing trend is taken for the exchange rate, with a doubling of the exchange rate value between 2019 and 2049. This evolution is the same as the one used for Colombia above, since we do not dispose of projections for Turkey. It is necessarily *ad hoc* and does not especially reflect the trends observed in Turkey in recent years.

The first two case studies present very similar results, indicating that the discount rate has little influence on the cost-optimal transition path of the Turkish energy system. The third case study, on the other hand, shows that currency depreciation can have significant impacts. Figure 6.3 compares the final energy consumption of Turkey in the first and third case study: in the third case study, depreciation of the currency directly penalises all fossils fuels (which are imported) except domestic coal. Local resources take a more prominent role in the transition, notably wet biomass and woody biomass at the beginning of the transition, and solar energy at the end.

[5] The resulting matrix giving the import content of each energy technology for Turkey can be found at the following link: `https://github.com/energyscope/EnergyScope_coupling_GEMMES/blob/eec22143ff7f8bbf37aa764ed2b6aec911df78a7/EnergyScope_Pathway/run/Technos_information_TK.csv`



(a) Case study 1: constant nominal exchange rate.



(b) Case study 3: currency depreciation.

Fig. 5.8 Final energy consumption of Turkey in the first and third case studies modelled with EnergyScope Pathway.

5.4 Conclusion

We showed in this chapter how EnergyScope could be used to study the energy system of Colombia and Turkey. In Section 5.2, we saw that the application of EnergyScope TD alone could already provide useful insights in the planning of the transition. In Section 5.3, we improved some features of EnergyScope Pathway, to better account for the broader economy within which the transition takes place. We observed that these macroeconomic aspects could significantly impact the simulation results of EnergyScope Pathway, especially the currency exchange rate. We will build upon these first modifications in Chapter 6, where we couple EnergyScope with GEMMES to study in an integrated framework the intertwine between energy transition, macroeconomic and financial dynamics.

6

Coupling an SFC model with an ESOM to study the impacts of the energy transition in Colombia

This chapter relies on the use of the EnergyScope model (see Chapter 5) and of the GEMMES model adapted to the Colombian economy. As the focus of this thesis is not on the development of GEMMES but rather on model coupling, the equations of GEMMES Colombia are not presented in detail. For a full description of these equations, together with the input data, data sources and asumptions used for calibration, see Chapter 2 of Godin et al. (2024). The Colombian transition scenarios developed in this thesis are based on and extend the scenarios presented in Chapter 3 of Godin et al. (2024). Prior reading of this work may prove useful for a full understanding of the present chapter.

6 | Coupling an SFC model with an ESOM to study the impacts of the energy transition in Colombia

In this chapter, we couple the Energy System Optimisation Model (ESOM) presented in Chapter 5 with an SFC model briefly presented in Chapter 2. The ESOM is the version of EnergyScope Pathway incorporating a carbon tax (see Appendix B.3), simply denoted by "EnergyScope" in the following pages. The latter model, GEMMES, can be seen as a country-specific version of the macroeconomic module used for TEMPLE. However, it is adapted to take into account the detail of all cross-border flows, which greatly complexify the model. Its number of economic equations is around ten times greater than TEMPLE. The following section introduces the work and presents the Colombian context, before giving the chapter's structure.

6.1 Introduction

The low-carbon transition presents a major economic and financial risk to fossil fuel exporting countries (Daumas, 2023b). Colombia is a good example of this. The country produced 1% of global oil in 2023 and ranked seventh worldwide in the list of coal exporters (IEA, 2024a). Fossil fuels accounted for 55% of Colombia's exports and represented 15% of government revenues in that year (Godin et al., 2024). Due to carbon neutrality pledges of the largest energy consuming countries, Colombian coal exports are expected to undergo a rapid decline (Willis Towers Watson, 2023). On the other hand, oil exports should also fall, namely due to the depletion of local reserves and the 2023 government ban on new exploration permits (The Guardian, 2023). The country will therefore need to cope with significant economic and financial imbalances at the same moment it tries to mobilise resources to invest in its green transition and reach its own target of carbon neutrality for the year 2050. Walking on such a thin rope requires a substantial amount of forward-looking analysis and planning. To this end, we develop a coupling between two existing models. The first one is GEMMES, an empirical model designed to represent the economic and financial dynamics undergone by a developing economy open to international financial flows. The second one is EnergyScope, a bottom-up energy model for analysing decarbonisation pathways for a country's energy system. Both models have already been used for a large number of works and case studies (e.g. Truong et al., 2023; Moreno et al., 2024; Rixhon et al., 2021; Borasio and Moret, 2022; Dumas et al., 2022). In this chapter, we develop a generic coupling methodology between the two models and apply it to Colombia. Different scenarios are presented for the Colombian transition and their impacts are analysed on the energy system, the real economy and the financial sphere.

This chapter is structured as follows. Section 6.2 reviews the relevant literature. Section 6.3 presents the two models, the coupling methodology and the modifications applied to both models for the purpose of model coupling and application to Colombia. Section 6.4 describes the scenarios analysed with the coupled model, while Section 6.5 presents the simulation results. Section 6.6 discusses the impacts of alternative scenarios and parameter values, as well as the strengths and weaknesses of the coupling. Finally, Section 6.7 concludes.

6.2 Literature review

6.2.1 Economic and financial risks of the energy transition for Colombia

Since the landmark speech of Carney (2015), a vast literature has developed on economic and financial risks associated with the low-carbon transition. Among the plurality of methodologies which emerged, an important framework for the analysis of transition risks was put forward by the Network for Greening the Financial System (NGFS), a global collaboration of central banks and financial supervisors. Such framework assesses transition risks by running alternative transition scenarios with macroeconomic models (Daumas, 2023b). Based on such scenarios, the pioneering work of Bernal-Ramírez et al. (2022) investigates transition risks on a series of macroeconomic and financial variables for the case of Colombia. However, their partial equilibrium approach does not allow to account for the interactions and feedback loops between the real economy and the financial sphere. Another assessment of the transition risk for Colombia is given in a report from Willis Towers Watson (2023). The authors use a bottom-up methodology, focusing on sectors from the real economy facing concentrated transition risk. It highlights a material downside risk in exports, between 2022 and 2050, equal to 27% of the 2019 Colombian GDP. Godin et al. (2024) use the GEMMES macroeconomic model applied to Colombia to further study the implications that such reduction in exports would have on financial variables, such as currency depreciation. Willis Towers Watson (2023) notes that the abatement of Colombian domestic emissions, in line with the country's decarbonisation target, *"will likely mean increased government spending at precisely the time when government revenues are falling because of the global transition"*. Godin et al. (2024), in turn, study the impacts of alternative schemes to finance the domestic green transition and shed light on the key role of re-industrialisation for ensuring the viability of the transition.

6.2.2 Modelling Colombia's energy system

Previous works for modelling the decarbonisation of the Colombian energy system have already been presented in Section 5.2.2. As noted, the intertwine between the energy system, cross-border financial flows and the national currency's exchange rate are considered in none of them. Plazas-Niño et al. (2023) explicitly mention the investigation of these links as a valuable path for future study.

6.2.3 Coupling macroeconomic models with ESOMs

Although they are able to provide a detailed bottom-up description of the entire energy system, ESOMs are highly dependent on exogenous inputs such as projections for the evolution of the energy demand, prices of fuels and costs of energy technologies. To reduce this fragility and analyse the macroeconomic impacts of the modelled energy pathways, it is common to couple an ESOM with a top-down macroeconomic model. Among others, Krook-Riekkola et al. (2017) coupled EMEC, a one-step recursive dynamic CGE model of the Swedish economy with the TIMES-Sweden model. Fattahi et al. (2023) performed a coupling for the case of the Netherlands between ThreeME, a Neo-Keynesian CGE model already incorporating a bottom-up description of the energy system with a more detailed ESOM, IESA-Opt. Crespo del Granado et al. (2018) present an advanced coupling between a CGE, an ESOM and several other technical modules, and provide a literature review of existing couplings and methodologies in the field. In all these cases, the coupled macroeconomic model is a Computable General Equilibrium (CGE) model, with all the limitations described in Section 2.2. To our knowledge, no coupling has ever been realised between an ESOM and an SFC model like GEMMES, allowing to represent the interactions and feedback loops between the real economy and the financial system. Including in the picture the financial dynamics which are at play is crucial for accurately discussing the impacts of the transition on Colombia, whose macroeconomic dynamics have become extensively dependent on the inflows and outflows of foreign capital since the early 1990s (Villar and Rincón, 2003; Botta et al., 2016).

6.3 Materials and methods

6.3.1 The Colombian versions of GEMMES and EnergyScope

GEMMES is already presented in Section 2.3.1. Godin et al. (2024) calibrated and adapted the model to the Colombian economy. Moreno et al. (2024) performed a sensitivity analysis with it and discussed the vulnerability of the Colombian economy to the low-carbon transition. While a full detail of the equations, structure and assumptions of the Colombian GEMMES model is given in Godin et al. (2024), it is worth outlining that this version of GEMMES includes 6 sectors: private firms (i.e. non-financial companies), financial companies, households, government, central bank and rest of the world. This model does not include an energy sector, an energy demand or an energy price. Yet, the weight of fossil fuels in the government budget, in exports, etc. is explicitly accounted for. The foreseen reduction in the exports of fossil fuels is implemented via an exogenous degrowth rate. Regarding EnergyScope Pathway, its application to Colombia and the related modifications are presented in Section 5.3.

6.3.2 Coupling between the two models

For coupling GEMMES and EnergyScope, we favour a soft-linking approach (see Chapter 1) since it allows us to preserve all details and richness of each model. More precisely, the coupling is a bi-directional soft-linking in the sense understood by Fattahi et al. (2023) and Fragkos and Fragkiadakis (2022): the two models are linked through a set of specific variables and an iterative process that guarantees convergence.

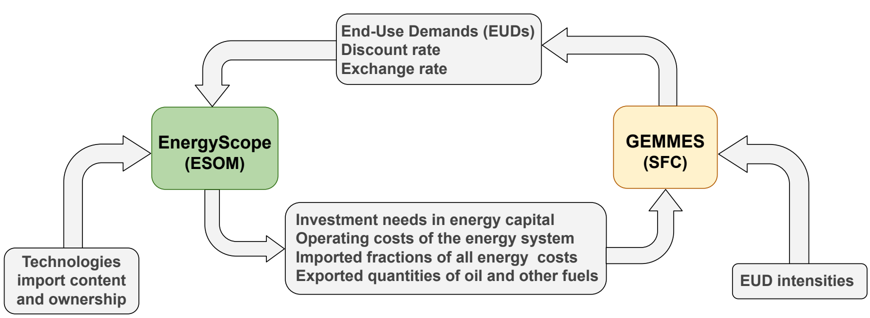


Fig. 6.1 Coupling of GEMMES with EnergyScope: information exchanged between the two models and additional exogenous inputs

Figure 6.1 lists the information which is exchanged between the two models throughout the process, as well as the additional exogenous inputs which are given to each model. Note that only the new inputs are shown in the figure; the original models already rely on a number of exogenous inputs (e.g. evolution of the cost of resources and technologies during the 30-year transition period for EnergyScope, evolution of the rest of the world GDP, interest rate and inflation for GEMMES). The additional information is exchanged via CSV files. In practice, fourteen CSV files are used, plus one CSV file providing an initial template for formatting EUDs and another one for saving intermediary results of EnergyScope:

- *r_discount.csv*;
- *Technos_information.csv*;
- *exchange_rate.csv*;
- *EUD_YEAR.csv* (7 such files are used, one every 5 years of the transition period);
- *Thetas.csv*;
- *Energy_system_costs.csv*;
- *shares_cooling.csv*;
- *shares_LTH.csv*;
- *EUD_template.csv* (file provided to give a template for *EUD_YEAR.csv*);
- *CO2_costs_COP.csv* (used by EnergyScope to temporarily save the trajectory of the carbon price expressed in local currency).

To be able to exchange and process such information, both models require adaptations. Hence, we describe in the following sections the main modifications which are applied to each model. Further information is provided in Appendix C. The architecture of the related codes is then described in Appendix D.

6.3.3 Computation of EnergyScope economic inputs with GEMMES

In Section 5.3.1, we described a series of new input data fed to EnergyScope. In the context of the coupling, these inputs are computed by GEMMES, as illustrated on Figure 6.1.

Discount rate

The discount rate represents the temporal preference between present and future financial value. In the case of EnergyScope, it is not especially supposed to represent the cost of financing a project. Furthermore, since EnergyScope takes the perspective of a central planner, the discount rate does not have to embody financial risks. We therefore use as discount rate the variable i^P from GEMMES:

$$r^{\text{discount}} = i^P \tag{6.1}$$

The discount rate is thus given by the central bank's interest rate rather than the commercial banks' interest rate, since the latter includes a risk mark-up.

International exchange rate

The exchange rate used by EnergyScope (i.e. $\frac{\text{COP}_y}{\text{USD}_y}$ in Equation B.5 in Appendix) is the nominal exchange rate e^N from GEMMES.

End-Use Demands

EnergyScope takes as inputs *End-Use Demands* (EUDs) (e.g. low-temperature heat for space heating, high-temperature heat for industrial processes, freight expressed in tons·km, etc.). The original GEMMES model does not explicitly include an energy system and requires additions to compute these EUDs. We choose to compute them sector-wise, based on the economic activity of each sector. Table 6.1 shows, for each economic sector in GEMMES, to which EUDs it contributes. It also indicates if the EUD is computed based on production (Y), capital stock (K) or number of workers (L) of the sector. The central bank and rest of the world are not mentioned in the table since they do not directly contribute to the domestic energy demand.

	Private firms	Financial Corporations	Government	Households
ELECTRICITY	∼Y	∼L	∼L	∼K
HEAT LOW T (SH)	∼K	∼L	∼L	∼K
HEAT LOW T (HW)	∼K			∼K
HEAT HIGH T	∼Y			
SPACE COOLING		∼L	∼L	∼K
PROCESS COOLING	∼Y			
MOB. PASSENGER				∼K
MOB. FREIGHT	∼Y			
NON-ENERGY	∼Y			

Table 6.1 Indicates for each economic sector in GEMMES and for each EUD in EnergyScope, if the sector contributes to the EUD or not. If the sector contributes to the EUD, it is indicated whether the demand is proportional to production ("Y"), capital stock ("K") or the number of workers ("L") of the sector. "∼"=proportional to. "T"=Temperature. "SH"=Space heating. "HW"=Heating water. "MOB."=Mobility.

For each entry of Table 6.1, the EUD is derived from the production, capital stock or number of workers from GEMMES through an exogenous EUD intensity θ^{EUD}_{Sector}. These intensities evolve through time; their values are read from the input file *Thetas.csv*. The calibration performed for the case of Colombia to obtain such values is described in Section 6.4.1. Finally, the sectoral EUDs computed in GEMMES are aggregated using the mapping given in Table 6.2 to match the sectoral decomposition of EUDs in EnergyScope.

GEMMES	EnergyScope
Households	Households
FCs Government	Services
NFCs	Industry
MOB. PASSENGER (Households) MOB. FREIGHT (NFCs)	Transportation

Table 6.2 Correspondence between EUD sectors in GEMMES and EnergyScope. "FCs"=Financial Corporations. "NFCs"=Non-Financial Corporations. "Mob."=Mobility.

Concretely, GEMMES reads a template from the input file *EUD_template.csv* and then writes, based on that template, the EUDs every five years in the files *EUD_YEAR.csv*.

6.3.4 Adding the energy system costs into GEMMES

All the information given from EnergyScope to GEMMES, summarised in Figure 6.1, transits through the file *Energy_system_costs.csv*. GEMMES did not previously include an energy system, except for the exogenously determined exports of fossil fuels. Handling those new inputs therefore requires to adapt GEMMES internal equations. All modifications applied to GEMMES equations, including the ones related to the computation of EUDs, are given in Appendix C.1. Part of the sectoral intermediate consumption, final consumption and investments in GEMMES are determined by exogenous inputs from EnergyScope, while the remaining fraction keeps being endogenously calculated as was previously the case. The costs of all resources are assigned to private firms, which then pass on to consumers the ones associated to domestic heating, cooling and mobility. The carbon tax from EnergyScope is also fed to GEMMES, to appear in the price function of private firms; it thus contributes to passing on the investment costs of decarbonisation onto energy consumers. Nevertheless, all revenues of the carbon tax paid by households and firms are immediately redistributed to them, in equal proportions to the amount of carbon tax collected. So we do not model a direct redistributive effect of the carbon tax through government intervention.

6.3.5 Post-processing of EnergyScope outputs

The energy system costs fed to GEMMES are not the raw inputs from EnergyScope. These raw inputs first necessitate a substantial amount of post-processing. Appendix C.2 describes in detail this post-processing process. Among others, EnergyScope gives the investments and operational costs per technology and per resource, but not per economic sector. The following files from GEMMES are used for attributing the costs related to EnergyScope heating and cooling technologies between the different economic sectors from GEMMES:

- *shares_cooling.csv*;
- *shares_LTH.csv*.

6.3.6 Execution

GEMMES is a continuous time model while EnergyScope has a discrete behaviour: its inputs and outputs are given as discrete values with an annual or five years frequency. To render both models compatible, the outputs from GEMMES need to be averaged over periods corresponding to the time resolution of EnergyScope. In turn, the discrete outputs of EnergyScope are converted to continous time using cubic splines interpolation[1]. This interpolation method allows to provide smooth outputs to avoid abrupt transitions. Thus, the coupled model consists in the combination of a linear program (EnergyScope) with a set of continuous differential equations. The linear program is solved using a linear optimisation solver, while the system of differential equations is solved numerically using the Dormand-Prince method. The codes of the coupled model are presented in Appendix D.

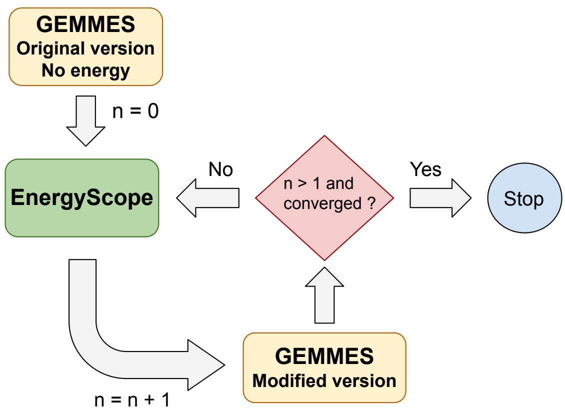


Fig. 6.2 Convergence process

Finally, we describe the convergence process between the two models based on the methodology from Fattahi et al. (2023). Figure 6.2 provides an overview of the different steps. As a start, the original model from Godin et al. (2024), which does not require any inputs from EnergyScope, is run. A first set of EUDs is computed out of its outputs using the method from Section 6.3.3. The convergence process can then effectively begin: at each iteration of the loop, EnergyScope, then GEMMES, are run taking inputs from each other. The convergence criterion is tested after each run of

[1]Note that the cubic splines algorithm which was chosen avoids any undesirable oscillatory behaviour in the interpolation.

