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

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ABSTRACT

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

1. Introduction

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

To fill this gap, we present an ecological, biophysical stock-flow consistent macroeconomic model calibrated at the global scale, that combines detailed projections for the evolution of the energy intensity of the productive sub-sectors and dynamic estimates of the Energy Return On Investment (EROI) for fossil fuels and renewable energy technologies. We then 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 paper is structured as follows. Section 2 examines the existing literature. Section 3 presents the materials, data and methods used. Section 4 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 5 evaluates the robustness of the results, underlines the limitations of the model and suggests perspectives for future research. Section 6 concludes.

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¹ All authors have contributed to the different stages.

2. Literature review

2.1. The emergence of ecological macroeconomics

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

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

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

2.2. Biophysical constraints to economic growth

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

2.2.1. 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).² 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;

² 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).

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

2.2.2. Materials

Minerals are finite resources too. They differ from energy resources though, in the sense that – among other things – they are inherently recyclable and do not deplete after initial production³ (Prior et al., 2012). There are still availability risks for mineral types with low remaining reserves, poor geographical distribution, limited adequate substitutes⁴ or subject to economic, social or environmental constraints (Meinert et al., 2016). The accessibility of these minerals is limited too by the energy intensity associated with their extraction, which is on the verge of rising for a number of metals, driven by thermodynamic limits and ore grade decline (Le Boulzec et al., 2022; Vidal et al., 2022). Such increases in energy extraction costs might potentially impact the EROI of different technologies which rely on these metals (Fizaine and Court, 2015).

2.2.3. Waste

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

³ Note that the recycling of metals requires a significant energy cost, which negatively affects the EROI of energy systems built using those recycled metals. Yet, the dispersive use of initially concentrated materials significantly reduces their recycling potential.

⁴ 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).

Table 1

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

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

2.2.4. Additional constraints

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

2.3. Biophysical-based ecological SFC models

Several authors have paved the way for integrating biophysical constraints to growth into ecological SFC macroeconomic models. We here review their contributions and find a total of 20 major studies, listed and classified in Table 1.

A number of observations can be made from the table. First of all, most contributions are very recent (i.e. after 2015), which testifies to the youth of this field of research. This novelty partly explains why no model integrates all of the previously identified biophysical constraints to growth – from the most represented (GHG) to the most absent (energy intensity of minerals, biodiversity loss and to some extent, pollutants directly affecting human health e.g. fine particles). Second, we find that most models are demand-driven but diverge on the economic sectors included. For instance, the presence of a government or a central bank varies greatly among models. Lastly, a more in-depth investigation of these models informs us that significant work remains to be done to study the interrelated dynamics between the biophysical constraints affecting the transitioning energy system and the real and financial spheres of the economy. Indeed, the most advanced biophysical SFC models in that respect are either describing a single country (Jackson and Jackson, 2021), assume simplistic EROI curves (Naqvi, 2015), or do not consider pivotal financial actors such as the central bank (Berg et al., 2015; Barth and Richters, 2019; Sers, 2021). Thus, we present in this paper a model (TEMPLE) aimed at studying thoroughly those dynamics at a global scale. This model includes a complete description of the world economy (even though disparities across regions are not represented) and includes biophysical constraints through detailed dynamic EROIs. Unlike all other models presented in Table 1, TEMPLE includes both the EROIs of renewable and non-renewable energies, as well as the availability constraint for renewable energy.

3. Materials and methods

3.1. 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. Fig. 1 gives an overview of the economic and financial flows between the different sectors in the model. As illustrated, the private sector is divided into energy firms and “other firms”. The former produces energy for the entire economy while the latter produces a homogeneous general-purpose good, named “final good”, for consumption and investment. Furthermore, a distinction is made between the workers (who receive their earning from their work) and capitalists (whose revenues depend on their capital investments). This distinction is of course a purely logical one, since one person can perceive both a salary and earnings from financial investments. TEMPLE also incorporates the banking sector, which grants loans and receives deposits, as well as the government, which intervenes (taxes, subsidies, regulations) on the different sectors of the economy and through its issuance and buy-back of public bonds. In the following subsections, we briefly describe the main features of the model. The Transaction Flow Matrix and balance sheet, which present in a more formal way the information conveyed by Fig. 1, are given in Appendix A. The equations of the model are detailed in Appendix C.

3.1.1. 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,⁵ 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

⁵ As made clear by Keen et al. (2019), energy is a fundamental factor of production.

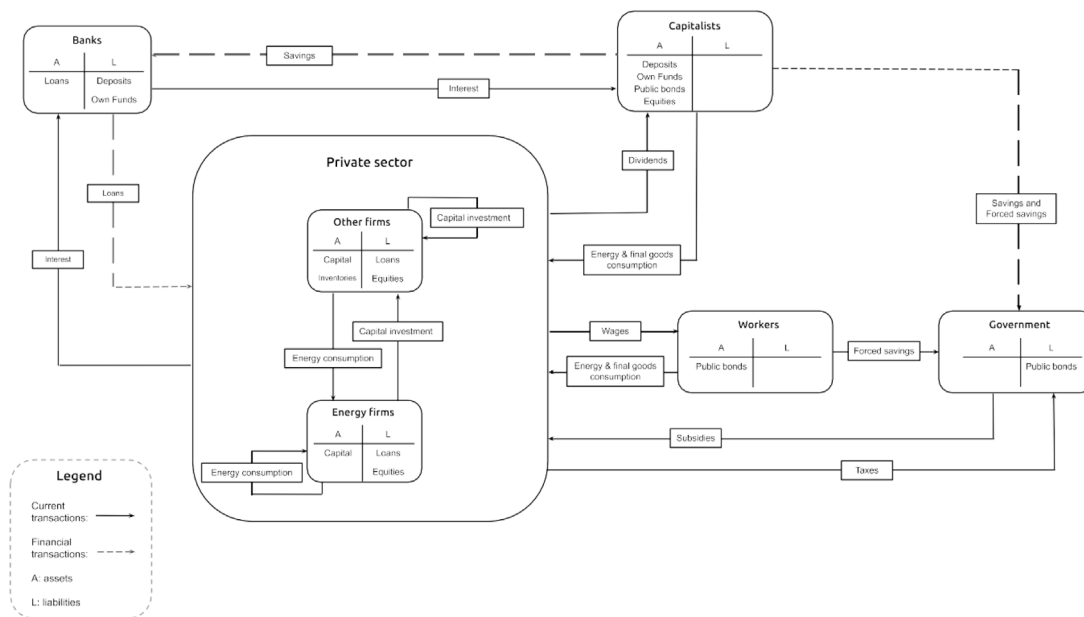


Fig. 1. Overall structure of the TEMPLE model — economic and financial flows.

intensity of the related sub-sector. These intensities evolve through time, as will be made clear in Section 3.3. Production decision determines the utilization rate of capital, defined as the ratio between actual output and practical full capacity output. The latter is the maximum level of production that allows normal maintenance and renovation of machinery to take place without impeding production (Eichner, 1976; Steindl, 1952). Unlike the supply-driven version of the TEMPLE model, presented in Appendix D, where the economy is always at full capacity, our demand-driven model allows the utilization rate to vary between zero and one. The energy demand is composed of energy needed to fuel the production of the energy and final goods sub-sectors, and energy consumed by workers and capitalists. On the other hand, final goods are required for investment into the capital stock of both productive sub-sectors and for the consumption of workers and capitalists. Moreover, the energy market is assumed to be at equilibrium at all times, unlike the market of 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.