GEMMES: if verified, the algorithm stops. If not, another iteration begins, and so on until the convergence criterion is finally met. We use the same convergence criterion as Fattahi et al. (2023), that the change in absolute value in all *EUDs* of all sectors *s* at any time *t* of the transition path between two iterations is lower than a certain value. The only difference is that we are satisfied with a value of 3%, while Fattahi et al. (2023) required 1%[2]:

$$\left| \frac{EUD_{s,t,n} - EUD_{s,t,n-1}}{EUD_{s,t,n-1}} \right| \leq 3\% \qquad \forall s,t \text{ and } n > 1.$$

6.4 Calibration and scenarios

6.4.1 Calibration to the case of Colombia

The calibration of GEMMES to Colombia is fully described in Godin et al. (2024) and their base year of 2019 is re-used as a starting point for our simulations. Since we modify some equations of GEMMES to incorporate inputs from EnergyScope, the parameters of these equations are re-calibrated thanks to the numerical optimisation method CMA-ES (Covariance Matrix Adaptation-Evolution Strategy). This algorithm is used to find the values of the parameters which minimise the distance between variables of the GEMMES-EnergyScope coupling in the baseline scenario (see below) and the same variables in the scenario *"Loss of fossil fuel exports with no export diversification – Global Transition"* from Chapter 3 of Godin et al. (2024).

The Calibration of EnergyScope Pathway to Colombia was already given in Section 5.3.2. According to information received from Departamento Nacional de Planeación (DNP - the National Planning Department), the Colombian energy sector, excluding fossil fuels extraction and refining and excluding the transport sector, accounted for 2.8% of the country GDP in 2021. This figure is used to adjust to each other the economic variables and costs given by both models.

Regarding EUD intensities (the θ^{EUD}_{Sector}, whose values are saved in the file *Thetas.csv*), they are computed such that our baseline scenario (see below) exhibits the same evolution for each EUD as the projections from Minenergía-UPME (2020), which assume important improvements in energy efficiency.

[2] In fact, in our case, the value of the convergence criterion remains larger than 1%, whatever the number of iterations of the loop. This is due to properties of the optimisation solvers used in EnergyScope.

6.4.2 Scenarios

Godin et al. (2024) envisage three scenarios which determine Colombia's exogenous exports of fossil fuels: a Baseline scenario, a Conservative scenario and a Global Transition Scenario. In this paper, we choose to only consider the Global Transition Scenario (more precisely, the scenario *"Loss of fossil fuel exports with no export diversification – Global Transition"*), which is the most adverse one to Colombia. According to that scenario, the ongoing energy transition in the rest of the world implies a fall in foreign demand for Colombian coal. Together with the depletion of domestic oil resources, this induces a reduction in Colombian fossil fuels exports at a constant rate of 8.5% per year (i.e. a reduction of coal exports by 12% and of oil exports by 6% per year). We further assume that the price of fossil fuels grows at a constant exogenous rate of 3%, like all international prices in the model. In a second step, alternative trajectories for the fossil fuels price will be discussed.

We investigate four scenarios with our coupled GEMMES-EnergyScope model:

1. The **baseline scenario** is obtained by running the coupling with no enforcement of the energy transition. EnergyScope optimises the cost of the energy system with a zero carbon price. Despite the absence of a carbon price, the cost-optimisation pushes the energy system to evolve and become more efficient. This scenario is very close to the one *"Loss of fossil fuel exports with no export diversification – Global Transition"* from Chapter 3 of Godin et al. (2024) but differs in some minor aspects[3];
2. In the **energy transition scenario**, we apply a carbon tax which grows linearly from 0 in 2021 to 70 USD_{2021} per t CO_2 in 2051. This latter value is the smallest carbon price which allows to obtain a carbon neutral energy system by 2051. The constraints on the speed of deployment of renewable energies are taken into account in EnergyScope. These constraints reflect namely the time required for the permitting process, for the engagement with indigenous communities affected by the projects, or the time to set up public auctions.
3. The **green industrialisation scenario** is the same as the previous

[3] Namely, the rate of decrease of fossil fuels exports receives an abrupt shock in the simulations from Chapter 3 of Godin et al. (2024), while in our case it ramps up progressively during the initial two years due to the cubic splines interpolation algorithm.

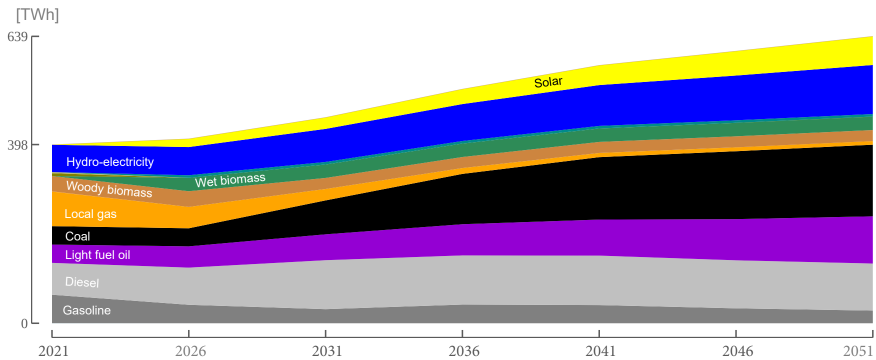
one, except that a different (lower) import content is used for the technologies PV, Onshore Wind, Offshore Wind, Electrical Cars and Electrical Motorcycles. This reflects the potential creation of new value chains in Colombia, centered around the green transition.

4. The **hydrogen export scenario** adds on top of green industrialisation the possibility to export hydrogen to international markets. The possibility for Colombia to play a role in these markets is indeed widely accepted (IEA, 2021a; IRENA, 2022). In this scenario, we allow for the maximal level of ambition described in Plazas-Niño et al. (2024) (the "Full Hydrogen Economy" scenario). That is, we consider an upper bound on green hydrogen production of 213 TWh/year (derived from the 6.4 Mt/year of Plazas-Niño et al. (2024) by using a conversion factor of 33.3 TWh/Mt). The limit is implemented in EnergyScope by imposing a maximum installed capacity for electrolysers, growing linearly from 0 GW in 2021 up to 27 GW in 2051.

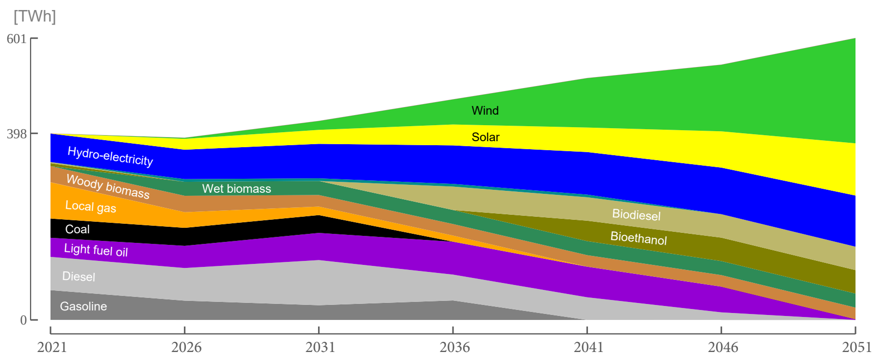
6.5 Results

The coupled model converges in three iterations for each scenario. Figure 6.3 shows the final energy consumption obtained in the baseline and transition scenarios, while Figure 6.4 gives the corresponding greenhouse gases emissions. Table 6.3 reports the installed capacities of several renewable energy technologies in the four scenarios.

In the baseline scenario, without a carbon tax, no transition takes place in Colombia. The local gas resource is used up and local oil continues to be extracted and consumed (assuming the ban on new exploration permits is lifted). Since imported gas is more expensive than local one, natural gas is progressively replaced by other energy sources. Growth in energy demand is met by increasing the domestic use of Colombian coal, which no longer finds buyers abroad due to the global green transition. The growth in energy demand is also met by installing new hydro power plants and solar panels, to reach 25 and 37 GW of installed capacity respectively by 2051. Greenhouse gases (GHG) emissions are temporarily reduced in 2026 thanks to improvements in energy efficiency and fuel substitution, before being overtaken by the rise in energy demand. By 2051, GHG emissions become 52% higher than in 2021. Regarding final energy consumption, it is 61% higher in 2051. When dividing energy consumption by the GDP expressed in constant 2021 USD, we see that final energy intensity, on the other hand, becomes reduced by 41% in 2051 compared to 2021.



(a) Baseline scenario



(b) Energy transition scenario

Fig. 6.3 Final energy consumption of Colombia in the studied scenarios

In the energy transition scenario, the local gas resource is also used up, but the consumption of oil is being reduced starting from 2031, to reach zero in 2051. Coal is phased out as soon as 2036. Energy demand becomes fulfilled mainly by wind (56 GW installed in 2051) and solar power (65 GW). Growth in hydroelectricity is identical to the baseline scenario, reaching the maximum potential assumed. Biomass is also cultivated (covering up to 2.5% of Colombia's surface) to supply bioethanol and biodiesel for buses and trucks. 8.6 GW of electrolysers are installed in 2051 to provide green hydrogen, transformed into methanol then into high-value chemicals to provide a substitute for petrochemicals. The final energy intensity of GDP becomes reduced by 47% in 2051 compared to 2021. This reduction is in line with the Colombian National Energy Plan (IEA, 2023). It is more important than in the baseline scenario thanks to a more pronounced electrification of the energy sector. Finally, gross GHG emissions of the energy sector are progressively reduced to reach a near-zero value in 2051.

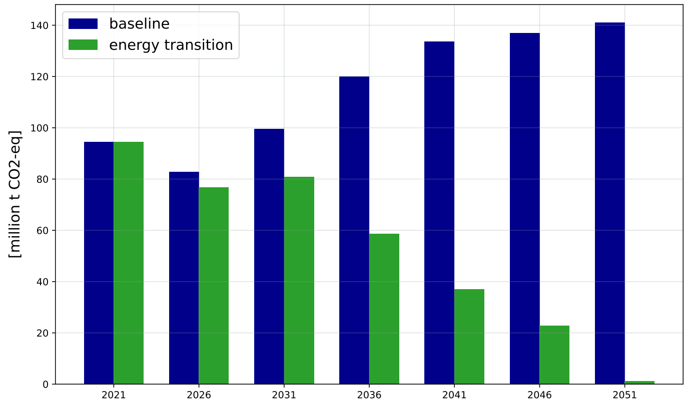
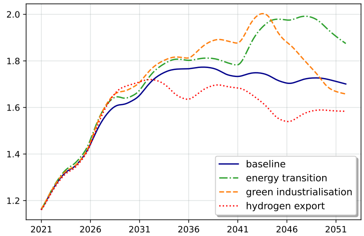


Fig. 6.4 Greenhouse gases emissions of the Colombian energy system in the two first scenarios. The GWP100a-IPCC2013 metric is used (Stocker et al., 2013). It covers the emissions related to the extraction, transportation and combustion of the resources used in the entire energy system.

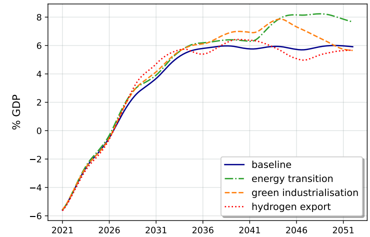
Table 6.3 further shows that the deployment of wind turbines and solar panels is slightly faster in the green industrialisation scenario compared to the energy transition scenario. The import content of these technologies indeed becomes lower with green industrialisation, hence reducing their cost and favouring their deployment. In the hydrogen export scenario, 132 GW of PV, 56 GW of wind and 23 GW of hydro are in place in 2051. They namely provide electricity to 16 GW of electrolysers, which produce 128 TWh of green hydrogen. This figure is broadly the same as in the third case study of Section 5.3.2, where EnergyScope's sensitivity analysis highlighted the strong dependence of green hydrogen exports upon the exchange rate trajectory. (Note that a hydrogen production of 128 TWh is only 60% of the maximal level of ambition described in Plazas-Niño et al. (2024) – more hydrogen production would only be profitable with an even stronger currency depreciation.) Around half of the hydrogen is exported, while the rest is transformed into methanol then into high-value chemicals as a substitute for petrochemicals. Electricity exports to neighbouring countries also reach 18 TWh in 2051, thanks to investments in 1.5 GW of additinal cross-border high-voltage lines. Such electricity exports of 18 TWh are a common feature between the four scenarios presented in this chapter. Overall, in the hydrogen export scenario, 14% of the country's final energy supply is used for the export of green hydrogen or electricity and the rest is dedicated to domestic energy consumption.

Scenario	Technology	2021	2031	2041	2051
Baseline	Hydro	11.9	16.8	20.8	25.0
	PV	0.1	13.9	24.4	36.8
	Onshore wind	0	0	0	0
	Offshore wind	0	0	0	0
	Electrolyser	0	0	0	0
Energy transition	Hydro	11.9	16.8	20.8	25.0
	PV	0.1	16.6	30.5	65.4
	Onshore wind	0	2.2	7.3	7.3
	Offshore wind	0	3.3	21.0	48.8
	Electrolyser	0	0	0	8.6
Green industrialisation	Hydro	11.9	16.8	20.8	25.0
	PV	0.1	18.7	35.6	63.0
	Onshore wind	0	2.2	7.3	7.3
	Offshore wind	0	5.5	26.1	48.8
	Electrolyser	0	0	0	8.1
Hydrogen export	Hydro	11.9	16.8	20.8	22.8
	PV	0.1	19.4	79.2	132.3
	Onshore wind	0	2.2	7.3	7.3
	Offshore wind	0	24.6	48.8	48.8
	Electrolyser	0	9.0	18.0	16.3

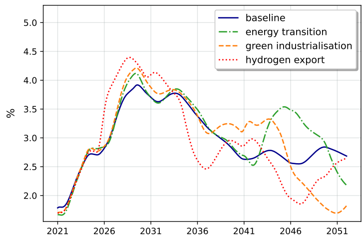
Table 6.3 Total installed capacities of selected renewable energy technologies in the four simulated scenarios.



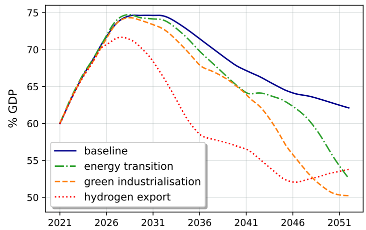
(a) Real exchange rate



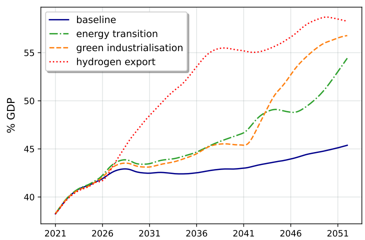
(b) Trade balance



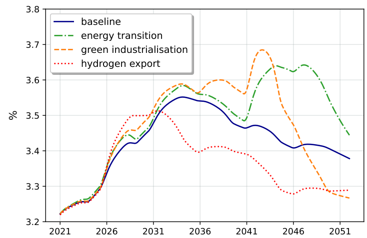
(c) Real GDP growth



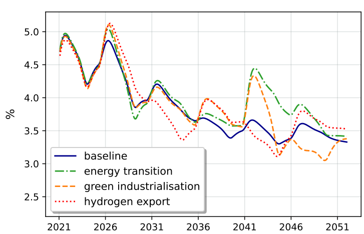
(d) Government total debt



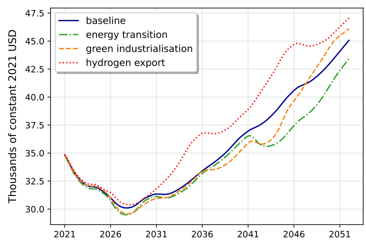
(e) Total debt of private firms



(f) Government foreign bond rate



(g) Consumer price inflation rate



(h) Per capita income

Fig. 6.5 Macroeconomic dynamics of the four scenarios simulated with the GEMMES-EnergyScope model

Figure 6.5 presents the macroeconomic dynamics obtained in the four scenarios[4]. The numerous bumps on the graph of the production price inflation rate are due to the values of the EnergyScope outputs transmitted to GEMMES: these outputs are originally piecewise constant functions, with constant values over five-year intervals. As described in Section 6.3.6, these functions are then smoothed using cubic splines to avoid abrupt transitions. Yet, the inflation rate, which is one of the variables most sensitive to the variations in the EnergyScope outputs, continues to be strongly affected by the changes every five years. A way to further smooth out the outputs from the coupled model would be to make an in depth modification of EnergyScope so that the energy system optimization would be run every year, instead of every five years. However, such modification would significantly increase the computational time of the coupled model.

The baseline scenario is very close to the scenario *"Loss of fossil fuel exports with no export diversification – Global Transition"* from Chapter 3 of Godin et al. (2024). In this scenario, given the fall in exports of fossil fuels and the drop in foreign direct investment to fossil fuel industry, peso depreciates strongly against the dollar in real terms (Panel a). In fact, the real depreciation of the PESO causes non-energy exports to rise significantly, which more than offsets the drop in fossil fuel exports, causing total exports to rise sharply. This pushes the trade balance to a surplus, which increases with the real depreciation of peso until mid 2030s (Panel b). As a result, the economy registers strong export-driven economic growth, which reaches over 3.5% annually in the same period (Panel c). There is consequently a slight decrease in the FX reserves to GDP ratio as the FX reserves growth cannot keep up with the growth of GDP. As a result, country risk increases, pushing up the interest rate on government foreign bond rate (panel f). Coupled with the increase on the domestic currency value of FX-denominated public debt and the fall in royalties and dividends from national oil and coal companies, total public debt to GDP ratio rises until mid 2030s (panel d), while the total indebtedness of private sector registers only a slight increase in the same period (panel e). Most importantly, the heavy depreciation of the domestic currency leads to a sharp drop in per capita income measured in 2021 US dollars (panel h) and it takes the country almost two decades

[4]The important variations which can be observed on most graphs in 2041 in the energy transition and green industrialisation scenarios are linked to evolutions in the energy mix of EnergyScope; they are not primarily caused by fluctuations endogenous to the macroeconomic model.

to reach back the 2021 per capita income levels. In short, the Colombian economy displays a typical depreciation-induced strong growth trajectory with low real incomes and low international purchasing power.

As the economy adjusts to the loss of fossil fuel exports and the absolute losses slow down around mid 2030s, the real exchange rate stabilises (panel a) and the dynamics we described above also stabilise or reverse. With a stable real exchange rate, the trade surplus flattens at around 6 per cent of GDP (panel b). Depreciation-driven GDP growth drops slightly and hovers between 2.5 and 3 per cent per annum between 2035 and 2050 (panel c). With a now stable currency, the country starts accumulating FX reserves and interest on public FX-denominated bonds (panel f) and public debt to GDP (panel d) start falling. Inflation also falls below the values in the first half of the simulation period (panel g) and per capita income in US dollars registers sustained growth (panel h)[5].

Now that we have described the general trends with the baseline scenario, we can discuss how the transition affects these dynamics in the three other scenarios. We observe that in the energy transition scenario, the additional investments performed in the energy system, which consist nearly entirely in imports, further increase the devaluation of the currency compared to the baseline scenario (Panel a). This leads to a stronger improvement in the trade balance than the baseline (panel b) and a stronger GDP growth rate (panel c). As a result, public debt to GDP ratio is lower, particularly in the second half of the simulation period (panel d). Finally, the high cost of energy investment imports causes the country risk to be higher and pushes up government FX bond rate (panel f).

Table 6.4 shows, for each of the three scenarios with an energy transition, the repartition by economic sectors of the extra investment compared to baseline. We see that most of this extra investment is carried by private firms. Part of it is passed on to consumers through rising prices (panel g) and the rest is absorbed by an increase in the debt of private firms (Panel e). Overall, the energy transition scenario results in lower living standards compared to baseline (Panel h). Note that the reduction of domestic oil consumption in the transition scenario allows to free more oil for exports.

[5]For a more thorough explanation of the dynamics described in this paragraph, see the description of the scenario *"Loss of fossil fuel exports with no export diversification – Global Transition"* in Chapter 3 from Godin et al. (2024).

Our coupling between the two models indeed includes the impact of the transition in the domestic energy sector (modelled with EnergyScope) on the degrowth rate of fossil fuels exports (modelled in GEMMES). However, such impact only arrives after 2031, when fossil fuels exports have already reached a low value. Thus, the macroeconomic dynamics are not greatly affected by this late, lower decrease in fossil fuels exports.

Scenario	Private firms	Financial Corporations	Government	Households
Energy transition	65%	0%	25%	10%
Green industrialisation	61%	0%	29%	10%
Hydrogen export	78%	0%	19%	3%

Table 6.4 Share of the energy transition investments between the four economic sectors modelled in GEMMES Colombia. These energy transition investments are computed as the additional investments compared to baseline.

On the other hand, green industrialisation scenario allows to partially offset the additional peso depreciation that we observe in the energy transition scenario, particularly in the last decade of the simulations. Hence the negative economic impacts induced by the energy transition are mitigated. Some indicators even end up in a better position in 2051 than in the baseline scenario, such as total public debt (Panel d), the interest rate on government bonds (Panel f) and the per capita income in constant dollars (Panel h). However, this comes at the expense of higher investments hence higher debt levels for private firms (Panel e).

Finally, the scenario with hydrogen exports on top of green industrialisation more than compensates for all the negative impacts of the domestic energy transition. The peso depreciates less than in baseline; total consumption, government debt, government bond rate and standard of living are all in better positions than in the three other scenarios. As indicated in Table 6.4, private firms carry as much as 78% of the extra investments compared to baseline (namely for the production of green hydrogen). To support these investments, the debt of private firms needs to increase substantially (Panel e). Even if the hydrogen export scenario exhibits promising results, we can notice that due to the lower nominal exchange rate, Colombian companies are less competitive on global markets than in the other scenarios. Real GDP growth rate is lower (Panel c) and unemployment (not shown in Figure 6.5) remains high, especially after 2040. In fact, the Colombian economy, by focusing disproportionately on the export of green hydrogen, falls back into a relative *Dutch disease* compared to other scenarios (Botta et al., 2016). However, as we expected, the hydrogen exports scenario delivers the highest per capita income for the Colombian economy.

In conclusion, we see that the Colombian economy is facing serious challenges in the period 2021-2031 due to the collapse of its fossil fuel exports. The energy transition, when combined with a green industrialisation strategy and with the export of green hydrogen, can help recover faster after this tense initial decade. Conversely, it appears that an energy transition without domestic manufacturing of green technologies has negative consequences for the Colombian economy. Adopting the right strategy is therefore key to turn the Colombian domestic energy transition into a major economic opportunity. One should note however that this transition is currently only in its infancy and needs time to gain momentum and produce any significant macroeconomic impact (i.e. its positive effects are only perceivable starting from year 2031 in the hydrogen export scenario).

6.6 Discussion

6.6.1 First-order local sensitivity analysis to parameters and adverse shocks

In this section, we present variants of the energy transition scenario and discuss their effects on the Colombian economy. First, we observed in the previous section that the transition had little short-term impact due to inertia in the energy system. We therefore run a scenario with a faster energy transition. In this scenario, we take a carbon price which grows linearly to reach 70 USD_{2021} per t CO_2 in 2046 already, then keeps a constant value. The constraints limiting the speed of deployment of renewable energies, due to legislative and administrative inertia and required time for dialogue with indigenous communities, are removed from this scenario. In parallel, we also run a scenario with a slower energy transition, whose carbon price increase is delayed by 10 years compared to the reference transition scenario.

The renewable capacities installed in these two scenarios are given in Table 6.5, as well as the total GHG emissions. The corresponding macroeconomic dynamics are displayed in Appendix C.4. We notice that embarking on a faster energy transition presents adverse macroeconomic impacts, which propagate after 2031. The faster decarbonisation of the energy sector and the corresponding slower decrease in oil exports fail to have a perceivable positive macroeconomic impact during the critical decade 2021-2031. Regarding the scenario with a slower energy transition, even though the increase in the carbon price is delayed by 10 years, the deployment of renewable energies is substantial. The macroeconomic dynamics are practically the same as in the standard energy transition scenario. Yet, the GHG emissions are much higher, especially during the decade 2041-2051. In conclusion, speeding up the deployment of renewable energies by neglecting the consultation process with indigenous communities does not have the potential for mitigating the challenges of the decade 2021-2031. Procrastinating the energy transition neither presents any macroeconomic advantages.

Scenario	Technology	2021	2031	2041	2051
Energy transition	Hydro	11.9	16.8	20.8	25.0
	PV	0.1	16.6	30.5	65.4
	Onshore wind	0	2.2	7.3	7.3
	Offshore wind	0	3.3	21.0	48.8
	Electrolyser	0	0	0	8.6
	Mt CO_2-eq	94.5	80.8	37.0	1.2
Faster transition	Hydro	11.9	17.8	23.8	25.0
	PV	0.1	16.6	34.9	62.2
	Onshore wind	0	2.2	7.3	7.3
	Offshore wind	0	4.9	17.9	48.8
	Electrolyser	0	0	8.2	8.2
	Mt CO_2-eq	94.5	61.6	27.0	0.7
Slower transition	Hydro	11.9	16.8	20.8	25.0
	PV	0.1	14.5	29.0	52.7
	Onshore wind	0	2.2	7.3	7.3
	Offshore wind	0	0	11.1	28.7
	Electrolyser	0	0	0	0
	Mt CO_2-eq	94.5	88.5	61.9	30.0

Table 6.5 Total installed capacities of selected renewable energy technologies and total GHG emissions in variants of the energy transition scenario.

Second, we run two scenarios which differ from the energy transition scenario in terms of the price of fossil fuels on international markets. In these scenarios, the fossil fuels price grows at an exogenous rate of 0% and 6%, respectively, while all other international prices keep growing at a 3% rate. Such differences allow us to envisage the impacts of possible alternative supply-demand interactions on global oil markets. The macroeconomic dynamics of these two scenarios are shown in Appendix C.4. We observe that the graphs of these two scenarios grossly form an envelope around the graphs of the energy transition scenario. Unsurprisingly, since Colombia is an oil exporting country, the higher the oil price, the better the economy.

Third, we investigate how the trajectory from the energy transition deviates in response to a sudden rise in global interest rates. Such rise could be due to a rapid tightening of monetary policies in the Global North, as happened in recent years. Thus, we apply an abrupt 1% increase in foreign interest rates in 2026, which then becomes persistent. In a variant of this scenario, we consider on top of it a response from the Colombian central bank, with domestic interest rates also increasing suddenly by 1% in 2026. The corresponding macroeconomic dynamics are plotted in Appendix C.4. The shock on foreign interest rate has a direct deteriorating effect on the current account of the balance of payments, since the repayment of all interests on loans in foreign currency (both public and private) suddenly becomes more expensive. Yet, these effects do not propagate much on the real economy and all real variables plotted in Appendix follow paths very close to the energy transition scenario. When we add on top of it the shock on domestic interest rate, we see that the combined shocks propagate. The shock propagation alters the solution of the optimisation problem in EnergyScope, which decides to install 17 GW of offshore wind 5 years earlier (i.e. during the phase 2041-2046 instead of 2046-2051). The high import content of wind turbines contributes to depreciate the peso, increase inflation and expand the debt of private firms, hence severely affecting macroeconomic dynamics during the phase 2041-2046.

6.6.2 Assessment of the impact of the coupling and further work

Based on the Colombian case study, we can draw general lessons about our coupled model. One of the interests of performing such bi-directional coupling with convergence is to observe how the dynamics of both models influence each other and jointly evolve. Many links are formed between the two models, some having more influence than other on the overall dynamics. Table 6.6 highlights several of these links and qualitatively assesses their impact.

Impacts EnergyScope → GEMMES	++
Impacts GEMMES → EnergyScope	+
Entire feedback loop	+
Retroactive impact of the energy transition on energy demand	– –
Propagation of energy costs through prices	–

Table 6.6 Assessment of the strength of the links in the coupling. For each link, a sign indicates its strength and impacts on the dynamics of the coupled model. "++" = strong. "+" = moderate. "–" = low. "– –" = very low.

The first link is the feeding to GEMMES of outputs from EnergyScope. We observed in Sections 6.5 and 6.6.1 that changes in the solution of EnergyScope optimisation problem, after being fed to GEMMES, are directly perceivable in the macroeconomic dynamics. Their impacts are more or less proportional to their magnitude. However, the converse is less true: most minor changes in GEMMES dynamics do not affect the solution of the optimisation problem in EnergyScope. Only more important changes from GEMMES are able to influence enough the optimisation algorithm to make it converge to another corner case. Yet, this does not mean that GEMMES has little impact on EnergyScope. The high increase in nominal exchange rate modelled with GEMMES, common to all scenarios in this paper, is determinant for the choice of energy technologies to install (as explicitly illustrated in Section 5.3.2 of the previous chapter). Regarding the full feedback loop of the coupling, it depends both on the impacts of EnergyScope outputs on GEMMES and on the impacts of GEMMES outputs on EnergyScope. The magnitude of the feedback loop is hence dependent upon the weakest of these two links.

Another important aspect of such model coupling is that it allows to discuss the retroactive effect of the energy system transition on the energy demand (to which this system is responding in the first place). Such retroactive loop is quite weak in the GEMMES-EnergyScope coupling. For example, the difference in energy demand in 2051 between the baseline and energy transition scenario is only of 5% for private firms, and less than 1% for government, banks and households. Such low impact of the transition on the energy demand especially derives from the inelasticity of energy demand regarding prices. Indeed, only economic aggregates are used to compute the energy demand in GEMMES, independently of the price level (see Section 6.3.3). Similarly, Table 6.6 indicates that the energy system costs only moderately propagate through prices. This is because the Colombian version of the GEMMES model does not include an energy sector or an energy price. The energy sector is just a subset of the private sector and its costs are diluted in the costs of all private firms. If the energy system was modelled independently, the variation of its costs would be strongly reflected in energy prices, which would snowball into the prices of other sectors. These two aspects point towards an obvious improvement for our coupling: transforming GEMMES into a multi-sectoral model – or at least a model with an independent energy sector. Doing so would allow to better incorporate both positive and negative feedback loops between the energy system and the economy, as is for example the case in the coupling of Fattahi et al. (2023). Besides, the incorporation of an input-output structure in GEMMES would allow to generate a multiplier effect on the investments given by EnergyScope. Likewise, it could be interesting to link the productivity gains in GEMMES with technology choices and investment from EnergyScope, as is done by Kemp-Benedict (2022, 2024).

When considering the specific case of Colombia, we need to remind that energy-related GHG emissions only represent one third of the country emissions. The main stake of the transition lies in the forestry, land-use and agriculture sectors, in relation with the preservation of the Amazon rainforest. Hence, only a fraction of the decarbonisation impacts are discussed here.

An important avenue for future research would be to discuss just transition issues, which are fundamental in Colombia. The energy transition and carbon tax from the scenarios described above have different impacts on various income groups, which share differentiated responsibilities for the degradation of the environment (Ministerio de Minas y Energía, 2024). This ought to be investigated by disaggregating the households sector in GEMMES. By considering several income groups, the evolution of social inequalities could be studied in relation with the transition. Alternative public policies to subsidise the investments and share differently the transition burden could also be examined.

6.7 Conclusion

In this chapter, a coupling methodology between GEMMES and EnergyScope was presented. The coupled model was then applied to the specific case of Colombia. As a fossil fuels exporting country, Colombia will be severely affected by the green transition of its trade partners. Thanks to the coupled model, we simulate the macroeconomic dynamics of the Colombian economy in the context of the global green transition. Through the exploration of several scenarios, we assess how the domestic Colombian energy transition can affect these dynamics. We observe that when combined with domestic manufacturing of green technologies and an integration into global hydrogen markets, the green transition can become an economic opportunity for Colombia. Yet, strategical choices are key for delivering such positive outcomes: the simulations also show that without a green industrialisation strategy, the domestic energy transition of Colombia brings adverse macroeconomic consequences. Besides, the transition is currently only in its infancy in Colombia and the energy system presents an important level of inertia, implying that the potential positive impacts of its decarbonisation can only perceived after a decade.

7

Conclusion and perspectives

Models play a central informational role in the development of public policy by democratic institutions and international organisations. They indeed allow to perform multiple data-based experiments to anticipate the impacts of policies, without exposing public decision-makers to any risks. In this thesis, we explore how combining models from the fields of engineering and macroeconomics can provide novel insights to navigate the complex and fastly evolving landscape of the energy transition. Two types of engineering models are used in this work: Energy System Optimisation Models (ESOMs), which are a standard and well-established tool for transition planning, and models from the Net Energy Analysis (NEA) field, which are currently gaining momentum thanks to a standardisation process and an emerging consensus among leading NEA researchers. The macroeconomic models used in this work have the particularity of not relying on general equilibrium theory or on an optimisation framework. Their goal is not to search for a "socially optimal transition", they thus follow a descriptive rather than prescriptive approach. They are used to answer questions of the type: *"What happens if we carry out the energy transition in one or another way ?"* This thesis provides three types of insights: (i) concrete answers regarding the macroeconomic dynamics of the energy transition; (ii) a glimpse of the state of the art of ecological macroeconomics and net energy analysis; (iii) new energy-economy modelling tools with multiple possible applications.

7.1 Main outcomes

This section summarises four important outcomes of the thesis.

(M-1) **Modelling the macroeconomic impacts of the energy transition can lead to very different results, depending on the scope and structure of the model used.** In Chapter 4 of this thesis, we model a rapid decarbonisation path for the global energy system. In Chapter 6, the focus is on the decarbonisation trajectory of a national energy system, modelled within a world economy itself undergoing an energy transition. The results presented in these two chapters are very contrasted. On one hand, it appears in Chapter 4 that the transition has important inflationary effects, is putting significant pressure on the job market and brings about an increase in economic growth, inducing a large rebound in energy demand. On the other hand, the energy transition of Colombia, analysed in Chapter 6, appears to have only moderate macroeconomic impacts on the country, with very little inflationary effects. One first reason for this is the difference in *scope* between the two models. TEMPLE (Chap. 4) represents the world economy; the important macroeconomic impacts of the transition mainly come from a supply constraint affecting the production of green technologies. In GEMMES-EnergyScope (Chap. 6), this constraint is eliminated thanks to the national scope of the model. Green technologies can be imported from the rest of the world at will, without any supply constraint since the manufacturing capacity in other countries is not explicitly modelled. The energy transition of the rest of the world is represented via its impact on the demand for Colombian fossil fuels, not via the increase in the price of green technologies. A second reason for the observed differences is the *structure* of the models. TEMPLE includes one energy sector, distinct from the non-energy sector. The inflation transmission mechanisms between both sectors are explicitly modelled. In GEMMES-EnergyScope however, there is no explicit distinction between both sectors, hence the inflation transmission mechanisms are much weaker.

(M-2) **Through the coupling of energy and macroeconomic models, new dynamics emerge, which were invisible through the lens of the models taken individually.** The interest of combining energy transition models with stock-flow consistent (SFC) models is not so much to represent the state of the final, decarbonised economy, but rather to study the out-of-equilibrium dynamics generated by the energy-economy interactions along the transition path. For example, the observed detrimental effect of higher rates of economic growth in TEMPLE emerges thanks to the combination of increasing renewable energy capital costs in the energy model with investment and labour market dynamics in the macroeconomic model. In the GEMMES-EnergyScope coupling, the deterioration of the exchange rate enables the development of a profitable industry for producing green hydrogen, which in turns dampens the currency depreciation and can reduce its own profitability. Such intertwined dynamics are at the heart of the ecological transition. One major contribution of interdisciplinary modelling works is to reveal and anticipate them.

(M-3) **Coupling between models presents obvious limits, which sometimes outweigh the benefits.** As explained above, coupling models from different fields brings numerous fruitful insights. Yet, it also comes with a cost. The coupling brings a lot of complexity and the model manipulation becomes more time-consuming. Besides, researchers working with the model are required to have a basic training both in energy and macroeconomics, which can greatly reduce the size of the pool of potential users. We therefore recommend to decide on a case-by-case basis if using a coupled model is the right solution to a given research question, contingent upon an evaluation of the anticipated costs and benefits associated with such an approach.

(M-4) **Models from ecological macroeconomics have a role to play in policy-making.** The categories of models presented in this thesis are not merely of academic interest. As explained in Chapter 2, advanced ecological macroeconomic models are capable of responding to the practical needs of policy makers. Currently, economic policy analysis relies nearly exclusively on the use of CGE and DSGE models. Chapter 2 highlights a series of weaknesses of those models, which become exacerbated in the context of the ecological transition. It argues that the extensions and additions to CGE and DSGE models do not fundamentally remedy them, while facing their own limits regarding complexity and tractability. Using models from ecological macroeconomics in complement would allow to reflect a plurality of methodologies and assumptions. The fact that the diversity of models adds to predictive accuracy is widely documented (Hong and Page, 2004; Guerrien and Jallais, 2009; Garnett et al., 2009; Page, 2007, 2010). Thus, performing analyses and projections with new tools from ecological macroconomics would significantly enhance the modelling capabilities of policy makers. As Page (2010) puts it in a very simple way:

Crowd of Models' Accuracy = Average Model Accuracy + Model Diversity

7.2 Limitations and perspectives

This section outlines four perspectives to overcome the limitations of this thesis.

(P-1) **In such a fast changing field as the energy transition, models need to be updated regularly to stay relevant.** Several limitations have been mentioned at the end of Chapter 4. Crucially, we pointed out that the data used for producing the EROI curves of the TEMPLE model come from Dupont et al. (2018, 2020). These works build on some life-cycle data dating back to 2017. Given the impressive, stronger-than-expected, fall in the costs of renewable energies which has happend since then, an update of those EROI curves would be welcome. Most importantly, carrying out such adjustment might render the results of Chapter 4 slightly closer to those of Chapter 6. The EnergyScope data for photovoltaic power and wind turbines used in the latter indeed draw on recent estimates.

(P-2) **Exploiting the full potential of the coupling between GEMMES and EnergyScope.** In Chapter 6, a generic coupling between an SFC macroeconomic model and an ESOM is presented for the first time. Such a coupling allows to study the interactions and feedback loops between the real economy, the financial and energy systems. It enables us to integrate the energy transition into a broader, evolving economy, subject to imbalances and instabilities. Yet, the work presented here is only a first seed which still deserves to grow. First, as explained in Section 6.6.2, transforming GEMMES into a multi-sectoral model (which is already the case for some versions of GEMMES, but not the Colombian one) would allow to better incorporate both positive and negative feedback loops between the energy system and the economy, namely regarding inflation transmission mechanisms and rebound effect on energy demand. Second, incorporating a disaggregation by household types would allow to investigate distributional impacts of decarbonisation measures and discuss just transition issues. Third, the financial dynamics could be given more importance in the models, both TEMPLE and GEMMES-EnergyScope. The majority (but not all) of the observed dynamics concerned the impacts of the energy system on the real economy and vice-versa. Developing further the financial part of the models could allow to address additional research questions, such as the possibility of having financial crises caused by the transition or the impacts of environmental degradation. Nevertheless, the question remains open whether more detailed financial dynamics would significantly affect the simulation results.