3.1.2. 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 – 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.

3.1.3. Profits, investment and debt

The firms' profits are determined by the price of the products they sell (energy or final goods), their unitary cost of production, the government taxes and subsidies and the interest that firms have to pay on their debt. Because of the mismatch between supply and demand in the final goods market, final goods firms also formulate expectations about their future profits, which differ from the actually

realized profits. These expected profits (or the realized profits in the case of energy firms) determine the amount of dividends paid by firms to their shareholders. The retained part of the firms' profits then serves to finance investment into new productive capital stock. The investment level of final goods firms is derived from their expected profits. On the other hand, the investment of energy firms into new capital is assumed to be independent of their profits and determined solely by their desire to fulfil at all times the energy demand targeting a specific utilization rate of capital.⁶ The difference between the firms' investment and their retained earnings is financed by issuing new debt⁷ (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.

3.1.4. Workers, banks, capitalists and public sector

The number of workers in employment in the global economy is determined by the production level of energy and final goods and by the labour intensity of these productions. The ratio of workers in employment to the world population (which evolves according to dynamics described in Section 3.3) determines the global employment rate.⁸ 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

⁶ 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.

⁷ 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.

⁸ 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 appear to be so low.

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 modelled only through its taxes on energy products and its subsidies to the energy firms. We therefore abstract from most of the public sector's actions in reality (i.e. we do not consider public expenditure or most of the fiscal revenues). The taxes and subsidies, which vary depending on the progress of the energy transition, lead to public bonds' emissions or repayment. These bonds are bought or sold by the capitalists and households as a form of savings. Since we do not focus on the sustainability of public finances in this paper, we assume that these bonds do not bear any interest.

All the equations which correspond to the model's features described above can be summarized, after performing the computations described in Appendix C.5, into a reduced form model. This reduced form model comprises 12 differential equations and is presented in Appendix C.6.

3.1.5. Calibration

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

3.2. 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 3.3. 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 modelling 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.

3.2.1. Renewables EROI

We use the global final EROI curves generated for wind and solar energies by Dupont et al. (2018, 2020).⁹ 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:

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

where E_{out} is the total amount of electricity produced throughout the lifetime of the facility, η_{op} is the fraction of this production that is directly auto-consumed on-site and $E_{in,cap}$ is the direct and indirect energy inputs needed to extract, process and transport the materials, build the facility, maintain it and decommission it at the end of its lifetime. E_{out} and $E_{in,cap}$ are both expressed as final energy. Note that $E_{in,cap}$ only relates to the energy embodied in wind turbines and solar panels themselves. They do not include the energy costs related to the necessary reinforcement of the electricity grid or the building of new storage capacity when the share of intermittent renewable energy sources increases, which we include later (see Section 3.3). 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 functions. Besides, future technological improvements are not considered in the calculation of EROI (that is, the EROI curves do not evolve with time).

3.2.2. 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)¹⁰ 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 F.

3.2.3. Global energy intensity of the economy

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

We here rely on EXIOBASE3 (Stadler et al., 2018), a global multi-regional input–output database (GMRIO) to calculate energy footprints of GDP for the period 2011–2017 and project their future evolution.

¹⁰ 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.

⁹ The code used to generate these EROI curves is open-source and available at <https://github.com/EliseDup/WorldEROI>.

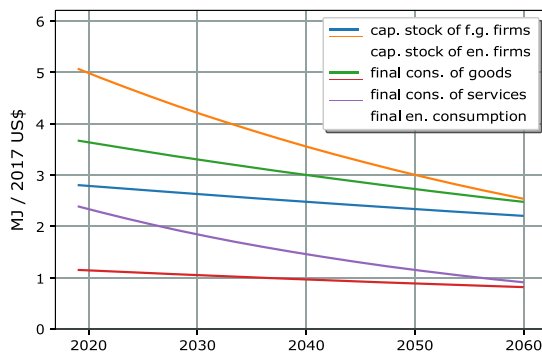


Fig. 2. Energy intensities of final goods production and consumption. Computed values for the year 2019 and projected evolution until 2060.

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 (Andrieu et al., 2022). Energy intensities for goods, services and energy are then calculated (and expressed in MJ/2017 US\$) to account for the final energy required for producing consumption goods and delivering services for workers and capitalists. Yearly improvements of 0.96%, 0.84% and 2.3% per year were computed for goods, services and energy, respectively.

We assume in our model that these energy intensities continue to decrease exponentially during the period 2019–2060 at these same constant rates as in 2011–2017.¹¹ 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 5.2. A similar methodology is used to compute the energy intensity of the production of capital. The energy intensity of the capital stock of the final goods sector is supposed to be that of Gross Fixed Capital Formation (GFCF) from EXIOBASE, corrected for purchasing power parity using ICP data and capital-details from Penn World Tables (PWT) (University of Groningen, 2021). Finally, the energy intensity of the production of energy capital stock is supposed to be equal to that of the Machinery and Equipment sector of EXIOBASE, also corrected for purchasing power parity using ICP and PWT data. This distinction is important since the energy intensity of Machinery and Equipment for the year 2017 is 81% above that of GFCF. However, the yearly improvement of the energy intensity of Machinery and Equipment is almost three times higher than that of GFCF (1.7 vs. 0.59% per year). Fig. 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). The corresponding values are given in Table 6 in Appendix F.

3.2.4. World population

As noted by Rozell (2017), population dynamics are a key feature for models of the ecological transition and should be represented as accurately as possible. In the TEMPLE model, the projection of global population growth rate from the reference scenario of Vollset et al. (2020), adapted in Fig. 3, is used. To our best knowledge, these authors present the most solid scenarios available today for the evolution of the world population. According to their projection, the world population will “peak at 9.73 billion (95% UI 8.84–10.9) people in 2064 and then decline to 8.79 billion (6.83–11.8) in 2100”. Future population is

¹¹ 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.