(P-3) **The need for modelling post-growth transition pathways.** At the end of Chapter 4, we show that a low-growth world economy is in fact at an advantage for accomplishing a rapid energy transition compared to a faster growing economy. We conclude that chapter by pointing towards the need for modelling post-growth transition scenarios. The core structure of ecological macroeconomic models, such as the ones used in this thesis, is entirely adapted for carrying out such a task. However, important additions would need to be made, for example sector-wise disaggregations allowing to distinguish between sectors which degrow and others which continue to grow, and how degrowth in the former impact the latter as well as international trade. Such claim is of course not new (see for example Hickel et al., 2021): the call was well heard and the field of degrowth modelling is currently starting to flourish (Lauer et al., 2025). Note however that in the current political and economic context, only countries of the global North could envisage to actually implement a post-growth economic strategy.

(P-4) **The importance of having a framework for comparing models.** As made clear throughout this thesis, different models can give highly divergent answers to the same question. Thus, the use of several models based on different assumptions and frameworks is essential when designing policies, by comparing their results and understanding where the divergences come from. However, such task is time consuming and not always easy to carry out (for example, it was not systematically done in Chapter 5 of this thesis, due to the time constraint and because most energy models previously applied to Colombia and Turkey were not open-source). Yet, an example of best practice in the use of various models while comparing their results in a rigorous way can be found in the climate sciences. The Coupled Model Intercomparison Project (CMIP), organised under the aegis of the World Climate Research Programme (WCRP) of the World Meteorological Organisation (WMO), has been centralising and standardising the process of models' comparison since 1997. Its first element is the standardisation of databases, so that differences in results are only due to differences between models. Its second element is the systematic and transparent comparison of models, functional forms, results and robustness, to enable continuous incrementation of collective modelling. Likewise, the EU Commission recently funded a framework[1] for comparing climate and energy models' results, and assessing their strengths and weaknesses on an empirical basis. Such initiative would greatly benefit from being replicated for macroeconomic modelling.

Thus, models are certainly a useful tool to guide us through the rapidly changing landscape of the green transition. The uninterrupted growth in computing power points to a further increase in their use and influence in the future. Namely, the Better Regulation guidelines in the European Union have made modelling nearly mandatory for the assessment of any new policy (Pollitt, 2018). Yet, models face numerous limitations, which are rarely explicit. As experienced during these four years of research, at a certain point, it seems that only the modeller himself can still differentiate exactly which part of the model's results is really robust and which part is weak and risky to rely on. A temptation can then rise to use models as an authoritative instrument outside of their field of validity. Indeed, curves are fascinating, numbers are compelling. Intellectual integrity remains our best rampart to make sure that models are used to humbly increase our knowledge about the world and not as an instrument of power.

Torture numbers, and they'll confess to anything.
Gregg Easterbrook.

The greatest enemy of knowledge is not ignorance, it is the illusion of knowledge.
Stephen Hawking.

[1] See the European Climate and Energy Modelling Forum: `https://www.ecemf.eu/`

APPENDIX

A

The TEMPLE model

A.1 Transaction Flow Matrix and Balance Sheet

The Transaction Flow Matrix (TFM) is shown in Table A.1. 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 A.2.

	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 A.2 Balance sheet

	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	$+W\left(L_e+L_f\right)$		$-W\,L_e$		$-W\,L_f$				0
Taxes and subsidies			$-T_e\,y_e$					$+T_e\,y_e$	0
Interests on loans			$-r\,D_e$		$-r\,D_f$		$+r\left(D_e+D_f\right)$		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				$\dot{K}_e$		$\dot{K}_f$			$\dot{K}_e+\dot{K}_f$
Change in inventories						$\dot{n}_f$			$\dot{n}_f$
Change in deposits		$\dot{M}$					$-\dot{M}$		0
Change in loans				$-\dot{D}_e$		$-\dot{D}_f$	$+\dot{D}_e+\dot{D}_f$		0
Change in public bonds	$+\dot{B}_{g,w}$	$+\dot{B}_{g,c}$						$-\dot{B}_g$	0
Change in own funds		$+\dot{OF}_b$					$-\dot{OF}_b$		0
Change in equities		$+\dot{\mathcal{E}}_e+\dot{\mathcal{E}}_e$		$-\dot{\mathcal{E}}_e$		$-\dot{\mathcal{E}}_f$			0
Σ (=Change in net worth)	$+\dot{B}_{g,w}$	$\dot{M}+\dot{B}_{g,c}+\dot{\mathcal{E}}_e+\dot{\mathcal{E}}_e+\dot{OF}_b$		0		0	0	$-\dot{B}_g$	$\dot{K}_e+\dot{K}_f+\dot{n}_f$

Table A.1 Transaction Flow Matrix

A.2 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

$y^e_{f,p}$ = expected yearly production of final goods

u^e_f = 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 rate 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 sourc
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 of type z divided by the capital stock o

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 fir

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 sharehol
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
λ_{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 cons
$f(\cdot)$ = function relating the households' energy consumption to the price of energ
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-secto
ϵ_{f,i_f} = energy intensity of the production of capital stock for the final goods sub-s

ϵ_{f,c_f}	=	aggregated energy intensity of the production of final goods and services for
$\epsilon_{f,c_f,g}$	=	energy intensity of the production of final goods (not services) for consumpti
$\epsilon_{f,c_f,s}$	=	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

A.3 Equations of the model

A.3.1 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:

$$y_{e,p} = \frac{e_e}{\epsilon_e} = u_e \, \alpha_e \, \frac{L_e}{\gamma_e} = u_e \, \frac{k_e}{\gamma_e} \tag{A.1}$$

$$y_{f,p} = \frac{e_f}{\epsilon_f} = \alpha_f \, L_f = u_f \, \frac{k_f}{\gamma_f} \tag{A.2}$$

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 4.5, 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 $c_{c,f}$[1].

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

We thus have the equations:

$$y_{e,d} = e_e + e_f + c_{w,e} + c_{c,e} \tag{A.3}$$

$$y_{f,d} = i_e + i_f + c_{w,f} + c_{c,f} \tag{A.4}$$

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 A.2, 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:

$$c_{z,e} = \epsilon_{\text{cons}}\, f(\frac{p_e}{p_f})\, c_{z,f} \qquad (z \in \{w, c\}) \tag{A.5}$$

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:

$$y_{e,p} = y_{e,d} \tag{A.6}$$

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.

$$\dot{n}_f = y_{f,p} - y_{f,d} - \delta_n\, n_f \tag{A.7}$$

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

$$u^e_f = \frac{\gamma_f\, y^e_{f,p}}{k_f} \tag{A.8}$$

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, through some proportionality factor $\beta_{n_f,1}$[2]:

$$\dot{y}^e_{f,p} = \hat{k}_f \, y^e_{f,p} + \beta_{n_f,1} \left(y_{f,d} + \delta_n \, n_f - y^e_{f,p} \right) \tag{A.9}$$

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 production[3]:

$$n_f^T = \eta \, y^e_{f,p} \tag{A.10}$$

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

$$y_{f,p} = y^e_{f,p} + \beta_{n_f,2} \left(n_f^T - n_f \right) \tag{A.11}$$

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

A.3.2 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:

$$W_e = W_f = W \tag{A.12}$$

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:

$$UC_x = \frac{W \, L_x + p_e \, e_x + p_f \, \delta_x \, k_x}{y_{x,p}} \qquad (x \in \{e, f\}) \tag{A.13}$$

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

$$\dot{p}_e = \beta_{p_e} \left(p_e^T - p_e \right) \tag{A.14}$$

$$p_e^T = \mu_e \, UC_e + T_e \tag{A.15}$$

This equation indicates that energy firms adjust their price p_e with a speed

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

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

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[4], 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:

$$\dot{p}_f = \beta_{p_f,1} \left(p_f^T - p_f \right) + \beta_{p_f,2} \left(p_f \frac{n_f^T - n_f}{k_f} \right) \tag{A.16}$$

$$p_f^T = \mu_f \, UC_f \tag{A.17}$$

A.3.3 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:

$$\Pi_e = y_e \left(p_e - UC_e - T_e \right) - r \, D_e \tag{A.18}$$

$$\Pi_f = y_{f,d} \, p_f - y_{f,p} \, UC_f - r \, D_f \tag{A.19}$$

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:

$$k_e^T = \frac{\gamma_e \, y_e}{u_e^T} \tag{A.20}$$

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

$$i_e = \beta_{i_e} \left(k_e^T - k_e \right) + \delta_e \, k_e \tag{A.21}$$

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

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

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:

$$\Pi_f^e = y_{f,p}\left(p_f - UC_f\right) - r\,D_f \tag{A.22}$$

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

$$\pi_f^e := \frac{\Pi_f^e}{p_f\,k_f} \tag{A.23}$$

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

$$i_f = k_f\,(\kappa_{f,0} + \kappa_{f,1}\,\pi_f^e + \delta_f) \tag{A.24}$$

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):

$$\Pi_{e,d} = \Delta\,\Pi_e \tag{A.25}$$

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:

$$\Pi_{f,d} = \Delta\,\Pi_f^e \tag{A.26}$$

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

$$\Pi_{x,u} = \Pi_x + p_f\,\delta_x\,k_x - \Pi_{x,d} \qquad (x \in \{e,f\}) \tag{A.27}$$

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

$$\dot{D}_x = p_f\,i_x - \Pi_{x,u} \qquad (x \in \{e,f\}) \tag{A.28}$$

Finally, the capital accumulation equation is as usual:

$$\dot{k}_x = i_x - \delta_x\,k_x \qquad (x \in \{e,f\}) \tag{A.29}$$

A.3.4 Workers, banks, capitalists and public sector

Let us call the world population POP and let us define the employment rate in sector x as

$$\lambda_x = \frac{L_x}{POP} \qquad (x \in \{e, f\}) \tag{A.30}$$

We then define the global employment rate as:

$$\lambda = \lambda_f + \lambda_e \tag{A.31}$$

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:

$$\widehat{W} = \omega_0 + \omega_1 \lambda + (1 - \omega_2)\, \hat{p}_f \tag{A.32}$$

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:

$$p_f\, c_{w,f} + p_e\, c_{w,e} = (1 - s_{F,w})\, W \cdot L \tag{A.33}$$

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:

$$\hat{\alpha}_f = \hat{\alpha}_e = \hat{\alpha} = \alpha_0 + \alpha_1 \lambda \tag{A.34}$$

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

$$r_{CB} = r^* + \hat{p}_f + \varphi \left(\hat{p}_f - \hat{p}_f^T \right) \tag{A.35}$$

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:

$$OF_b^T = \mu_b\, (D_f + D_e) \tag{A.36}$$

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:

$$\Pi_{b,u} = \beta_b \left(OF_b^T - OF_b \right) \tag{A.37}$$

$$\dot{OF_b} = \Pi_{b,u} \tag{A.38}$$

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

$$\Pi_{b,d} = r \left(D_f + D_e \right) - \Pi_{b,u} \tag{A.39}$$

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:

$$r^T = r_{CB} + \lambda_{r^T} \frac{OF_b^T - OF_b}{OF_b^T} \tag{A.40}$$

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:

$$\dot{r} = \beta_r \left(r^T - r \right) \tag{A.41}$$

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:

$$C_{c,f} = (1 - s_c - s_{F,c}) \left(\Pi_{f,d} + \Pi_{e,d} + \Pi_{b,d} \right) \tag{A.42}$$

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 A.15 and A.18. 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:

$$-\dot{B}_g = T_e\, y_e \tag{A.43}$$

A.3.5 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:

$$\mathcal{K}_e := \frac{k_e}{k_f} \qquad \mathcal{P}_e := \frac{p_e}{p_f} \qquad \omega_x := \frac{W}{\alpha_x\, p_x} \qquad d_x := \frac{D_x}{p_f\, k_x} \tag{A.44}$$

$$\pi_x := \frac{\Pi_x}{p_f\, k_x} \qquad \pi_{x,d} := \frac{\Pi_{x,d}}{p_f\, k_x} \qquad \pi_{b,u} := \frac{\Pi_{b,u}}{p_f\, k_f} \qquad of_b := \frac{OF_b}{p_f\, k_f} \tag{A.45}$$

$$uc_x := \frac{UC_x}{p_x} \qquad \kappa_{z,f} := \frac{c_{z,f}}{k_f} \qquad \nu_f := \frac{n_f}{k_f} \qquad \mathcal{T}_e := \frac{T_e}{p_e} \tag{A.46}$$

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:

$$\hat{\omega}_x = \widehat{W} - \hat{\alpha}_x - \hat{p}_x \qquad (x \in \{e, f\}) \tag{A.47}$$

which becomes, when we insert equations A.32 and A.34:

$$\hat{\omega}_e = \omega_0 + \omega_1\,\lambda - \omega_2\,\hat{p}_f + (\hat{p}_f - \hat{p}_e) - \alpha_0 - \alpha_1\,\lambda \tag{A.48}$$

$$\hat{\omega}_f = \omega_0 + \omega_1\,\lambda - \omega_2\,\hat{p}_f - \alpha_0 - \alpha_1\,\lambda \tag{A.49}$$

We know from equations A.1 and A.2 that[5]:

$$L_e = \frac{k_e}{\alpha_e} \tag{A.50}$$

$$L_f = \frac{y_{f,p}}{\alpha_f} \tag{A.51}$$

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

$$\hat{\lambda}_x = \hat{L}_x - \widehat{POP} \qquad (x \in \{e, f\}) \tag{A.52}$$

$$\hat{\lambda}_e = \hat{k}_e - \alpha_0 - \alpha_1\,\lambda - \widehat{POP} \tag{A.53}$$

$$\hat{\lambda}_f = \hat{y}_{f,p} - \alpha_0 - \alpha_1\,\lambda - \widehat{POP} \tag{A.54}$$

$$\hat{\lambda}_f = \hat{k}_f + \hat{u}_f - \alpha_0 - \alpha_1\,\lambda - \widehat{POP} \tag{A.55}$$

By inserting into equation A.4 the definitions of $\mathcal{K}_e$, $\kappa_{w,f}$, $\kappa_{c,f}$ and equation A.29, we also have:

$$\frac{y_{f,d}}{k_f} = \frac{i_e + i_f + c_{w,f} + c_{c,f}}{k_f} \tag{A.56}$$

$$= \mathcal{K}_e\,\frac{i_e}{k_e} + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} \tag{A.57}$$

$$= \mathcal{K}_e\,(\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} \tag{A.58}$$

[5]As 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.

We then obtain from equations A.8, A.9 and A.58:

$$\hat{u}_f^e = \hat{y}_{f,p}^e - \hat{k}_f \tag{A.59}$$

$$= \frac{-\beta_{n_f,1}\left(y_{f,p}^e - y_{f,d} - \delta_n\, n_f\right)}{y_{f,p}^e} \tag{A.60}$$

$$= -\beta_{n_f,1}\left(1 - \frac{\gamma_f}{u_f^e}\,\frac{y_{f,d}}{k_f} - \delta_n\,\frac{\gamma_f}{u_f^e}\,\frac{n_f}{k_f}\right) \tag{A.61}$$

$$= -\beta_{n_f,1}\left(1 - \frac{\gamma_f}{u_f^e}\left(\mathcal{K}_e\,(\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f}\right) - \delta_n\,\frac{\gamma_f}{u_f^e}\,\nu_f\right) \tag{A.62}$$

$$\dot{u}_f^e = \beta_{n_f,1}\left(\gamma_f\left(\mathcal{K}_e\,(\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} + \delta_n\,\nu_f\right) - u_f^e\right) \tag{A.63}$$

Similarly, by definition of ν_f and by equations A.7 and A.58, we have:

$$\hat{\nu}_f = \hat{n}_f - \hat{k}_f \tag{A.64}$$

$$= \frac{1}{n_f}\left(y_{f,p} - y_{f,d}\right) - \delta_n - \hat{k}_f \tag{A.65}$$

$$\dot{\nu}_f = \frac{y_{f,p}}{k_f} - \frac{y_{f,d}}{k_f} - \left(\hat{k}_f + \delta_n\right)\nu_f \tag{A.66}$$

$$= \frac{u_f}{\gamma_f} - \left(\mathcal{K}_e\,(\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f}\right) - \left(\hat{k}_f + \delta_n\right)\nu_f \tag{A.67}$$

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

$$\dot{d}_x = \frac{\dot{D}_x}{p_f\,k_x} - d_x\left(\hat{p}_f + \hat{k}_x\right) \qquad (x \in \{e, f\}) \tag{A.68}$$

After inserting equations A.27, A.28, A.29 and the definition of π_x, we obtain:

$$\dot{d}_x = \frac{i_x}{k_x} - \frac{\Pi_{x,u}}{p_f\,k_x} - d_x\left(\hat{p}_f + \hat{k}_x\right) \tag{A.69}$$

$$= \frac{i_x}{k_x} - \frac{\Pi_x + p_f\,\delta_x\,k_x - \Pi_{x,d}}{p_f\,k_x} - d_x\left(\hat{p}_f + \hat{k}_x\right) \tag{A.70}$$

$$= \hat{k}_x - \frac{\Pi_x - \Pi_{x,d}}{p_f\,k_x} - d_x\left(\hat{p}_f + \hat{k}_x\right) \tag{A.71}$$

We can then insert A.25 and A.26 into this equation to get:

$$\dot{d}_e = \hat{k}_e - (1-\Delta)\,\pi_e - d_e\left(\hat{p}_f + \hat{k}_e\right) \tag{A.72}$$

$$\dot{d}_f = \hat{k}_f - \pi_f + \Delta\,\pi_f^e - d_f\left(\hat{p}_f + \hat{k}_f\right) \tag{A.73}$$

Given $of_b := \frac{OF_b}{p_f\,k_f}$ and equation A.38, we have:

$$\dot{of}_b = \frac{\dot{OF}_b}{p_f\,k_f} - of_b\left(\hat{p}_f + \hat{k}_f\right) \tag{A.74}$$

$$= \pi_{bu} - of_b\left(\hat{p}_f + \hat{k}_f\right) \tag{A.75}$$

We can also transform equation A.11 into:

$$\frac{k_f}{\gamma_f}\,u_f = \frac{k_f}{\gamma_f}\,u_f^e + \beta_{n_f,2}\left(\eta\,\frac{k_f}{\gamma_f}\,u_f^e - k_f\,\nu_f\right) \tag{A.76}$$

$$u_f = u_f^e + \beta_{n_f,2}\left(\eta\,u_f^e - \gamma_f\,\nu_f\right) \tag{A.77}$$

Given $uc_x := \frac{UC_x}{p_x}$ and equation A.13, we further have:

$$UC_e = \frac{\gamma_e\,W}{\alpha_e\,u_e} + \epsilon_e\,p_e + p_f\,\frac{\gamma_e\,\delta_e}{u_e} \tag{A.78}$$

$$uc_e = \frac{\gamma_e}{u_e}\,\omega_e + \epsilon_e + \frac{\gamma_e\,\delta_e}{\mathcal{P}_e\,u_e} \tag{A.79}$$

and

$$UC_f = \frac{W}{\alpha_f} + \epsilon_f \, p_e + p_f \, \frac{\gamma_f \, \delta_f}{u_f} \tag{A.80}$$

$$uc_f = \omega_f + \epsilon_f \mathcal{P}_e + \frac{\gamma_f \, \delta_f}{u_f} \tag{A.81}$$

With $\pi_e := \frac{\Pi_e}{p_f \, k_e}$ and $\mathcal{T}_e := \frac{T_e}{p_e}$, equation A.18 becomes:

$$\pi_e = \frac{\mathcal{P}_e \, u_e}{\gamma_e} \left(1 - uc_e - \mathcal{T}_e\right) - r \, d_e \tag{A.82}$$

Similarly, equation A.22 leads to:

$$\pi^e_f = \frac{u_f}{\gamma_f} \left(1 - uc_f\right) - r \, d_f \tag{A.83}$$

Using equation A.58, we can also rewrite equation A.19 as:

$$\pi_f = \frac{p_f \, y_{f,d} - p_f \, y_{f,p} \left(uc_f + \frac{\gamma_f}{u_f} r \, d_f\right)}{p_f \, k_f} \tag{A.84}$$

$$= \mathcal{K}_e \left(\hat{k}_e + \delta_e\right) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} - \frac{u_f}{\gamma_f} \, uc_f - r \, d_f \tag{A.85}$$

With $\kappa_{w,f} := \frac{c_{w,f}}{k_f}$, we obtain, by combining equations A.5 and A.33:

$$c_{w,f} \left(p_e \, \epsilon_{\text{cons}} \, f(\mathcal{P}_e) + p_f\right) = \left(1 - s_{F,w}\right) W \cdot L \tag{A.86}$$

$$c_{w,f} = \frac{\left(1 - s_{F,w}\right) \omega_f}{\mathcal{P}_e \, \epsilon_{\text{cons}} \, f(\mathcal{P}_e) + 1} \, \alpha_f \left(L_f + L_e\right) \tag{A.87}$$

$$c_{w,f} = \frac{\left(1 - s_{F,w}\right) \omega_f}{\mathcal{P}_e \, \epsilon_{\text{cons}} \, f(\mathcal{P}_e) + 1} \left(y_{f,p} + \frac{\alpha_f}{\alpha_e} \, k_e\right) \tag{A.88}$$

$$\kappa_{w,f} = \frac{\omega_f}{\mathcal{P}_e \, \epsilon_{\text{cons}} \, f(\mathcal{P}_e) + 1} \left(\frac{y_{f,p}}{k_f} + \frac{\alpha_f}{\alpha_e} \, \mathcal{K}_e\right) \tag{A.89}$$

$$\kappa_{w,f} = \frac{\left(1 - s_{F,w}\right) \omega_f}{\mathcal{P}_e \, \epsilon_{\text{cons}} \, f(\mathcal{P}_e) + 1} \left(\frac{u_f}{\gamma_f} + \frac{\alpha_f}{\alpha_e} \, \mathcal{K}_e\right) \tag{A.90}$$

Similarly, with $\kappa_{c,f} := \frac{c_{c,f}}{k_f}$ and equations A.25, A.26, A.39, equation A.42 becomes:

$$\kappa_{c,f} = (1 - s_c - s_{F,c}) \left(\Delta \pi_f^e + \mathcal{K}_e \, \Delta \pi_e + r \left(d_f + \mathcal{K}_e \, d_e \right) - \pi_{b,u} \right) \quad \text{(A.91)}$$

Furthermore, by combining equations A.3, A.5 and the definition of u_e, we obtain:

$$u_e = \frac{\gamma_e}{(1 - \epsilon_e)} \left(\frac{e_f + c_{w,e} + c_{c,e}}{k_e} \right) \quad \text{(A.92)}$$

$$= \frac{\gamma_e}{(1 - \epsilon_e) \, \mathcal{K}_e} \left(\frac{\epsilon_f \, u_f}{\gamma_f} + \frac{c_{w,e} + c_{c,e}}{k_f} \right) \quad \text{(A.93)}$$

$$= \frac{\gamma_e}{(1 - \epsilon_e) \, \mathcal{K}_e} \left(\frac{\epsilon_f \, u_f}{\gamma_f} + \epsilon_{\text{cons}} \, f(\mathcal{P}_e) \left(\kappa_{w,f} + \kappa_{c,f} \right) \right) \quad \text{(A.94)}$$

Let us divide both sides of equation A.21 by k_e. It gives:

$$\frac{i_e}{k_e} = \beta_{i_e} \left(\frac{k_e^T}{k_e} - 1 \right) + \delta_e \quad \text{(A.95)}$$

$$\hat{k}_e = \beta_{i_e} \left(\frac{u_e}{u_e^T} - 1 \right) \quad \text{(A.96)}$$

Finally, we combine equations A.36 and A.40 to have:

$$r^T = r_{CB} + \lambda_{r^T} \frac{\mu_b \left(D_f + D_e \right) - OF_b}{\mu_b \left(D_f + D_e \right)} \quad \text{(A.97)}$$

$$r^T = r_{CB} + \lambda_{r^T} \frac{\mu_b \left(d_f + \mathcal{K}_e \, d_e \right) - of_b}{\mu_b \left(d_f + \mathcal{K}_e \, d_e \right)} \quad \text{(A.98)}$$

A.3.6 Reduced form model

The reduced form model is the set of differential equations:

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

with the following intermediate variables:

$$\begin{aligned}
u_f &= u^e_f + \beta_{n_f,2}\left(\eta\,u^e_f - \gamma_f\,\nu_f\right) \\
\pi_{b,u} &= \beta_b\left(\mu_b\,(d_f + \mathcal{K}_e\,d_e) - of_b\right) \\
uc_f &= \omega_f + \epsilon_f\mathcal{P}_e + \frac{\gamma_f\,\delta_f}{u_f} \\
\pi^e_f &= \frac{u_f}{\gamma_f}\left(1 - uc_f\right) - r\,d_f \\
\hat{k}_f &= \kappa_{f,0} + \kappa_{f,1}\,\pi^e_f \\
\kappa_{w,f} &= \frac{(1 - s_{F,w})\,\omega_f}{\mathcal{P}_e\,\epsilon_{\text{cons}}\,f(\mathcal{P}_e) + 1}\left(\frac{u_f}{\gamma_f} + \frac{\alpha_f}{\alpha_e}\,\mathcal{K}_e\right)
\end{aligned}$$

$$
\begin{aligned}
\kappa_{c,f} &= (1 - s_c - s_{F,c}) \left(\Delta\, \pi_f^e + \mathcal{K}_e\, \Delta\, \pi_e + r\, (d_f + \mathcal{K}_e\, d_e) - \pi_{b,u}\right) \\
u_e &= \frac{\gamma_e}{(1-\epsilon_e)\, \mathcal{K}_e} \left(\frac{\epsilon_f\, u_f}{\gamma_f} + \epsilon_{\text{cons}}\, f(\mathcal{P}_e) \left(\kappa_{w,f} + \kappa_{c,f}\right)\right) \\
uc_e &= \frac{\gamma_e}{u_e}\, \omega_e + \epsilon_e + \frac{\gamma_e\, \delta_e}{\mathcal{P}_e\, u_e} \\
\hat{p}_e &= \beta_{p_e}\, \left(\mu_e\, uc_e + \mathcal{T}_e - 1\right) \\
\pi_e &= \frac{\mathcal{P}_e\, u_e}{\gamma_e}\, (1 - uc_e - \mathcal{T}_e) - r\, d_e \\
\hat{k}_e &= \beta_{i_e} \left(\frac{u_e}{u_e^T} - 1 \right) \\
\pi_f &= \mathcal{K}_e\, (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} - \frac{u_f}{\gamma_f}\, uc_f - r\, d_f \\
\lambda &= \lambda_f + \lambda_e \\
v_f &= \beta_{n_f,1} \left(\gamma_f \left(\mathcal{K}_e\, (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} + \delta_n\, \nu_f \right) - u_f^e \right) \\
\hat{p}_f &= \beta_{p_f,1} \left(\mu_f\, uc_f - 1 \right) + \beta_{p_f,2} \left(\eta\, \frac{u_f}{\gamma_f} - \nu_f \right) \\
r_{CB} &= r^* + \hat{p}_f + \varphi \left(\hat{p}_f - \hat{p}_f^T \right) \\
r^T &= r_{CB} + \lambda_{r^T}\, \frac{\mu_b\, (d_f + \mathcal{K}_e\, d_e) - of_b}{\mu_b\, (d_f + \mathcal{K}_e\, d_e)}
\end{aligned}
$$

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

$$GDP = I_e + I_f + C_{w,f} + C_{c,f} + C_{w,e} + C_{c,e} \tag{A.99}$$

$$\frac{GDP}{p_f} = i_e + i_f + c_{w,f} + c_{c,f} + (c_{w,e} + c_{c,e})\,\mathcal{P}_e \tag{A.100}$$

$$\frac{GDP}{p_f\,k_f} = \mathcal{K}_e\,(\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e\,\epsilon_{\text{cons}}\,f(\mathcal{P}_e))\,(\kappa_{w,f} + \kappa_{c,f}) \tag{A.101}$$

We also have, when combining equations A.5 and A.33:

$$(1 - s_{F,w})\,W \cdot L = c_{w,f}\left(p_f + p_e\,\epsilon_{\text{cons}}\,f(\mathcal{P}_e)\right) \tag{A.102}$$

$$\frac{W \cdot L}{p_f\,k_f} = \frac{\kappa_{w,f}}{(1 - s_{F,w})}\,(1 + \mathcal{P}_e\,\epsilon_{\text{cons}}\,f(\mathcal{P}_e)) \tag{A.103}$$

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

$$\Omega = \frac{\frac{\kappa_{w,f}}{(1-s_{F,w})}\,(1 + \mathcal{P}_e\,\epsilon_{\text{cons}}\,f(\mathcal{P}_e))}{\mathcal{K}_e\,(\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e\,\epsilon_{\text{cons}}\,f(\mathcal{P}_e))\,(\kappa_{w,f} + \kappa_{c,f})} \tag{A.104}$$

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

$$\Pi = \frac{\pi_f + \delta_f + r\,d_f + \mathcal{K}_e\,(\pi_e + \delta_e + r\,d_e)}{\mathcal{K}_e\,(\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e\,\epsilon_{\text{cons}}\,f(\mathcal{P}_e))\,(\kappa_{w,f} + \kappa_{c,f})} \tag{A.105}$$

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:

$$1 - \Omega - \Pi = \frac{\frac{\mathcal{K}_e\,\mathcal{P}_e\,u_e}{\gamma_e}\,\mathcal{T}_e}{\mathcal{K}_e\,(\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e\,\epsilon_{\text{cons}}\,f(\mathcal{P}_e))\,(\kappa_{w,f} + \kappa_{c,f})} \tag{A.106}$$

The consumption share $\mathcal{C}$ is:

$$\mathcal{C} = \frac{(\kappa_{w,f} + \kappa_{c,f})\,(1 + \mathcal{P}_e\,\epsilon_{\text{cons}}\,f(\mathcal{P}_e))}{\mathcal{K}_e\,(\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e\,\epsilon_{\text{cons}}\,f(\mathcal{P}_e))\,(\kappa_{w,f} + \kappa_{c,f})} \tag{A.107}$$

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

$$\mathcal{I} = 1 - \mathcal{C} \tag{A.108}$$

$$= \frac{\mathcal{K}_e\,(\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f}{\mathcal{K}_e\,(\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e\,\epsilon_{\text{cons}}\,f(\mathcal{P}_e))\,(\kappa_{w,f} + \kappa_{c,f})} \tag{A.109}$$

A.4 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:

$$y_{e,p} = y_{e,d} := y_e \tag{A.110}$$

$$y_{f,p} = y_{f,d} := y_f \tag{A.111}$$

The constraint A.110 was already enforced in the demand model from section A.3. However, constraint A.111 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 A.7-A.11 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 A.24. Instead, it is defined as the residual of equation A.111:

$$y_{f,p} = y_{f,d} \tag{A.112}$$

$$\frac{k_f}{\gamma_f} = i_e + i_f + c_{w,f} + c_{c,f} \tag{A.113}$$

$$i_f = \frac{k_f}{\gamma_f} - i_e - c_{w,f} - c_{c,f} \tag{A.114}$$

A.4.1 Reduced form of the supply-driven model

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

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

with the following intermediate variables:

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

$$
\begin{aligned}
\hat{k}_f &= \frac{1}{\gamma_f} - \left(\mathcal{K}_e\,(\hat{k}_e + \delta_e) + \delta_f + \kappa_{w,f} + \kappa_{c,f}\right)\\
\lambda &= \lambda_f + \lambda_e\\
\hat{p}_f &= \beta_{p_f}\left(\mu_f\,uc_f - 1\right)\\
r_{CB} &= r^* + \hat{p}_f + \varphi\left(\hat{p}_f - \hat{p}_f^T\right)\\
r^T &= r_{CB} + \lambda_{r^T}\,\frac{\mu_b\,(d_f + \mathcal{K}_e\,d_e) - of_b}{\mu_b\,(d_f + \mathcal{K}_e\,d_e)}
\end{aligned}
$$

A.5 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 A.3.6 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' database[6]. 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 A.3 and A.4 describe the results of the calibration. Table A.3 refers to the model's variables at steady-state (both the variables which have an associated differential equation and the intermediary variables). Table A.4 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 given[7], 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.

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

[7] in which the abbreviation "f.g." is used to refer to the final goods subsector

In the last rows of Tables A.3 and A.4, 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:

$$\frac{\alpha_f}{\alpha_e} = \frac{\lambda_e}{\lambda_f} \frac{u_f}{\gamma_f} \frac{1}{\mathcal{K}_e} \tag{A.115}$$

$$\omega_e = \omega_f \frac{\alpha_f}{\alpha_e} \frac{1}{\mathcal{P}_e} \tag{A.116}$$

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 A.5 is assumed to be of the form:

$$f(\mathcal{P}_e) = a_0 \left(\frac{a_1}{\mathcal{P}_e} + a_2 \right) \tag{A.117}$$

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 A.3 and A.4. The values of a_0, a_1 and a_2 are given in Table A.4.

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 $\left(\frac{2017US\$}{GJ}\right)$
λ	-	-	0.437	Penn World Table 10.0	Global employment rate
$\frac{\lambda_e}{\lambda_f}$	0.005	0.02	0.02	IRENA (2020)	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 A.3 Results of the calibration - variables

Parameter	Min	Max	Value	Source of range of values	Description (Unit)
$\widehat{POP}$	-	-	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 rate 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. $\left(\frac{\text{MJ}}{\text{2017US\\$}}\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. $\left(\frac{\text{2017US\\$}}{\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
$\beta_{p_f,1}$	1	3	1.32	Range of reasonable values	cost-push infl. adj. speed - f.g.
$\beta_{p_f,2}$	1	3	1.53	Range of reasonable values	demand-pull infl. adj. speed - f.g.
β_{p_e}	1	3	2.56	Range of reasonable values	Inflation adjustment speed - energy
$\beta_{n_f,1}$	0.5	2	1.23	Range of reasonable values	Expected prod. adj. factor - f.g.
$\beta_{n_f,2}$	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 $\left(\frac{\text{GJ}}{\text{2017US\\$}}\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_{i_e}	-	-	3	-	Param. for invest. decis. - energy
β_r	-	-	0.08	-	Interest rate adjustment speed
φ	-	-	0.4	-	Parameter in Taylor's rule
λ_{r^T}	-	-	0.018	-	Param. in banks target int. rate
ϵ_{cons}	-	-	0.0024	-	Technology parameter from equ. A.5
a_0	-	-	1.06	-	Param. of func. $f(\cdot)$ from equ. A.5
a_1	-	-	3.2	-	Param. of func. $f(\cdot)$ from equ. A.5
a_2	-	-	0.84	-	Param. of func. $f(\cdot)$ from equ. A.5

Table A.4 Results of the calibration - parameters

A.6 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 (A.2) and (A.4), we have:

$$e_f = \epsilon_f \, y_{f,p} \tag{A.118}$$

$$y_{f,d} = i_e + i_f + c_{w,f} + c_{c,f} \tag{A.119}$$

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

$$\begin{aligned}
e_f &= \epsilon_f \, y_{f,p} && \text{(A.120)}\\
&\simeq \epsilon_f \, y_{f,d} && \text{(A.121)}\\
&\simeq \epsilon_{f,i_e} \, i_e \quad + \ \epsilon_{f,i_f} \, i_f \quad + \ \epsilon_{f,c_f} \left(c_{w,f} + c_{c,f} \right) && \text{(A.122)}\\
\epsilon_f &\simeq \epsilon_{f,i_e} \frac{i_e}{y_{f,d}} + \ \epsilon_{f,i_f} \frac{i_f}{y_{f,d}} + \ \epsilon_{f,c_f} \frac{c_{w,f} + c_{c,f}}{y_{f,d}} && \text{(A.123)}\\
\epsilon_f &\simeq \epsilon_{f,i_e} \frac{i_e}{y_{f,d}} + \ \epsilon_{f,i_f} \frac{i_f}{y_{f,d}} + \left(\theta_g \, \epsilon_{f,c_f,g} + \theta_s \, \epsilon_{f,c_f,s} \right) \frac{c_{w,f} + c_{c,f}}{y_{f,d}} && \text{(A.124)}
\end{aligned}$$

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 4.1.2, 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 A.5. The rate of degrowth of ϵ_{cons} is computed in a similar way and also presented in Table A.5. Finally, thanks to equation (A.124), 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):

$$y_{e,p} = y_{nre,p} + y_{re,p} \tag{A.125}$$

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

$$\chi = \frac{y_{re,p}}{y_{e,p}} \tag{A.126}$$

$\chi = 3\%$ in 2019; the transition is completed once $\chi = 1$. We can thus rewrite equation A.125 as:

$$\begin{aligned} y_{e,p} &= y_{nre,p} + y_{re,p} && \text{(A.127)} \\ &= (1-\chi)\, y_{e,p} + \chi\, y_{e,p} && \text{(A.128)} \end{aligned}$$

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:

$$\begin{aligned} \gamma_e &= (1-\chi)\, \gamma_{nre} + \chi\, \gamma_{re} && \text{(A.129)} \\ \epsilon_e &= (1-\chi)\, \epsilon_{nre} + \chi\, \epsilon_{re} && \text{(A.130)} \end{aligned}$$

ϵ_{re} is supposed to be constant, at the value computed for grid losses in Chapter 5.1.1 of Dupont (2021).

To provide the formula for γ_{re}, we have to remind that:

$\text{EROI}_{re} = \frac{E_{out}}{E_{in}}$;

E_{out} is the total energy harvested from the renewable energy facility during its entire lifetime, in [MJ];

E_{in} is the total energy input (invested at the construction of the renewable energy facility), in [MJ];

ϵ_{f,i_e} is the energy intensity of the production of energy capital stock, in [MJ/$];

$\frac{1}{\delta_e}$ is the lifetime of a (renewable) energy facility, in [years].

Hence, $\frac{E_{in}}{\epsilon_{f,i_e}}$ is the investment cost at the construction of the renewable energy facility, in [$];

and $E_{out}\,\delta_e$ the yearly energy output of the renewable energy facility, in [MJ/year].

This leads us to:

$$\gamma_{re} = \text{the investment required to have an energy production of 1 MJ/year} \tag{A.131}$$

$$\gamma_{re} = \frac{E_{in}}{\epsilon_{f,i_e}} \times \frac{1}{E_{out}\,\delta_e} \tag{A.132}$$

$$\gamma_{re} = \frac{1}{\text{EROI}_{re}\,\epsilon_{f,i_e}\,\delta_e} \tag{A.133}$$

After replacing in equation A.133 EROI_{re} by the EROI curves from Dupont et al. (2018, 2020), we obtain the capital intensity curve depicted in Figure A.1[8,9].
As explained in Section 4.1.3, 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 A.5, while the computation 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

[8]Note that we use ϵ_{f,i_e} and not ϵ_f in equation (A.133). 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.