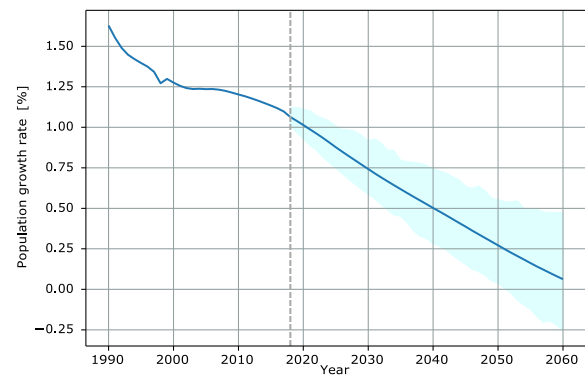


Fig. 3. Projection of the global population growth rate in the reference scenario with 95% UI.

Source: Adapted from Vollset et al. (2020).

modelled as a function of fertility and mortality rates, the former being driven by education level and access to contraception. To ensure more reliability, completed cohort fertility at age 50 is used rather than total fertility rate. Yet, the effects of climate change and pessimism about the future on fertility and mortality rates are neither studied, nor included in these scenarios.

3.3. 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 paper and are ignored in our scenarios, just like the consequences of international conflicts. We then depart from the steady-state by adding the changes in energy intensities from Fig. 2 and the population growth from Fig. 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; EIA, 2020). According to the IEA statistics, wind and solar represented 3% of the total final energy supply in 2019 i.e. $\chi(2019) = 0.03$. We define a first scenario for the energy transition by exogenously imposing a sigmoid profile for the evolution of χ .¹² This sigmoid profile is represented in Fig. 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.^{13,14} Thus, the goal of our work is not to study the required measures to unlock the energy transition, but

¹² Other profiles than a sigmoid are of course possible for the evolution of χ , as discussed in Section 5.

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

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

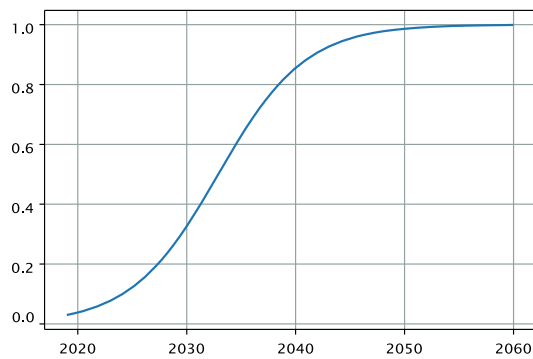


Fig. 4. Degree of progress of the energy transition, i.e. χ , as a function of time in the second and third scenarios.

rather to assume that a rapid energy transition takes place and assess the economic consequences thereof.

In the *TEMPLE* model, the energy transition materializes through the evolution of the capital and energy intensities of the energy subsector. Indeed, these intensities are rewritten as the weighted averages of the intensities of non-renewable and renewable energy production, the weights being respectively $(1 - \chi)$ and χ . As in Dupont (2021), the energy intensity of renewable energy production is assumed to be the fraction of renewable electricity which is lost through grid losses. The capital intensity of renewable energy production is deduced from the EROI of renewable energy, as explained in Appendix F. 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 $(1 + \frac{11}{9})$ 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 modelled through the evolution of the capital and energy intensities of energy production. The evolution of the energy intensity of final goods production is also modelled in detail, as explained in Section 3.2.3. Regarding the capital intensity of final goods production, we assume that it stays constant throughout the transition. Indeed, this parameter has remained stable at world level for the last 30 years (Dupont et al., 2021b). We investigate three scenarios with *TEMPLE*:

1. The **baseline scenario** is the quasi-steady state economy, as described at the beginning of Section 3.2.
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.¹⁵ 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, 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 Fig. 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 F for the equations' details).

4. Results and discussion

Fig. 5 presents the macroeconomic dynamics obtained in the energy transition scenario.¹⁶ Fig. 6 complements them by showing the biophysical dynamics of the energy system under that same scenario. Finally, Fig. 7 underlines the most relevant differences between the energy transition scenario and the two other scenarios. To avoid hazardous projections too far into the future, the results are shown only until the year 2060, once the energy transition is completed and a certain number of variables have converged. Note that the model does not converge to a steady-state after 2060, because the intensities of the factors of production (the capital intensity of energy production, mainly) exogenously evolve during the simulations. These ultimately limit economic growth, but discussing such limits is out of the scope of this paper, which focuses on the energy transition.

4.1. 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 F, 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 3, 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 Fig. 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.¹⁷ The savings of workers and capitalists correspond to the buying of public bonds. Those new funds are used by the government to subsidize the energy sector, as described below. Besides, one can observe two kinks, in 2024 and 2041, on the curves presented in Fig. 5. The first kink corresponds to inventories of final goods hitting a minimum value of zero: in fact,

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

¹⁷ 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 G.