[9]In 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.

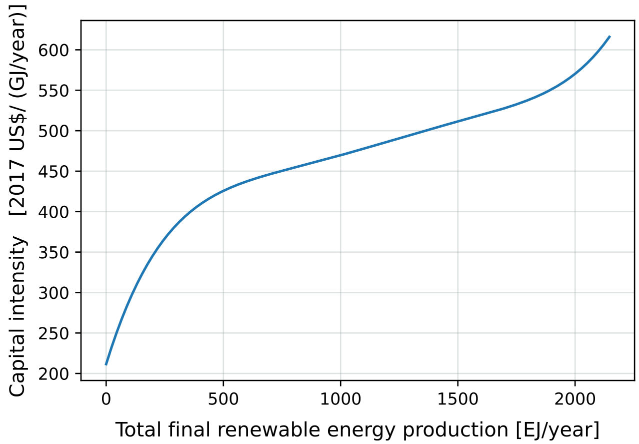


Fig. A.1 Capital intensity of renewable energy production worldwide γ_{re} as a function of total renewable energy production $y_{re,p}$

formulae:

$$\gamma_{nre} = \frac{\gamma_e - \chi \gamma_{re}}{1 - \chi} \tag{A.134}$$

$$\epsilon_{nre} = \frac{\epsilon_e - \chi \epsilon_{re}}{1 - \chi} \tag{A.135}$$

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:

$$\gamma_{nre} = \gamma_{nre}(2019)\,\frac{\text{EROI}_{nre}(2019)}{\text{EROI}_{nre}} \tag{A.136}$$

$$\epsilon_{nre} = \epsilon_{nre}(2019)\,\frac{\text{EROI}_{nre}(2019)}{\text{EROI}_{nre}} \tag{A.137}$$

EROI_{nre}, in turn, is a function of the total cumulated non-renewable energy production since the year 2019, as explained in Section 4.1.2. This function takes the following form (x being the cumulative production since 2019, in exajoules):

$$\text{EROI}_{nre} = 1 + 6.50 \times e^{-0.00002 \cdot x} \tag{A.138}$$

Parameter	Value	Source	Description (Unit)
ϵ_{f,i_e}	5.07	EXIOBASE and PWT 10.0	en. intens. of en. cap. stock. prod. $\left(\frac{\text{MJ}}{\text{2017US\\$}}\right)$
ϵ_{f,i_f}	2.80	EXIOBASE and PWT 10.0	en. intens. of f. g. cap. stock. prod. $\left(\frac{\text{MJ}}{\text{2017US\\$}}\right)$
$\epsilon_{f,c_f,g}$	3.67	EXIOBASE and PWT 10.0	en. intens. of f.g. prod. for cons. $\left(\frac{\text{MJ}}{\text{2017US\\$}}\right)$
$\epsilon_{f,c_f,s}$	1.15	EXIOBASE and PWT 10.0	en. intens. of f.g. prod. for cons. $\left(\frac{\text{MJ}}{\text{2017US\\$}}\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 A.4	Cap. intens. of en. prod. $\left(\frac{\text{2017US\\$}}{\text{GJ}}\right)$
γ_{re}	223.05	Equation A.133	Cap. intens. of r.e. prod. $\left(\frac{\text{2017US\\$}}{\text{GJ}}\right)$
γ_{nre}	24.98	Equation A.134	Cap. intens. of n.r.e. prod. $\left(\frac{\text{2017US\\$}}{\text{GJ}}\right)$
ϵ_e	0.082	Table A.4	En. intens. of en. prod.
ϵ_{re}	0.087	Dupont (2021)	En. intens. of r.e. prod.
ϵ_{nre}	0.104	Equation A.135	En. intens. of n.r.e. prod.

Table A.5 Energy and capital intensities: calibrated values for the year 2019 and projected constant rates of change for the period 2019-2060

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 energy (sub-)sector. These energy inputs can be separated into direct energy inputs and energy embodied into the capital stock. Using Equation A.1, 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 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 4.1.3, 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 A.24 is not constant anymore, but decreases in a sigmoid way, as shown on Figure A.2. In this scenario, the final goods firms begin progressively to decrease their investment rate 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 A.24. This scenario enables us to discuss the impact of economic growth on the energy transition.

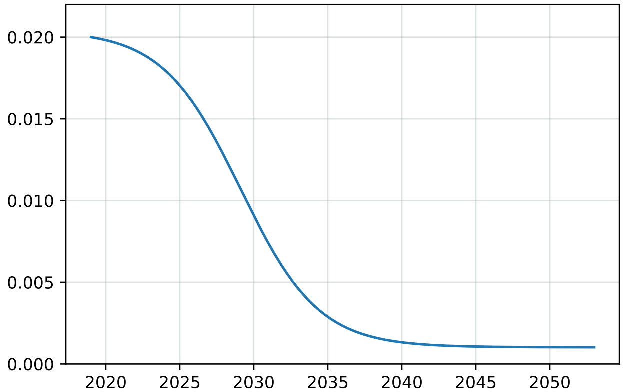


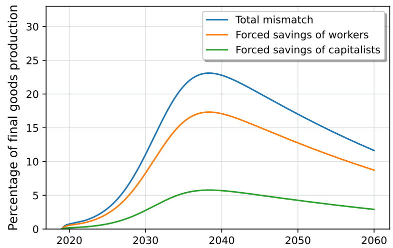
Fig. A.2 Imposed decrease for the parameter κ_{f0} from equation A.24 in the “slow growth" scenario

A.7 Results of the supply-driven version of the model

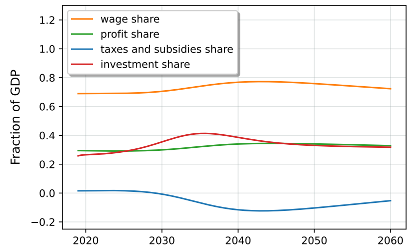
Figure A.3 gives the simulation results obtained with the supply-driven version of the model for the scenario of a rapid global energy transition compatible with the 1.5°C objective of the Paris Agreement. These results are extremely similar to the ones of the demand-driven version of the model, presented in Section 6.5.

A.8 Sensitivity analysis

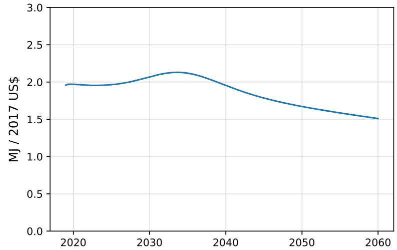
The results of the sensitivity analysis described in Section 4.3.2 are displayed in Figures A.4 and A.5. For concision, only the results for the investment rate and the inflation in final goods price are shown.



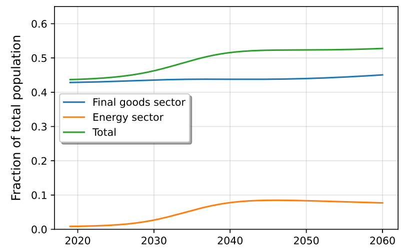
(a) Mismatch between demand and supply



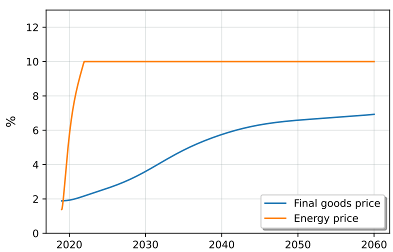
(b) GDP shares



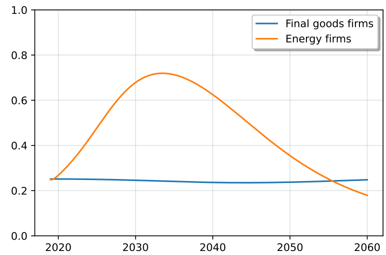
(c) Mean energy intensity of final goods production



(d) Employment level

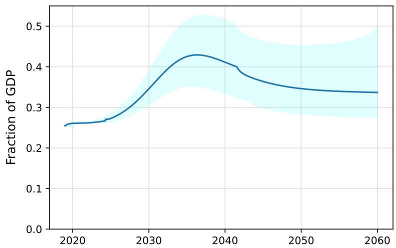


(e) Inflation

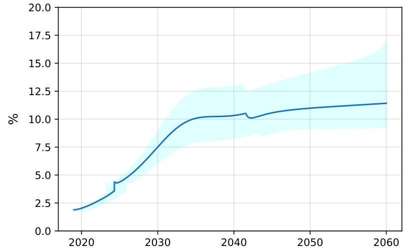


(f) Debt ratios

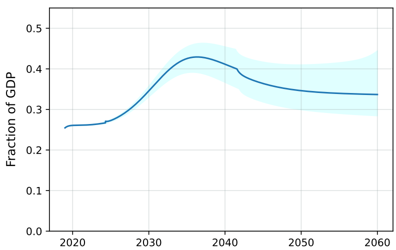
Fig. A.3 Simulated macroeconomic dynamics of the energy transition obtained with the supply-driven version of the model.



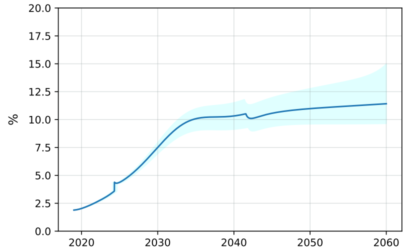
(a) Effect of γ_e on the investment rate



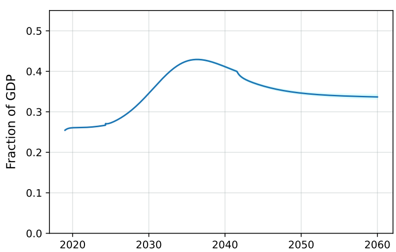
(b) Effect of γ_e on the inflation in final goods price



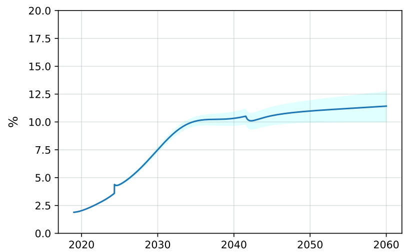
(c) Effect of the degrowth rate of the energy intensities on the investment rate



(d) Effect of the degrowth rate of the energy intensities on the inflation

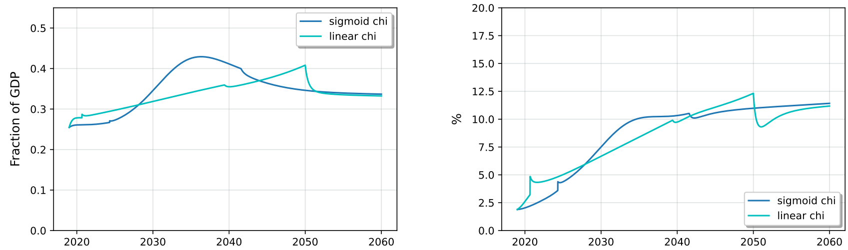


(e) Effect of population growth rate on the investment rate



(f) Effect of population growth rate on the inflation in final goods price

Fig. A.4 Effect of different parameters on the model's results



(a) Effect of the curve shape for χ on the investment rate

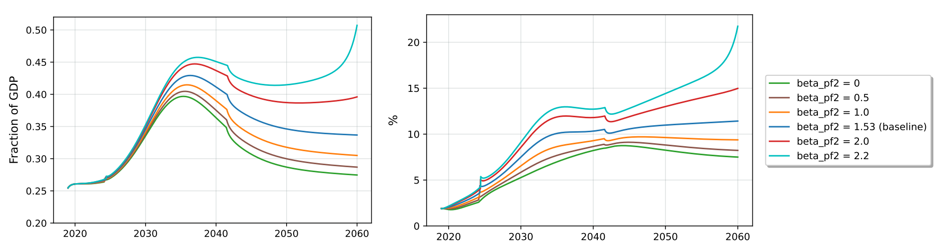
(b) Effect of the curve shape for χ on the inflation in final goods price

Fig. A.5 Effect of different parameters on the model's results – continued

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 $t = 2019$:

$$\beta_{p_f,1}\left(\mu_f\, uc_f - 1\right) + \beta_{p_f,2}\left(\eta\,\frac{u_f}{\gamma_f} - \nu_f\right) = 0.019$$

Figure A.6 displays the corresponding simulations' results.



(a) Effect on the investment rate

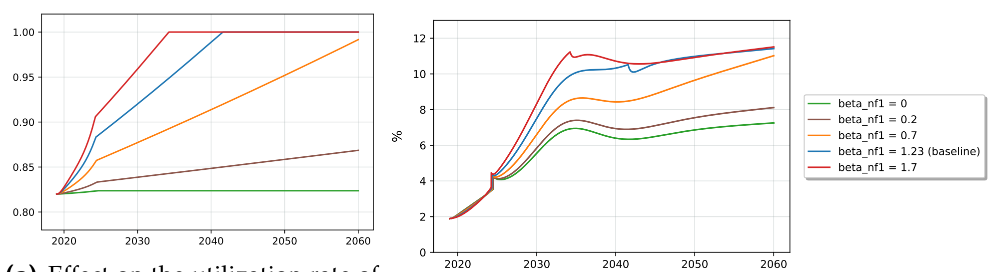
(b) Effect on the inflation in final goods price

Fig. A.6 Effects on the model's results of varying jointly the adjustment speeds for cost-push and demand-pull inflation in the final goods' price

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 A.3.6):

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

$v_f = 0$ at $t = 2019$ so changing the value of $\beta_{n_f,1}$ has no impact on the initial steady-state. Figure A.7 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 on the utilization rate of capital in the final goods sector

(b) Effect on the inflation in final goods price

Fig. A.7 Effects on the model's results of varying the adjustment speed for the utilization rate of the final goods firms' capital stock

B

Modifications applied to EnergyScope Pathway

This appendix describes modifications to the equations of the EnergyScope Pathway model. For a full description of the original equations of EnergyScope, see Limpens et al. (2019) (EnergyScope Typical Day) and Limpens et al. (2024) (EnergyScope Pathway).

B.1 Improving the macroeconomic features of EnergyScope

EnergyScope Pathway is adapted in three directions, to allow it to better take into account fluctuating economic conditions. They are described in the following sections. In this Appendix, "EnergyScope" refers to "EnergyScope Pathway" unless indicated otherwise.

B.1.1 Discount rate

EnergyScope includes different types of costs at different years. To adapt all cash flows to present values on which the cost-optimisation algorithm can be applied, a discount rate is used. This discount rate thus represents the temporal preference between present and future financial values. Based on this broad definition, several methods of computing the discount rate exist. Most of these methods incorporate the banks' interest rate. Such interest rate is subject to important fluctuations through time, especially in emerging economies. Hence, it is sound to allow the discount rate r^{discount} in EnergyScope to evolve. This constitues an improvement compared to previous versions of EnergyScope, where the discount rate was kept constant throughout the entire transition period.

Since temporal evolutions are represented only every five years in EnergyScope, r^{discount} is kept constant over each five-year phase. In practice, it is not r^{discount} which directly transforms all costs in EnergyScope (expressed as "costs per 5-year phase") into present values, but the annualisation factor per phase. The work therefore consists in modifying the formula of the annualisation factor per phase to be able to incorporate a variable discount rate. The annualisation factor thus becomes defined by the following recurrence formula:

$$annualised\_factor(p) = \begin{cases} \frac{1}{\left(1+r^{\text{discount}}(p)\right)^{2.5}} & \text{if } p = \text{"phase 0"} \\ annualised\_factor(p-1) \times & \\ \frac{1}{\left(1+r^{\text{discount}}(p-1)\right)^{2.5}} \times \frac{1}{\left(1+r^{\text{discount}}(p)\right)^{2.5}} & \text{otherwise} \end{cases} \tag{B.1}$$

This formula takes into account the 5-year length of the phases in EnergyScope: all elements in the first phase are discounted as if they were at the middle of the phase i.e. at year 2.5. For the next phases, all elements are discounted as if they were at the middle of the phase as well. This means multiplying the previous phase's annualisation factor by a 2.5 years discount factor using the previous phase's discount rate and by a 2.5 years discount factor using the current phase's discount rate.

B.1.2 Implementing imports in EnergyScope

In previous verions of EnergyScope, there was no distinction between locally-produced and imported technologies and all costs were given in constant €$_{2015}$. However, emerging economies like Colombia and Turkey have volatile currencies, and the imported or local character of technologies can have an important impact on the energy system cost. We therefore apply several modifications to EnergyScope. The first one is to convert all costs to the international currency (USD) for the year 2021. It is done by applying the following formula:

$$\text{Cost}[\text{USD}_{2021}] = \frac{\text{CEPCI}_{2021}\ [\text{USD}_{2021}]}{\text{CEPCI}_{2015}\ [\text{USD}_{2015}]} \times \frac{\text{USD}_{2015}}{€_{2015}} \times \text{Cost}[€_{2015}] \tag{B.2}$$

$$= 1.27 \times 1.11 \times \text{Cost}[€_{2015}] \tag{B.3}$$

$$= 1.41 \times \text{Cost}[€_{2015}] \tag{B.4}$$

In this formula, the historical exchange rate for 2015 is retrieved from the online data of the European Central Bank (2024). The CEPCI (Chemical Engineering, 2016) is an index taking into account the evolution of the equipment cost. The CEPCI values for recent years, extracted from Towering Skills (2020), are given in Table B.1.

Table B.1 Yearly values of the Chemical Engineering's Plant Cost Index (CEPCI), extracted from Towering Skills (2020)

Year	CEPCI
2010	550.8
2011	585.7
2012	584.6
2013	567.3
2014	576.1
2015	556.8
2016	541.7
2017	567.5
2018	603.1
2019	607.5
2020	596.2
2021	708.8
2022	816.0

For resources, the evolution of the cost from 2015 to 2021 is not computed using the CEPCI, but instead using local data about the evolution of energy prices (e.g. data from Minenergía-UPME (2020) for the case of Colombia). All costs in the input data files of EnergyScope become thus written in constant 2021 USD. In this thesis, USD always refers to constant 2021 USD unless specified otherwise.

The first modification described in the previous paragraphs defines the standard specification of costs in EnergyScope. The second modification is to make those costs vary on a case-by-case basis, to account for the particularities of the country under consideration. This modification is summarised in Equation B.5. The equation is written for the case of Colombia, where the local currency is the Colombian Peso (COP). It can easily be adapted to Turkey or any other country.

$$\begin{aligned}\text{Cost}[\text{COP}_{2021}] = \text{Cost}[\text{USD}_{2021}] \times \frac{\text{COP}_{2021}}{\text{USD}_{2021}} \times \\ \left([\text{Local fraction}] + [\text{Imported fraction}] \times \frac{\frac{\text{COP}_y}{\text{USD}_y}}{\frac{\text{COP}_{2021}}{\text{USD}_{2021}}} \right) \end{aligned} \quad \text{(B.5)}$$

First, we define the import content of each technology, which depends on the country's industrial setor. This content is specified in the input file *Technos_information.csv*. It determines the respective values of the two fractions [Local fraction] and [Imported fraction], which sum up to one. To be able to incorporate how the imported fraction is affected by fluctuations of the exchange rate, it is natural to perform the cost optimisation problem in local currency. All standard costs in 2021 USD are hence converted into the local currency (i.e. through the factor $\frac{\text{COP}_{2021}}{\text{USD}_{2021}}$ in Equation B.5). Then, the exchange rate given in the input file *exchange_rate.csv* is normalised so that it takes a unitary value in 2021 (i.e. fraction $\frac{\frac{\text{COP}_y}{\text{USD}_y}}{\frac{\text{COP}_{2021}}{\text{USD}_{2021}}}$, where y is the year index of the time series). The imported fraction of all costs is multiplied by this normalised time series. By doing so, the relative evolution of the exchange rate will directly affect the optimisation problem of EnergyScope, but the absolute value in 2021 will not (it will only multiply the result of the optimisation problem by a constant).