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

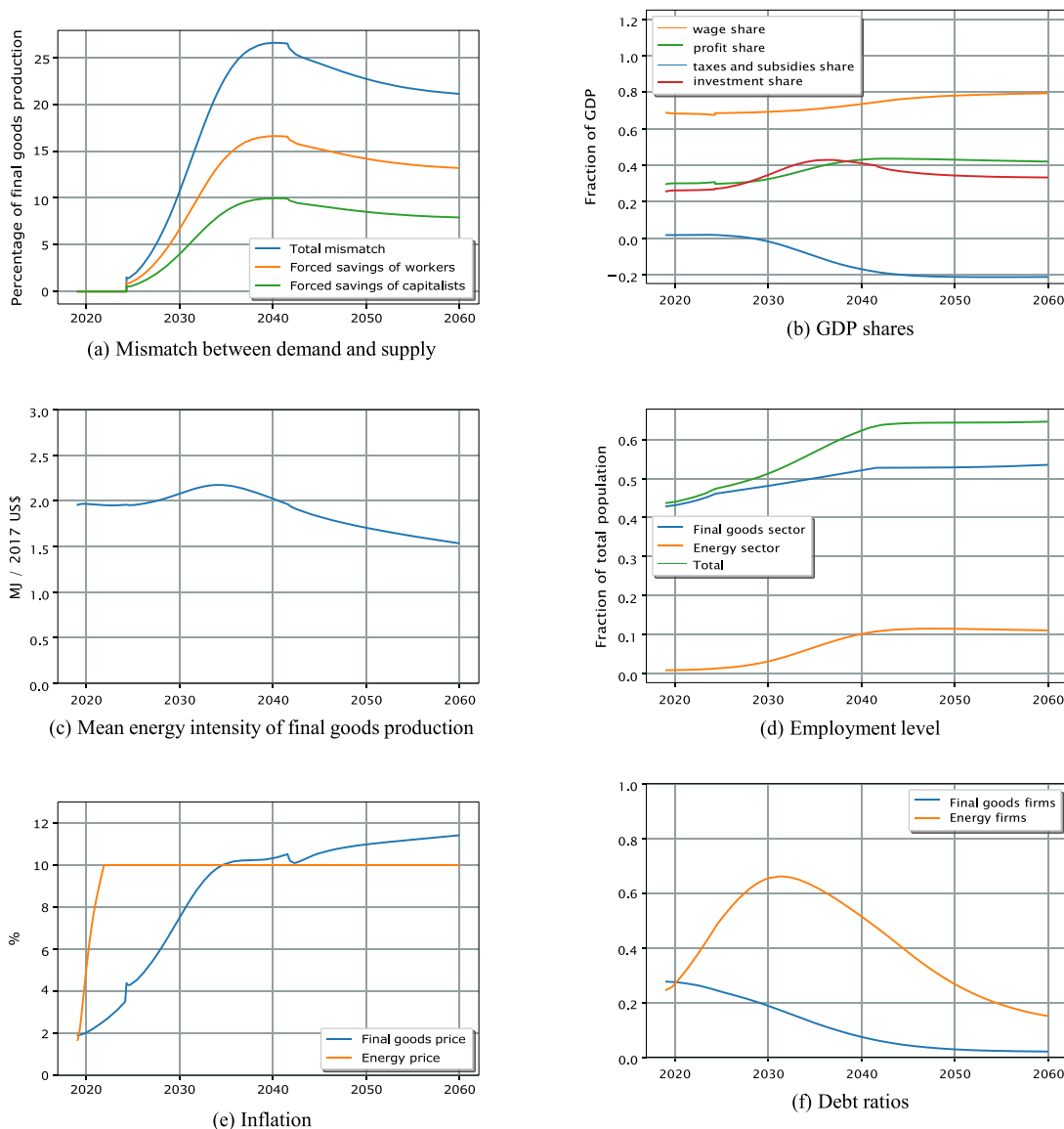


Fig. 5. Simulated macroeconomic dynamics of the energy transition under the second scenario: “energy transition scenario”.

before constraining the consumption of workers and capitalists, the mismatch between demand and supply is first absorbed by depleting inventories. They become null in 2024 and keep this zero value until the end of the simulation. The mismatch also creates a pressure to increase the utilization rate of the capital stock of final goods firms. This utilization rate progressively increases until hitting the ceiling value of 1, which causes the kink in 2041.

4.2. Towards a war economy?

Fig. 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 C.6. In addition, Fig. 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 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.

4.3. 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), Fig. 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 Fig. 2),

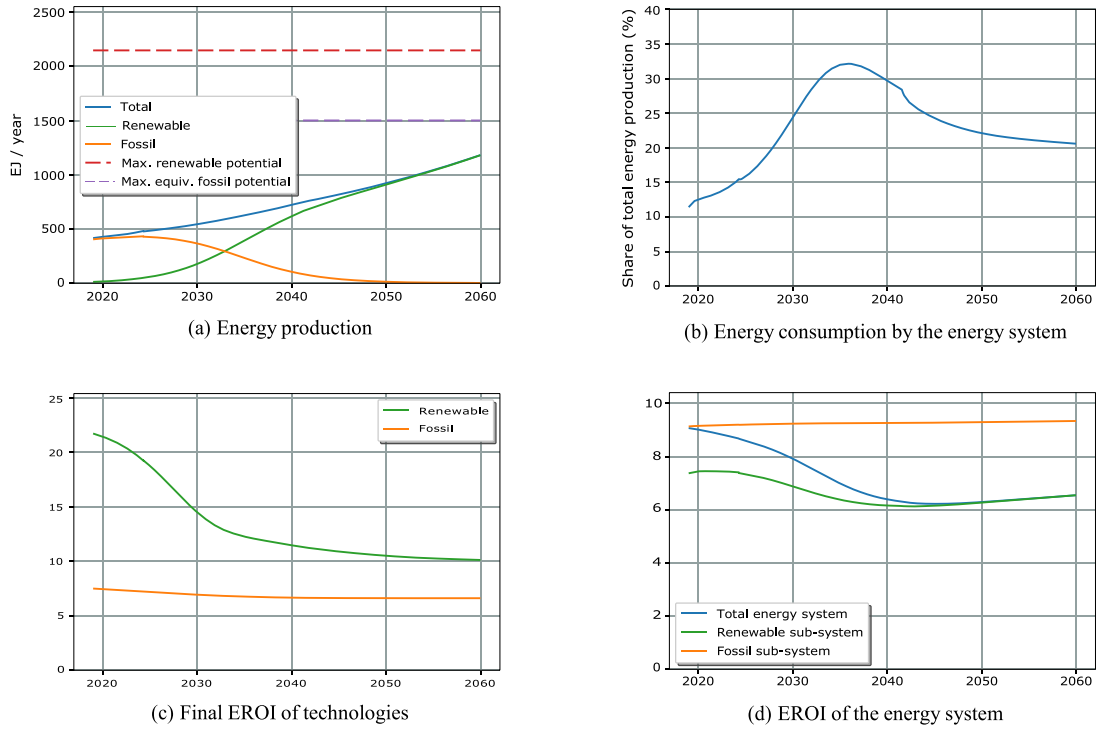


Fig. 6. Simulated biophysical dynamics of the energy system under the second scenario: “energy transition scenario”.

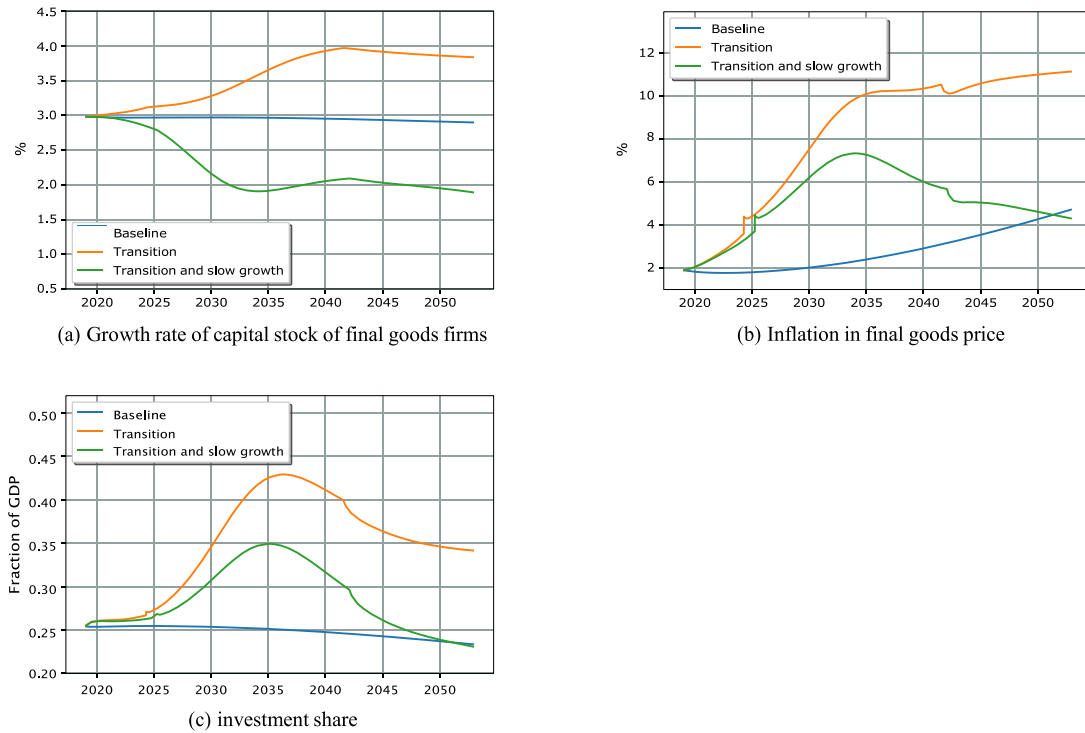


Fig. 7. Major differences in the macroeconomic dynamics of the three scenarios modelled with TEMPLE.

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.

4.4. High employment, high inflation

The evolution of employment during the transition, shown in Fig. 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 (Fig. 3).

Another key figure of our scenario is the evolution of inflation. The capital costs of renewable energy are much higher compared to fossil fuels. The energy firms try to pass these costs onto their clients and the inflation in energy prices soars as soon as the transition starts. As stated in Section 3.3 and as made clear in Fig. 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.

4.5. 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 Fig. 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%. Fig. 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.

4.6. An EROI perspective on the transition

Coming back to the biophysical constraints, Fig. 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 2.2.1). Indeed, Fig. 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 7230 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) and Wang and Bentley (2020). As a stylized comparison with the maximum potential of renewables, we represent in Fig. 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 Fig. 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, Fig. 6(c), and the EROI of the energy system¹⁸, Fig. 6(d). Renewables display a higher point of use EROI than fossil fuels, while showing a marked decrease during the transition, as the best locations for wind and solar facilities become progressively saturated. On the contrary, the EROI of fossil fuels does not evolve substantially between 2019 and 2060 as their extraction declines abruptly in the assumed energy transition. When taking into account electrical losses in the grid (mainly) and investment in storage facilities (to a lesser extent), the EROI of the entire renewable energy sub-system is in fact smaller than its non-renewable counterpart. After a period of decline during the transition, the overall EROI of the energy system rebounds after 2040, in similar proportions as in Fabre (2019) or the S2-M and S5-R scenarios of Slameršak et al. (2022). Besides, the system's EROI and its evolution take practically the same values as in the “low green capital” baseline simulation of Jackson and Jackson (2021).

An important insight is that the main stumbling block of the transition does not lie in the required quantity of energy for building and operating the energy system, but rather in the form which these required energy inputs must take and how this interacts with the rest of the economy. The transition implies to shift from an energy sector relying chiefly on direct energy inputs (for operating the oil and gas fields, the refineries, etc.) to an energy sector whose energy inputs are overwhelmingly “embedded into the capital stock”. This was already foreseen in previous works (Jacques, 2019; Dupont et al., 2021b) and explains why integrating biophysical with macroeconomic perspectives is essential when studying the transition. These insights face however several limitations, discussed in detail in Section 5.3.

4.7. What if the economy grows more slowly?

The previous subsections have described the results of the energy transition scenario. Fig. 7 contrasts the main results of this scenario with the two other scenarios outlined in Section 3.3. 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 Fig. 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 modelled 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 Fig. 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 Fig. 7(b)). Similarly, Fig. 7(c) shows that in the slower growth scenario, the transition can be completed with a peak in investment share at

¹⁸ 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 F.

“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 realizes 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.

5. Robustness, limitations and further work

5.1. 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 modelling assumptions^{19,20}: (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%²¹; (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;

¹⁹ 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 modelling assumptions described here.

²⁰ Note that 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.

²¹ At the steady-state in 2019, those 3% are split between 1.9% of productivity growth and 1.1% of population growth.

(iii) the choice of calibration for demand-pull and cost-push inflation adjustment speeds in TEMPLE (see the sensitivity analysis in next Section). Due to these three reasons, the required investments in the energy sector are higher than in TranSim 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 modelled 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.²²

5.2. Sensitivity analysis

The sensitivity of our results in the second scenario are tested regarding key parameters of the model. First, we re-ran the simulations after modifying the capital intensity of renewable energies by $\pm 30\%$. As outlined by the literature review of Murphy et al. (2022), there still exists a large uncertainty on the EROI of renewable energies, on which our computation of capital intensity is based. For example, when using some of the assumptions and data from Fthenakis and Leccisi (2021) to compute the EROI of PV panels worldwide with the method from Dupont et al. (2020), we obtain capital intensity values 30% lower for solar energy. Second, we re-ran the simulations after modifying the degrowth rates of the energy intensity of each final goods sub-sector by $\pm 50\%$. 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 $\pm 10\%$. 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 Fig. 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 Fig. 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 H. 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 Fig. 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

²² The third scenario modelled 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%.

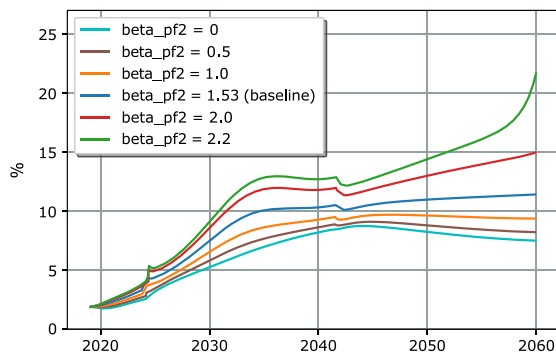


Fig. 8. Impact on inflation of varying jointly the adjustment speeds for cost-push and demand-pull inflation in the final goods' price.

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 G. 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 H), 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 H.

5.3. Limitations and further work

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

If it allows to conclude that the transition comes with major challenges, TEMPLE still remains very conservative in many aspects. Indeed, it neglects among others : (i) the issues related to the electrification of entire sectors (ii) the climate change damages on the global economy and on the energy system (iii) geopolitical factors and competition for energy supply (iv) extreme events that might change the course of dynamics, e.g. a climatic tipping point is passed or peak oil is reached before being prepared to it (v) the multiple planetary limits not related to energy (e.g. biodiversity). Our work also focuses only on the impacts of the point-of-use EROI, and does not regard the decline of standard EROI of fossil fuels and the ties it may have with the energy price (King and Hall, 2011; Heun and de Wit, 2012).