Equation B.5 is applied to the investment costs, maintenance costs and resource costs of EnergyScope. Regarding maintenance costs, they are supposed to be fully local ([Imported fraction] = 0) since they mostly consist in labour costs. For resources, the local and imported fractions are not determined by *Technos_information.csv*. Instead, new resource types are added in EnergyScope (e.g. *IMPORTED_COAL*, *LOCAL_COAL*) and each resource type is either fully imported ([Imported fraction] = 1) or fully local ([Imported fraction] = 0)

B.1.3 Energy Demand projections

Adding external energy demand projections does not require any modification in the code of the optimisation problem. The external projections are CSV files which give the values of End-Use Demands (EUD) every five years (e.g. *EUD_2021.csv*, *EUD_2026.csv*, ...). The values of EUD already defined within EnergyScope are simply overwritten by the values from the CSV files.

B.2 Duplication of several technologies to smooth out the investment pattern

Another modification has to be made to EnergyScope before coupling it with GEMMES. Indeed, the investments in EnergyScope are splitted into 5-year phases. All the capacity of one technology is installed during one single phase, and decommissioned all at once when it reaches the end of its lifetime. Such discrete investment behaviour implies a lot of investment in some phases and little investment in others. Besides being unrealistic, such investment pattern causes stability issues when fed to a macroeconomic model like GEMMES.

In reality, the capacity of one given technology type is renewed on a more or less constant basis and not all at once during a single five-year phase. To reflect this, the technologies representing the biggest investment costs are dupplicated in EnergyScope. The following new technologies are thus introduced in the model:

- CAR_GASOLINE_BIS
- BUS_COACH_DIESEL_BIS
- TRUCK_DIESEL_BIS
- TRUCK_GASOLINE_BIS

The capacity of the corresponding technologies is thus splitted in the model between the technology and the technology "bis". The initial age of the technology and its dupplicate at the starting age of the transition pathway are set at different values, such that they are not renewed during the same five-year phase. Doing so allows to significantly smooth out the investment pattern of EnergyScope.

B.3 Adding a carbon tax in EnergyScope

In previous versions of both EnergyScope TD and EnergyScope Pathway, the optimisation problem was of the form:

$$\text{Minimise system cost such that CO}_2\text{ emissions } \leq \text{ carbon budget}$$

We now allow the user to choose between the form above and the following new one:

$$\text{Minimise system cost} + \text{cost of carbon} \times \text{CO}_2\text{ emissions}$$

B.4 Addition of export of electrofuels in EnergyScope

Electrofuels (or e-fuels) are a recent type of fuel. They are produced using (renewable) electricity. Thus, they do not act as an energy source but rather as an energy carrier. The export of e-fuels is frequently cited as a possible strategy for partially compensating for the planned decrease in fossil fuels exports in Colombia (IEA, 2021a; IRENA, 2022). We therefore introduce four e-fuels as new resource types in EnergyScope:

- H2_EXPORT
- GAS_RE_EXPORT
- AMMONIA_EXPORT
- METHANOL_EXPORT

The Belgian Hydrogen Import Coalition (2020) computed a projection of the import costs of e-fuels from international markets for the year 2035. They indicate that 85% of the cost would correspond to production cost, local transmission and local terminalling. The rest would correspond to shipping and remote terminalling. Thus, the revenue of an e-fuel exporter like Colombia would be equal to 85% of the computed import cost. Revenues from e-fuels exports are hence computed in EnergyScope as fractions of the import costs of those same fuels, already documented for Belgium in Rixhon (2024). See Jacques and Limpens (2024) for more details.

C

Coupling an SFC model with an ESOM to study the impacts of the energy transition in Colombia

This appendix describes the coupling between EnergyScope Pathway and GEMMES adapted to the Colombian economy. Only adaptations and deviations from the original equations of the models are presented. For a full description of the original equations of GEMMES Colombia, see Chapter 2 of Godin et al. (2024).

C.1 Modifications to GEMMES equations

In this section, we give an exhaustive description of all modifications made to GEMMES equations for the coupling. The modifications apply to the equations from Godin et al. (2024). They are therefore given for the particular case of the Colombian version of GEMMES, but could easily be generalised to other versions. Table C.1 gives a summary of the variables provided by EnergyScope in the file *Energy_system_costs.csv*.

	NFC	FC	G	H
Investment in the energy capital stock	I_F^{KE}	I_B^{KE}	I_G^{KE}	I_H^{KE}
Import content of the energy capital stock	$\sigma_{KE,F}^M$	$\sigma_{KE,B}^M$	$\sigma_{KE,G}^M$	$\sigma_{KE,H}^M$
Cost of the locally-produced energy capital stock	$p_F^{KE,CO}$	$p_B^{KE,CO}$	$p_G^{KE,CO}$	$p_H^{KE,CO}$
Cost of the imported energy capital stock	$p_F^{KE,M}$	$p_B^{KE,M}$	$p_G^{KE,M}$	$p_H^{KE,M}$
(Intermediary) energy-related consumption	ICE_F	ICE_B	ICE_G	CE_H
Import content of the (intermediary) energy-related consumption	$\sigma_{ICE,F}^M$	$\sigma_{ICE,B}^M$	$\sigma_{ICE,G}^M$	$\sigma_{CE,H}^M$
Cost of the imported energy intermediary consumption	p_{ICE}^M	p_{ICE}^M	p_{ICE}^M	p_{ICE}^M
Carbon tax	CT_F	CT_B	CT_G	CT_H
Export of electrofuels	X_{EF}			

Table C.1 Exogenous variables contained in *Energy_system_costs.csv*. "NFC"=Non-Financial Corporations. "FC"=Financial Corporations. "G"=Government. "H"=Households.

Each variable has four instances, one for each economic sector. The I^{KE} represent investments in energy capital stock, expressed in real terms (i.e. they are given as "numbers of machines" with an abstract unit, which could be assimilated to GW for most energy technologies). The ICE, in turn, represent the maintenance costs and the costs of resources, grouped as *"(intermediary) consumption costs related to the energy system"*. They are also expressed in real terms, with an abstract unit. The word *"intermediary"* is put between brackets because for households, these quantities fall in final instead of intermediary consumption. The σ^M then split the I^{KE} and ICE between local and imported quantities. The multiplication factors p^{CO} are used to convert local quantities into local currency, while the p^M convert imported quantities into USD. Besides units' conversions, the evolution of the p^{CO} and p^M also reflect the evolution of the costs of individual technologies, as well as the changing composition of the technology mix. Finally, the amounts of carbon tax collected are given by CT and the total export of electrofuels is provided by X_{EF}. Note also that whenever an exogenous shock (e.g. on the interest rate) needs to be applied to GEMMES, it can be done by treating the corresponding parameter as an exogenous variable and by specifying its values through time, including the shock, in *Energy_system_costs.csv*.

The modifications applied to GEMMES' equations to integrate all the new exogenous variables are given below. All additions are indicated in blue. Whenever the equation presented builds upon an equation already existing in Godin et al. (2024), the corresponding equation number from Godin et al. (2024) is indicated between brackets.

$$Y^{P,D} = Y^P - M - M_F^{KE} - M_B^{KE} - M_G^{KE} - M_H^{KE} - M_F^{ICE} - M_B^{ICE} - M_G^{ICE} - M_H^{CE} \tag{8}$$

$$Y^D = C + CE_H \cdot p_H^{CE} + IC + ICE_F \cdot p_F^{ICE} + ICE_B \cdot p_B^{ICE} + ICE_G \cdot p_G^{ICE} + I^K + X + I_F^{KE} \cdot p_F^{KE} + I_B^{KE} \cdot p_B^{KE} + I_G^{KE} \cdot p_G^{KE} + I_H^{KE} \cdot p_H^{KE} \tag{9}$$

$$Y^{D,r} = \frac{C}{p^C} + CE_H + \frac{IC}{p^{IC}} + ICE_F + ICE_B + ICE_G + \frac{I^K}{p^K} + \frac{X}{p^X} + I_F^{KE} + I_B^{KE} + I_G^{KE} + I_H^{KE} \tag{10}$$

$$X = X_C + X_{NC} + X_{EF} \tag{14}$$

$$IM = M \cdot p^W \cdot e^N + (M_F^{KE} \cdot p_F^{KE,M} + M_B^{KE} \cdot p_B^{KE,M} + M_G^{KE} \cdot p_G^{KE,M} + M_H^{KE} \cdot p_H^{KE,M} + (M_F^{ICE} + M_B^{ICE} + M_G^{ICE} + M_H^{ICE}) \cdot p_{ICE}^M) \cdot p^W \cdot e^N \tag{20}$$

$$M_F^{KE} = \sigma_{KE,F}^M \cdot I_F^{KE}$$

$$M_B^{KE} = \sigma_{KE,B}^M \cdot I_B^{KE}$$

$$M_G^{KE} = \sigma_{KE,G}^M \cdot I_G^{KE}$$

$$M_H^{KE} = \sigma_{KE,H}^M \cdot I_H^{KE}$$

$$M_F^{ICE} = \sigma_{ICE,F}^M \cdot I_F^{ICE}$$

$$M_B^{ICE} = \sigma_{ICE,B}^M \cdot I_B^{ICE}$$

$$M_G^{ICE} = \sigma_{ICE,G}^M \cdot I_G^{ICE}$$

$$M_H^{CE} = \sigma_{CE,H}^M \cdot I_H^{CE}$$

$$GDP = C + CE_H \cdot p_H^{CE} + I^K + I_F^{KE} \cdot p_F^{KE} + I_B^{KE} \cdot p_B^{KE} + I_G^{KE} \cdot p_G^{KE} + I_H^{KE} \cdot p_H^{KE} + INS_H + Com_H + G_C + X - IM \tag{32}$$

$$UC = \frac{(1+\theta_{W,F}) \cdot W_F \cdot L_F + p^{IC} \cdot IC_F + p_F^{ICE} \cdot ICE_F + CT_F + \tau_F^Y \cdot Y^{P,D}}{Y^{P,D}} \tag{37}$$

$$p^X = \frac{X}{x_C + \sigma_{X_N} \cdot GDP_W + X_{EF}} \tag{41}$$

The following eight equations define the prices for the capital investments and intermediary consumption related to the energy system. As stated above, the factors p^{CO} and p^{M} reflect both the evolution of the costs of technologies and the evolution of the composition of the technology mix. These factors are then multiplied by a price (p for local and p^{W} for imported) to incorporate inflation. The price of imports is multiplied by the exchange rate to convert it to the local currency.

$$p_F^{KE} = \left(1-\sigma_{KE,F}^{M}\right)\cdot p_F^{KE,CO}\cdot p + \left(1+\tau^{M}\right)\cdot\sigma_{KE,F}^{M}\cdot p_F^{KE,M}\cdot p^{W}\cdot e^{N}$$

$$p_B^{KE} = \left(1-\sigma_{KE,B}^{M}\right)\cdot p_B^{KE,CO}\cdot p + \left(1+\tau^{M}\right)\cdot\sigma_{KE,B}^{M}\cdot p_B^{KE,M}\cdot p^{W}\cdot e^{N}$$

$$p_G^{KE} = \left(1-\sigma_{KE,G}^{M}\right)\cdot p_G^{KE,CO}\cdot p + \left(1+\tau^{M}\right)\cdot\sigma_{KE,G}^{M}\cdot p_G^{KE,M}\cdot p^{W}\cdot e^{N}$$

$$p_H^{KE} = \left(1-\sigma_{KE,H}^{M}\right)\cdot p_H^{KE,CO}\cdot p + \left(1+\tau^{M}\right)\cdot\sigma_{KE,H}^{M}\cdot p_H^{KE,M}\cdot p^{W}\cdot e^{N}$$

$$p_F^{ICE} = \left(1-\sigma_{ICE,F}^{M}\right)\cdot p + \left(1+\tau^{M}\right)\cdot\sigma_{ICE,F}^{M}\cdot p_{ICE}^{M}\cdot p^{W}\cdot e^{N}$$

$$p_B^{ICE} = \left(1-\sigma_{ICE,B}^{M}\right)\cdot p + \left(1+\tau^{M}\right)\cdot\sigma_{ICE,B}^{M}\cdot p_{ICE}^{M}\cdot p^{W}\cdot e^{N}$$

$$p_G^{ICE} = \left(1-\sigma_{ICE,G}^{M}\right)\cdot p + \left(1+\tau^{M}\right)\cdot\sigma_{ICE,G}^{M}\cdot p_{ICE}^{M}\cdot p^{W}\cdot e^{N}$$

$$p_H^{ICE} = \left(1-\sigma_{CE,H}^{M}\right)\cdot p + \left(1+\tau^{M}\right)\cdot\sigma_{CE,H}^{M}\cdot p_{ICE}^{M}\cdot p^{W}\cdot e^{N}$$

$$\begin{aligned} GOS_F &= Y^{D} - IM - T^{P} - T^{M} - T^{V} - \tau^{Y,F}\cdot Y^{P,D} - p^{IC}\cdot IC_F \\ &\quad + p_F^{ICE}\cdot ICE_F - INS_F - Com_F - (1+\tau_{W,F})\cdot W_F\cdot L_F \end{aligned} \tag{51}$$

$$TFNF = p^{K}\cdot I_F^{K} + p_F^{KE}\cdot I_F^{KE} - RE_F \tag{66}$$

$$GOS_B = Y^{B} - p^{IC}\cdot IC_B - p_B^{ICE}\cdot ICE_B - \tau_B^{Y}\cdot Y^{B} - (1+\tau_{W,B})\cdot W_B\cdot L_B \tag{73}$$

$$\begin{aligned} TFNF_B &= \left[\dot{L^d} + \dot{Bg}_B + \dot{Rd} + I_B + I_B^{KE}\cdot p_B^{KE}\right] \\ &\quad - \left[(1+lr)\cdot\dot{D^d} + \dot{OF}_B + FDI_B + \dot{TIR}_H\right] \\ &\quad + \left[\dot{D_B^{FX}}\cdot e^{N} + \dot{L_F^{FX,B}}\cdot e^{N} + \dot{R_B^{FX}}\cdot e^{N} - \dot{L_B^{FX,W}}\cdot e^{N}\right] \end{aligned} \tag{97}$$

$$C_H^{NE,T} = C_H^{T} - CE_H\cdot p_H^{CE}$$

$$\dot{C}_H = \beta_C\cdot\left(C_H^{NE,T} - C_H\right) \tag{126}$$

$$S_H = YD_H - C_H - CE_H\cdot p_H^{CE} \tag{133}$$

$$TFN_H = I_H + I_H^{KE}\cdot p_H^{KE} - S_H \tag{134}$$

$$\dot{L}_H^{d,I} = \eta_{LI} \cdot \left(I_H + I_H^{KE} \cdot p_H^{KE} \right) \tag{137}$$

$$\begin{aligned} G_P &= C_G + (1 + \tau_{W,G}) \cdot W_G \cdot L_G + p^{IC} \cdot IC_G + p_G^{ICE} \cdot ICE_G \\ &\quad + p^K \cdot I_G + p_G^{KE} \cdot I_G^{KE} + ST_G \end{aligned} \tag{149}$$

$$FDI = \psi^{FDI} \cdot \left(p^K \cdot I_F + p_F^{KE} \cdot I_F^{KE} \right) \tag{181}$$

Finally, the EUDs to feed to EnergyScope are computed by adding the following equations:

$$El_F = \theta_F^{El} \cdot Y^{P,D} \tag{C.1}$$
$$HLTSH_F = \theta_F^{HLTSH} \cdot K_F \tag{C.2}$$
$$HLTHW_F = \theta_F^{HLTHW} \cdot K_F \tag{C.3}$$
$$HHT_F = \theta_F^{HHT} \cdot Y^{P,D} \tag{C.4}$$
$$PC_F = \theta_F^{PC} \cdot Y^{P,D} \tag{C.5}$$
$$MF_F = \theta_F^{MF} \cdot Y^{P} \tag{C.6}$$
$$NE_F = \theta_F^{NE} \cdot Y^{P,D} \tag{C.7}$$

$$El_B = \theta_B^{El} \cdot L_B \tag{C.8}$$
$$HLTSH_B = \theta_B^{HLTSH} \cdot L_B \tag{C.9}$$
$$SC_B = \theta_B^{SC} \cdot L_B \tag{C.10}$$

$$El_G = \theta_G^{El} \cdot L_G \tag{C.11}$$
$$HLTSH_G = \theta_G^{HLTSH} \cdot L_G \tag{C.12}$$
$$SC_G = \theta_G^{SC} \cdot L_G \tag{C.13}$$

$$El_H = \theta_H^{El} \cdot K_H \tag{C.14}$$
$$HLTSH_H = \theta_H^{HLTSH} \cdot K_H \tag{C.15}$$
$$HLTHW_H = \theta_H^{HLTHW} \cdot K_H \tag{C.16}$$
$$SC_H = \theta_H^{SC} \cdot K_H \tag{C.17}$$
$$MP_H = \theta_H^{MP} \cdot K_H \tag{C.18}$$

C.2 Post-processing of EnergyScope outputs for the coupling

The original output costs of EnergyScope consist in the CAPEX and OPEX of the technologies installed in the energy system, as well as the OPEX of the energy resources used. The energy system costs fed to GEMMES, as mentioned in Section 6.3.4, are quite different from these. The outputs from EnergyScope hence necessitate a substantial amount of post-processing, which we describe in this section.

In Section B.1.2, we explained how the input costs used in EnergyScope first had to be divided between the local and imported fractions, in order for the currency exchange rate to play a role. EnergyScope outputs, in turn, are expressed in 2021 Colombian pesos, with imported and local fractions of technologies blended again. The first step is thus to separate again these imported and local fractions. The CAPEX are splitted using the CSV file *Technos_information.csv*. The OPEX consist mainly in labour costs and are therefore assumed to be fully local.

The second step is to assign the costs of technologies across the economic sectors defined in GEMMES. We use the following assumptions for Colombia, based on information received from DNP, the National Planning Department:

- All energy production assets belong to private firms;
- 80% of the national electricity grid belongs to the private sector and 20% to the public sector. The same proportions are taken for the future hydrogen grid;
- 70% of District Heating Networks (DHN) belongs to the private sector and 30% to the public sector;
- 65% of cross-border electricity transmission lines belongs to the private sector and 35% to the public sector;
- 50% of charging stations for electric vehicles are owned by the public sector and 50% by households;
- Private mobility means belong entirely to households;
- Public mobility means belong entirely to the public sector;
- Freight vehicles belong entirely to the private sector.

Moreover, the breakdowns of low-temperature heating (LTH, i.e. space heating) demand and cooling demand between GEMMES economic sectors are saved by GEMMES in the CSV files *shares_LTH.csv* and *shares_cooling.csv*. These proportions are used for attributing the costs related to EnergyScope heating and cooling technologies across the economic sectors.

Similarly to technology costs, resources are divided between local, imported and exported. All resource costs are assigned to the private sector.