Several factors tend to overestimate or underestimate the EROI values used in the study. They might for instance impact the EROI of fossil fuels but, in this case and as argued in Appendix D of de Castro and Capellán-Pérez (2020), the different factors tend to cancel

out. Plus, the EROI of fossil fuels plays a minor role in our study as the transition to renewables is carried out quickly. Second, we assume that the best locations for wind and solar facilities on the global scale (for instance in the Sahara) are used first, which might prove to be unrealistic. Another feature that might lead to optimistic EROIs for renewables is the relatively low estimation for the grid and storage costs. This is however discussed in the literature (Carbajales-Dale et al., 2014; Diesendorf and Wiedmann, 2020; Schill, 2020; Ruhnau and Qvist, 2022) and calls for a more precise description of the electricity sector in a future version of TEMPLE. Furthermore, we neglect the probable increase in energy consumption per kilogram of extracted metal due to a falling ore grade which cannot eternally be compensated by technological progress, especially for copper. As discussed in Section 2.2.2, renewable technologies being very copper-intensive, including this decrease in ore grade could result into an EROI which decreases with time. Moreover, we assume that our scenario does not require carbon capture and storage technologies, overlooking their potential material, energy, economic and human requirements (Sgouridis et al., 2019). On the contrary, our assumption to neglect technological and industrial improvements might lead to underestimating the future EROI of PV and wind (Louwen et al., 2016; Steffen et al., 2018). Taken together, all these assumptions make our estimates optimistic, and generally above the general average one can obtain from the literature (Murphy et al., 2022). Still, the dynamic EROI of the energy production system is similar to other analysis, and its drop seems rather consistent (Capellán-Pérez et al., 2019).

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

6. Conclusion

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

We are able to estimate the biophysical and macroeconomic dynamics that the world economy would undergo if an energy transition compatible with the 1.5 °C objective of the Paris Agreement was undertaken. Since action needs to be taken rapidly, the model shows that the classical market-based mechanisms of price and quantity adjustment are not sufficient to force the required investments. We find in fact that (i) the transition can only be completed thanks to a high level of investment share, unseen in Western economies since WWII (ii) strong inflationary dynamics arise (iii) the overall EROI of the energy system decreases during the transition (iv) energy firms undergo a decline in profitability and therefore need substantial help from the government. This last finding questions the appropriateness of the privatization of the energy sector. Our results further indicate that a slower growth rate eases the transition by smoothing out the inflationary dynamics. We finally conduct a sensitivity analysis of our results and conclude that they prove to be robust to changes in the values of key parameters.

Our modelling 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

Table 2
Transaction flow matrix.

	Workers	Capitalists	Energy firms		Final goods firms		Banks	Gov.	Σ
			Current	Capital	Current	Capital			
Consumption	$-C_{w,e} - C_{w,f}$	$-C_{c,e} - C_{c,f}$	$+C_{w,e} + C_{c,e}$		$+C_{w,f} + C_{c,f}$				0
Investment				$-I_e$	$+I_e + I_f$	$-I_f$			0
Intermediary consumption			$+E_f$		$-E_f$				0
Wages	$+W(L_e + L_f)$		$-W L_e$		$-W L_f$				0
Taxes and subsidies			$-T_e Y_e$					$+T_e Y_e$	0
Interests on loans			$-r D_e$		$-r D_f$		$+r(D_e + D_f)$		0
Banks dividends		$+\Pi_{b,d}$					$-\Pi_{b,d}$		0
Firms dividends		$+\Pi_{e,d} + \Pi_{f,d}$	$-\Pi_{e,d}$		$-\Pi_{f,d}$				0
Retained earnings			$-\Pi_{e,u}$	$+\Pi_{e,u}$	$-\Pi_{f,u}$	$+\Pi_{f,u}$			0
Σ (=Savings)	$+sav_w$	$+sav_c$	0	$+sav_e$	0	$+sav_f$	$+sav_b$	$+sav_g$	0
Change in capital stock				\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		$+\dot{O}F_b$				$-\dot{O}F_b$			0
Change in equities		$+\dot{\mathcal{E}}_e + \dot{\mathcal{E}}_f$		$-\dot{\mathcal{E}}_e$	$-\dot{\mathcal{E}}_f$				0
Σ (=Change in net worth)	$+\dot{B}_{g,w}$	$\dot{M} + \dot{B}_{g,c} + \dot{\mathcal{E}}_e + \dot{\mathcal{E}}_f + \dot{O}F_b$	0	0	0	0	0	$-\dot{B}_g$	$\dot{K}_e + \dot{K}_f + \dot{n}_f$

Table 3
Balance sheet.

	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		$O F_b$			$-O F_b$		0
Equity		$\mathcal{E}_e + \mathcal{E}_f$	$-\mathcal{E}_e$	$-\mathcal{E}_f$			0
Σ (=Net worth)	$B_{g,w}$	$M + B_{g,c} + \mathcal{E}_e + \mathcal{E}_f + O F_b$	0	0	0	$-B_g$	$K_e + K_f + n_f$

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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data and code used in this article are open-source. A link to a github repository is indicated in the article.

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Appendix A. Transaction Flow Matrix and balance sheet

The Transaction Flow Matrix (TFM) is shown in Table 2. The first part of the TFM concerns all non-financial transactions, i.e. all transactions regarding the real economy as well as the redistribution of income through wages or dividends. The lower part of the TFM is the Flow-of-Funds (FOF) table, which shows how savings are allocated across the different financial assets of the economy. The corresponding balance sheet (i.e. how all stocks are allocated across sectors) is shown in Table 3.

Appendix B. 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 $z \in \{w, c\}$.

$$y_{x,p} = \text{yearly production of sub-sector } x$$

- e_x = yearly energy consumption of sub-sector x
- L_x = number of workers in sub-sector x
- k_x = capital stock of sub-sector x
- u_x = utilization rate of capital in sub-sector x
- $y_{e,d}$ = total yearly energy demand
- $y_{f,d}$ = total yearly demand for final goods
- $y_{f,p}^e$ = expected yearly production of final goods
- u_f^e = expected utilization rate of capital in the final goods sub-sector
- $c_{z,e}$ = energy consumption of households of type z
- $c_{z,f}$ = final goods consumption of households of type z
- i_x = capital investment in sub-sector x
- p_e = unit price of energy
- p_f = unit price of final goods
- n_f = level of inventories of final goods
- W = nominal wages of workers in both productive sub-sectors
- T_e = unitary tax on energy products
- UC_x = firms' unit cost of production in sub-sector x
- D_x = aggregated debt of firms in sub-sector x
- r = interest rate
- r^T = target interest rate of banks
- r_{CB} = target interest rate of the central bank
- $s_{F,w}$ = forced saving rate of workers during the energy transition
- $s_{F,c}$ = forced saving rate of capitalists during the energy transition
- B_g = stock of public bonds
- OF_b = banks' own funds