According to information received from DNP, the Colombian energy sector, excluding fossil fuels extraction and refining and excluding the transport sector, accounted for 2.8% of the country GDP in 2021. Based on this figure, we compute an adjustment factor and apply it to the costs from EnergyScope.

As mentioned above, all resource costs are assigned to the private sector. Still, we need to add to the OPEX of households, government and banks the bills they pay to private firms for buying fuels and electricity. To this end, the costs of resources per MWh are reconstructed based on EnergyScope outputs. Similarly, an electricity price is computed based on the electricity mix and on the CAPEX and OPEX of the related technologies. The carbon tax on the different sectors is also computed, based on information previously saved by EnergyScope in the CSV file *CO2_costs_COP.csv*.

Once the energy bills paid by households, government and banks to the private sector have been added to their OPEX, we have two CAPEX and OPEX for each economic sector: one local and one imported. All these CAPEX and OPEX are expressed in 2021 Colombian pesos. We compute the $I^{KE,CO}$ and $I^{KE,M}$ based on the installed capacities of the different technologies and on how they are splitted between the different sectors, and between local and imported. Then, the variables used in GEMMES equations are calculated with the following formulae:

$$I_F^{KE} = I_F^{KE,CO} + I_F^{KE,M} \qquad I_B^{KE} = I_B^{KE,CO} + I_B^{KE,M}$$
$$I_G^{KE} = I_G^{KE,CO} + I_G^{KE,M} \qquad I_H^{KE} = I_H^{KE,CO} + I_H^{KE,M}$$
$$\sigma_{KE,F}^{M} = \frac{I_F^{KE,M}}{I_F^{KE}} \qquad \sigma_{KE,B}^{M} = \frac{I_B^{KE,M}}{I_B^{KE}}$$
$$\sigma_{KE,G}^{M} = \frac{I_G^{KE,M}}{I_G^{KE}} \qquad \sigma_{KE,H}^{M} = \frac{I_H^{KE,M}}{I_H^{KE}}$$
$$p_F^{KE,CO} = \frac{CAPEX_F^{CO}}{I_F^{KE,CO}} \qquad p_B^{KE,CO} = \frac{CAPEX_B^{CO}}{I_B^{KE,CO}}$$
$$p_G^{KE,CO} = \frac{CAPEX_G^{CO}}{I_G^{KE,CO}} \qquad p_H^{KE,CO} = \frac{CAPEX_H^{CO}}{I_H^{KE,CO}}$$
$$p_F^{KE,M} = \frac{CAPEX_F^{M}}{I_F^{KE,M} \cdot e^N} \qquad p_B^{KE,M} = \frac{CAPEX_B^{M}}{I_B^{KE,M} \cdot e^N}$$
$$p_G^{KE,M} = \frac{CAPEX_G^{M}}{I_G^{KE,M} \cdot e^N} \qquad p_H^{KE,M} = \frac{CAPEX_H^{M}}{I_H^{KE,M} \cdot e^N}$$
$$\sigma_{ICE,F}^{M} = \frac{OPEX_F^{M}}{ICE_F} \qquad \sigma_{ICE,B}^{M} = \frac{OPEX_B^{M}}{ICE_B}$$
$$\sigma_{ICE,G}^{M} = \frac{OPEX_G^{M}}{ICE_G} \qquad \sigma_{CE,H}^{M} = \frac{OPEX_H^{M}}{CE_H}$$
$$ICE_F = OPEX_F^{CO} + OPEX_F^{M} \qquad ICE_B = OPEX_B^{CO} + OPEX_B^{M}$$
$$ICE_G = OPEX_G^{CO} + OPEX_G^{M} \qquad CE_H = OPEX_H^{CO} + OPEX_H^{M}$$
$$p_{ICE}^{M} = p_{ICE}^{M} = p_{ICE}^{M} = p_{ICE}^{M} = \frac{1}{e^N} \qquad X_{EF} = \frac{EXPORTS^{CO}}{e^N}$$

These variables are saved in the CSV file *Energy_system_costs.csv*. The divisions by e^N allow to express the imported costs and export revenues in 2021 USD instead of COP.

C.3 Assumptions for the studied scenarios

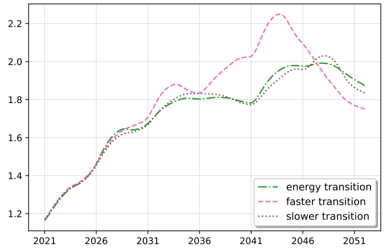
The various scenarios studied in Chapter 6 differ namely by the constraints that they are subject to and by parameter values. The corresponding data files can be found on the Github repository at url `https://github.com/energyscope/EnergyScope_coupling_GEMMES/tree/eec22143ff7f8bbf37aa764ed2b6aec` `EnergyScope_Pathway/ESMY/STEP_2_Pathway_Model/Colombia/Files%20for%20other%20scenarios`. (The standard data files and parameter values used in the code from the repository correspond to the energy transition scenario of Chapter 6.)

In particular, in the green industrialisation scenario, the modified matrix gives the following import content for green energy technologies:

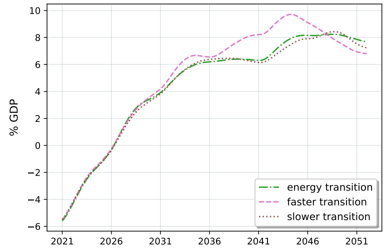
- CAR_BEV: 32% local (instead of 0.5%). The same import content as CAR_GASOLINE in the baseline scenario is used.
- MOTORCYCLE_ELECTRIC: 28% local (instead of 1%). The same import content as MOTORCYCLE in the baseline scenario is used.
- PV: 58% local (instead of 10%). This number corresponds to what was achieved in South Africa in 2022 (USAID, 2022).
- Onshore and offshore wind: 58% local (instead of 30% for onshore and 0% for offshore). In the absence of data, the same number as for PV is used.

C.4 Sensitivity analysis to parameters and adverse shocks

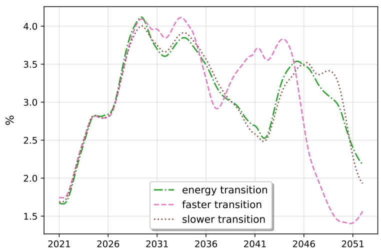
Figures C.1, C.2 and C.3 display the results from the sensitivity analysis and adverse shocks of Section 6.6.1.



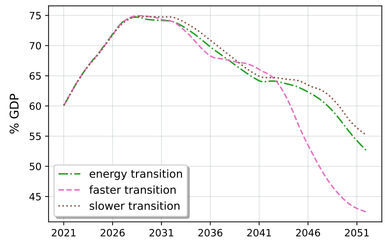
(a) Real exchange rate



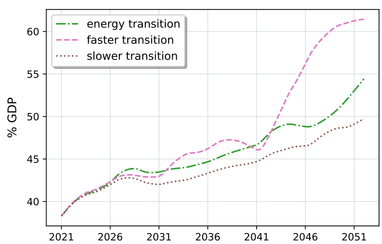
(b) Trade balance



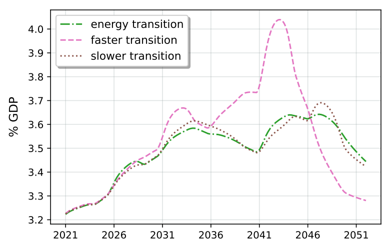
(c) Real GDP growth



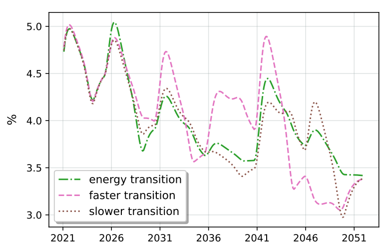
(d) Government total debt



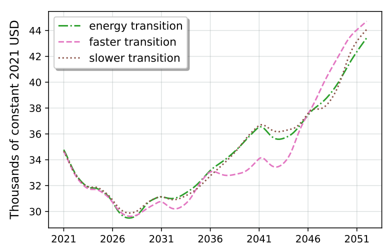
(e) Total debt of private firms



(f) Government foreign bond rate

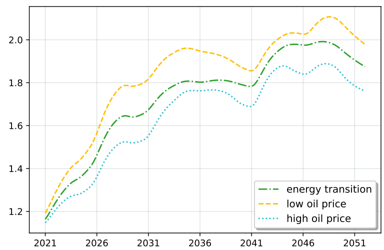


(g) Consumer price inflation rate

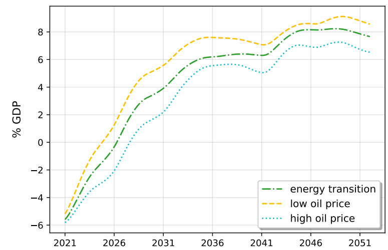


(h) Per capita income

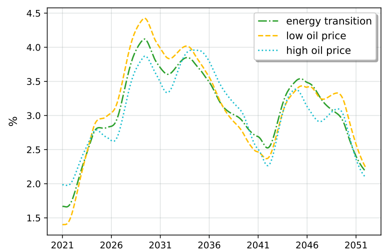
Fig. C.1 Variations in macroeconomic dynamics as a function of the speed of the energy transition



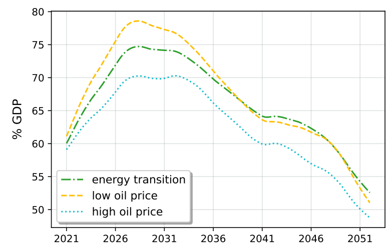
(a) Real exchange rate



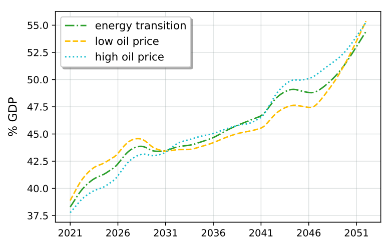
(b) Trade balance



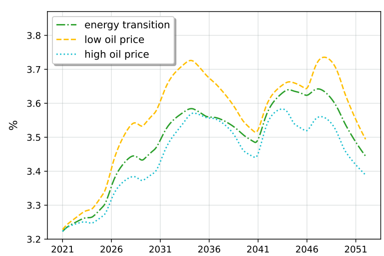
(c) Real GDP growth



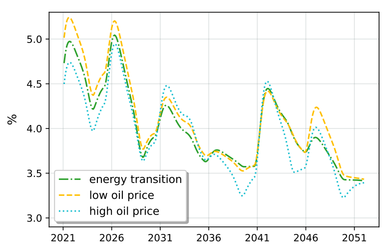
(d) Government total debt



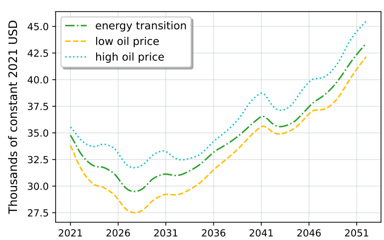
(e) Total debt of private firms



(f) Government foreign bond rate

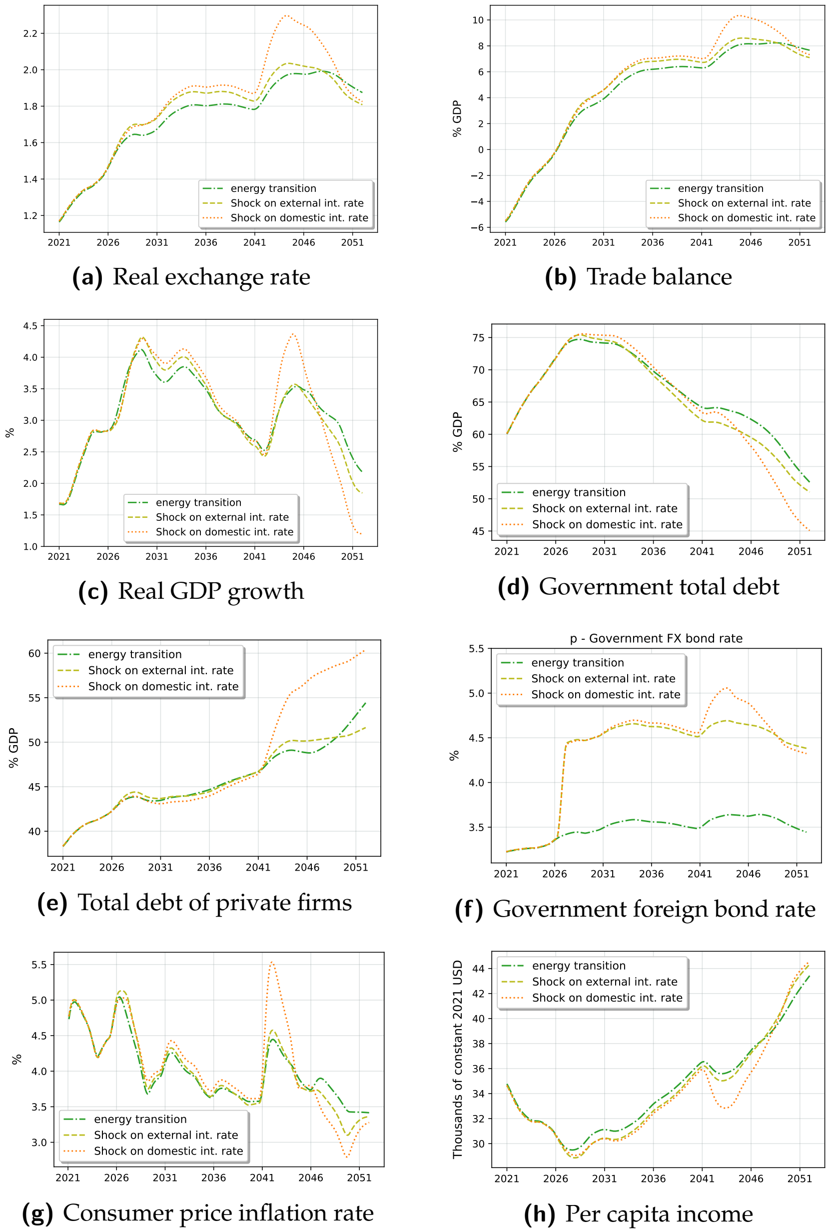


(g) Consumer price inflation rate



(h) Per capita income

Fig. C.2 Variations in macroeconomic dynamics as a function of the international oil price



(a) Real exchange rate
(b) Trade balance
(c) Real GDP growth
(d) Government total debt
(e) Total debt of private firms
(f) Government foreign bond rate
(g) Consumer price inflation rate
(h) Per capita income

Fig. C.3 Variations in macroeconomic dynamics in response to a shock on the foreign and/or domestic interest rate

D
Structure of the EnergyScope and GEMMES codes

Figure D.1 gives an overview of the programming languages used in GEMMES, in EnergyScope and in the coupling between the two models. As outlined in the Figure:

- GEMMES' equations are written in R;
- GEMMES then transforms these equations in C++ (the user can execute this process through the R interface);
- EnergyScope's optimisation problem is written in AMPL;
- A python wrapper allows to manipulate all aspects of EnergyScope other than the equations of the optimisation problem;
- Exchange of information between the two models is performed in python;
- The pre- and post-processing of input data to make them compatible from one model to another is carried out in pyhon;
- Python successively calls the C++ code of GEMMES and the AMPL optimization problem of EnergyScope through the iteration process described in Section 6.3.6;

- The GEMMES' equations written in R are available upon request;
- All codes except GEMMES' equations written in R are available on a public Github repository [1]. The instructions for installing the required energyscope package in python are given in Jacques and Limpens (2024).

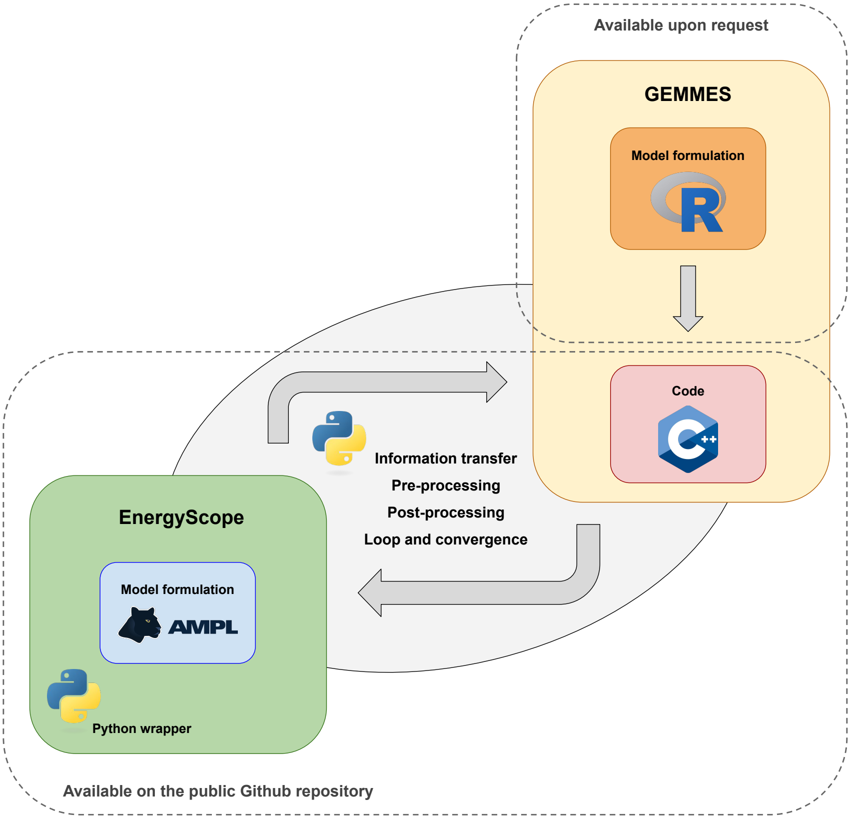


Fig. D.1 Programming languages behind the GEMMES-EnergyScope coupling

[1] https://github.com/energyscope/EnergyScope_coupling_GEMMES/tree/eec22143ff7f8bbf37aa764ed2b6aec911df78a7/EnergyScope_Pathway

On the public Github repository, the file *run_GEMMES_EnergyScope.py* located in the folder *run* was built based on the code from Rixhon (2024) after having removed all aspects related to reinforcement learning. Three main options are available for the parameter *mode* in this file:

- *mode = 'GEMMES-EnergyScope'* allows to run the coupling between GEMMES and EnergyScope (to obtain the results from Chapter 6);
- *mode = 'EnergyScope_only'* allows to run EnergyScope Pathway without coupling (to obtain the results from Chapter 5);
- *mode = 'GEMMES_only'* allows to run GEMMES without coupling (not used directly in this thesis, but gives results similar to those of Godin et al., 2024).

The code *run_GEMMES_EnergyScope.py* also allows to choose the country to study: Turkey (only currently available with *mode = 'EnergyScope_only'*) or Colombia.

A final option allows to choose the time resolution of EnergyScope:

- *EnergyScope_granularity = 'TD'* sets an hourly granularity with the use of the typical days method. This setting was used for producing all results presented in Chapters 5 and 6[2];
- *EnergyScope_granularity = 'MO'* sets a monthly granularity. It allows EnergyScope to run much faster, but comes with a loss regarding the model's accuracy. This setting was used to perform exploratory runs when developing EnergyScope and when coupling it with GEMMES.

[2]Note that only the EnergyScope Pathway codes are discussed in this Appendix. The codes for EnergyScope TD (Section 5.2) are on the public Github repository `https://github.com/energyscope/EnergyScope_coupling_GEMMES/tree/eec22143ff7f8bbf37aa764ed2b6aec911df78a7/EnergyScope-TD`

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