- $\Pi_{b,u}$ = banks' retained earnings
- $\Pi_{b,d}$ = dividends distributed to shareholders by banks
- Π_x = profits of firms in sub-sector x
- Π_f^e = expected profits of final goods firms
- $\Pi_{x,d}$ = dividends distributed to shareholders by firms of sub-sector x
- $\Pi_{x,u}$ = retained earnings of firms in sub-sector x
- i_x = investment into new capital stock in sub-sector x
- \hat{k}_f = growth rate of the capital stock in sub-sector x
- POP = world population
- λ_x = employment rate in sub-sector x
- λ = global employment rate
- GDP = GDP of the global economy
- s = investment 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 sources
- $EROI_{re}$ = aggregated energy return on investment of renewable energy sources

Non-dimensionalized variables

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

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

Parameters

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

- ϵ_x = energy intensity of sub-sector x
- α_x = labour intensity of sub-sector x
- γ_x = capital intensity of sub-sector x
- δ_x = rate of depreciation of capital in sub-sector x
- δ_n = rate of depreciation of final goods' inventories
- n_f^T = target level of final goods' inventories
- η = ratio of inventories to expected production of final goods
- $\beta_{nf,1}$ = proportionality factor for the adjustment of expected final goods' production
- $\beta_{nf,2}$ = 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_{pe} = adjustment speed in the price of energy
- $\beta_{pf,1}$ = cost-push adjustment speed in the price of final goods
- $\beta_{pf,2}$ = 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_{ie} = adjustment speed in the investment decision of energy firms
- $\kappa_{f,0}$ = parameter in the investment decision of final goods firms

- $\kappa_{f,1}$ = parameter in the investment decision of final goods firms
- Δ = fraction of the profits or expected profits paid as dividends to the shareholders
- ω_0 = parameter of the Phillips curve
- ω_1 = parameter of the Phillips curve
- ω_2 = parameter of the Phillips curve
- α_0 = parameter of the Kaldor–Verdoorn equation
- α_1 = parameter of the Kaldor–Verdoorn equation
- r^* = “natural” rate of interest
- φ = parameter in Taylor’s rule
- \hat{p}_f^T = inflation target of the central bank
- μ_b = banks’ prudential ratio
- OF_b^T = banks’ required level of own funds
- β_b = adjustment speed of banks’ own funds
- β_r = adjustment speed of banks’ interest rate
- λ_{rT} = parameter in the computation of banks’ target interest rate
- s_c = constant saving rate of capitalists
- ϵ_{cons} = technological parameter for computation of households’ direct energy consumption
- $f(\cdot)$ = function relating the households’ energy consumption to the price of energy
- a_0 = parameter in function $f(\cdot)$
- a_1 = parameter in function $f(\cdot)$
- a_2 = parameter in function $f(\cdot)$
- ϵ_{f,i_e} = energy intensity of the production of capital stock for the energy sub-sector
- ϵ_{f,i_f} = energy intensity of the production of capital stock for the final goods sub-sector
- ϵ_{f,c_f} = aggregated energy intensity of the production of final goods and services for consumption
- $\epsilon_{f,c_f,g}$ = energy intensity of the production of final goods (not services) for consumption
- $\epsilon_{f,c_f,s}$ = energy intensity of services (not final goods) for consumption
- θ_g = share of goods in final consumption
- θ_s = share of services in final consumption
- ϵ_{nre} = energy intensity of non-renewable energy production
- ϵ_{re} = energy intensity of renewable energy production
- γ_{nre} = capital intensity of non-renewable energy production
- γ_{re} = capital intensity of renewable energy production

Appendix C. Equations of the model

C.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:

$$y_{e,p} = \frac{e_e}{\epsilon_e} = u_e \alpha_e \frac{L_e}{\gamma_e} = u_e \frac{k_e}{\gamma_e} \quad (2)$$

$$y_{f,p} = \frac{e_f}{\epsilon_f} = \alpha_f L_f = u_f \frac{k_f}{\gamma_f} \quad (3)$$

in which ϵ_x , α_x and γ_x denote respectively the energy, labour and capital intensity of production in sector x and u_x is the utilization rate of capital, which must always stay below unity. The number of workers required in the final goods sector is proportional to the production $y_{f,p}$. However, we assume that the number of workers in the energy sector is instead proportional to the capital stock k_e . Indeed, as it is made clear in Fig. 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 $c_{c,f}$.²³ We thus have the equations:

$$y_{e,d} = e_e + e_f + c_{w,e} + c_{c,e} \quad (4)$$

$$y_{f,d} = i_e + i_f + c_{w,f} + c_{c,f} \quad (5)$$

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

$$c_{z,e} = \epsilon_{\text{cons}} f\left(\frac{p_e}{p_f}\right) c_{z,f} \quad (z \in \{w, c\}) \quad (6)$$

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

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

$$y_{e,p} = y_{e,d} \quad (7)$$

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

$$\dot{n}_f = y_{f,p} - y_{f,d} - \delta_n n_f \quad (8)$$

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

$$u_f^e = \frac{\gamma_f y_{f,p}^e}{k_f} \quad (9)$$

Firms expectations on production evolve according to two different factors: the current trend (represented by the growth rate of their capital

²³ Note that $c_w + c_c$ is not firmly restricted to the consumption of households. These terms also include government spending.

stock) and the expected excess demand, through some proportionality factor $\beta_{n_f,1}$ ²⁴:

$$\dot{y}_{f,p}^e = \hat{k}_f y_{f,p}^e + \beta_{n_f,1} (y_{f,d} + \delta_n n_f - y_{f,p}^e) \quad (10)$$

Moreover, it is assumed that firms wish to keep their inventories at a certain level n_f^T , equal to a given fraction η of their expected production²⁵:

$$n_f^T = \eta y_{f,p}^e \quad (11)$$

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

$$y_{f,p} = y_{f,p}^e + \beta_{n_f,2} (n_f^T - n_f) \quad (12)$$

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

C.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:

$$W_e = W_f = W \quad (13)$$

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

$$UC_x = \frac{W L_x + p_e e_x + p_f \delta_x k_x}{y_{x,p}} \quad (x \in \{e, f\}) \quad (14)$$

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

$$\dot{p}_e = \beta_{p_e} (p_e^T - p_e) \quad (15)$$

$$p_e^T = \mu_e UC_e + T_e \quad (16)$$

This equation indicates that energy firms adjust their price p_e with a speed β_{p_e} , such that p_e tends towards a certain target price p_e^T . This target price is equal to the firms' unit cost of production multiplied by a markup μ_e ²⁶ plus a certain government tax T_e . The markup μ_e is strictly superior to one in order to ensure positive profits to the energy firms.

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

$$\dot{p}_f = \beta_{p_f,1} (p_f^T - p_f) + \beta_{p_f,2} \left(p_f \frac{n_f^T - n_f}{k_f} \right) \quad (17)$$

$$p_f^T = \mu_f UC_f \quad (18)$$

C.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:

$$\Pi_e = y_e (p_e - UC_e - T_e) - r D_e \quad (19)$$

$$\Pi_f = y_{f,d} p_f - y_{f,p} UC_f - r D_f \quad (20)$$

²⁴ In this paper, we follow Robinson (1969) in that firms might make mistakes in their estimation of output growth, creating unwanted excess capacity.

²⁵ Such a desired inventory to expected sales ratio η is also used in Franke (1996), Chiarella and Flaschel (2000) and Charpe et al. (2011).

²⁶ This determination of prices by firms based on target-return pricing is inspired from Lavoie (1992).

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 :

$$k_e^T = \frac{y_e y_e}{u_e^T} \quad (21)$$

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

$$i_e = \beta_{i_e} (k_e^T - k_e) + \delta_e k_e \quad (22)$$

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

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

$$\Pi_f^e = y_{f,p} (p_f - UC_f) - r D_f \quad (23)$$

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

$$\pi_f^e := \frac{\Pi_f^e}{p_f k_f} \quad (24)$$

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

$$i_f = k_f (\kappa_{f,0} + \kappa_{f,1} \pi_f^e + \delta_f) \quad (25)$$

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

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

$$\Pi_{e,d} = \Delta \Pi_e \quad (26)$$

with the subscript d standing for "dividends".

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

$$\Pi_{f,d} = \Delta \Pi_f^e \quad (27)$$

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

$$\Pi_{x,u} = \Pi_x + p_f \delta_x k_x - \Pi_{x,d} \quad (x \in \{e, f\}) \quad (28)$$

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

$$\dot{D}_x = p_f i_x - \Pi_{x,u} \quad (x \in \{e, f\}) \quad (29)$$

Finally, the capital accumulation equation is as usual:

$$\dot{k}_x = i_x - \delta_x k_x \quad (x \in \{e, f\}) \quad (30)$$

C.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

$$\lambda_x = \frac{L_x}{POP} \quad (x \in \{e, f\}) \quad (31)$$

We then define the global employment rate as:

$$\lambda = \lambda_f + \lambda_e \quad (32)$$

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

$$\widehat{W} = \omega_0 + \omega_1 \lambda + (1 - \omega_2) \hat{p}_f \quad (33)$$

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

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

$$p_f c_{w,f} + p_e c_{w,e} = (1 - s_{F,w}) W \cdot L \quad (34)$$

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

$$\hat{\alpha}_f = \hat{\alpha}_e = \hat{\alpha} = \alpha_0 + \alpha_1 \lambda \quad (35)$$

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

$$r_{CB} = r^* + \hat{p}_f + \varphi (\hat{p}_f - \hat{p}_f^T) \quad (36)$$

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

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

$$OF_b^T = \mu_b (D_f + D_e) \quad (37)$$

The banks' retained earnings $\Pi_{b,u}$ are thus computed such that their own funds OF_b converge towards their required level, with a convergence speed β_b :

$$\Pi_{b,u} = \beta_b (OF_b^T - OF_b) \quad (38)$$

$$OF_b = \Pi_{b,u} \quad (39)$$

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

$$\Pi_{b,d} = r (D_f + D_e) - \Pi_{b,u} \quad (40)$$

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

$$r^T = r_{CB} + \lambda_{rT} \frac{OF_b^T - OF_b}{OF_b^T} \quad (41)$$

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

$$\dot{r} = \beta_r (r^T - r) \quad (42)$$

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

$$C_{c,f} = (1 - s_c - s_{F,c}) (\Pi_{f,d} + \Pi_{e,d} + \Pi_{b,d}) \quad (43)$$

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

The only source of taxation by the government is found in Eqs. (16) and (19). The tax on energy products, T_e can also be turned into a subsidy (by changing its sign and value) in order to support energy firms during the transition. So, the modelled taxes and subsidies lead to public bonds emissions or repayment:

$$-\dot{B}_g = T_e y_e \quad (44)$$

C.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:

$$\mathcal{K}_e := \frac{k_e}{k_f} \quad \mathcal{P}_e := \frac{p_e}{p_f} \quad \omega_x := \frac{W}{\alpha_x p_x} \quad d_x := \frac{D_x}{p_f k_x} \quad (45)$$

$$\pi_x := \frac{\Pi_x}{p_f k_x} \quad \pi_{x,d} := \frac{\Pi_{x,d}}{p_f k_x} \quad \pi_{b,u} := \frac{\Pi_{b,u}}{p_f k_f} \quad of_b := \frac{OF_b}{p_f k_f} \quad (46)$$

$$uc_x := \frac{UC_x}{p_x} \quad \kappa_{z,f} := \frac{c_{z,f}}{k_f} \quad v_f := \frac{n_f}{k_f} \quad \mathcal{T}_e := \frac{T_e}{p_e} \quad (47)$$

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

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

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

$$\hat{\omega}_x = \widehat{W} - \hat{\alpha}_x - \hat{p}_x \quad (x \in \{e, f\}) \quad (48)$$

which becomes, when we insert Eqs. (33) and (35):

$$\hat{\omega}_e = \omega_0 + \omega_1 \lambda - \omega_2 \hat{p}_f + (\hat{p}_f - \hat{p}_e) - \alpha_0 - \alpha_1 \lambda \quad (49)$$

$$\hat{\omega}_f = \omega_0 + \omega_1 \lambda - \omega_2 \hat{p}_f - \alpha_0 - \alpha_1 \lambda \quad (50)$$

We know from Eqs. (2) and (3) that²⁷:

$$L_e = \frac{k_e}{\alpha_e} \quad (51)$$

$$L_f = \frac{y_{f,p}}{\alpha_f} \quad (52)$$

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

$$\hat{\lambda}_x = \hat{L}_x - \widehat{POP} \quad (x \in \{e, f\}) \quad (53)$$

$$\hat{\lambda}_e = \hat{k}_e - \alpha_0 - \alpha_1 \lambda - \widehat{POP} \quad (54)$$

$$\hat{\lambda}_f = \hat{y}_{f,p} - \alpha_0 - \alpha_1 \lambda - \widehat{POP} \quad (55)$$

$$\hat{\lambda}_f = \hat{k}_f + \hat{u}_f - \alpha_0 - \alpha_1 \lambda - \widehat{POP} \quad (56)$$

By inserting into Eq. (5) the definitions of \mathcal{K}_e , $\kappa_{w,f}$, $\kappa_{c,f}$ and Eq. (30), we also have:

$$\frac{y_{f,d}}{k_f} = \frac{i_e + i_f + c_{w,f} + c_{c,f}}{k_f} \quad (57)$$

$$= \mathcal{K}_e \frac{i_e}{k_e} + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} \quad (58)$$

$$= \mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} \quad (59)$$

We then obtain from Eqs. (9), (10) and (59):

$$\hat{u}_f^e = \hat{y}_{f,p}^e - \hat{k}_f \quad (60)$$

$$= \frac{-\beta_{n_f,1} (y_{f,p}^e - y_{f,d} - \delta_n n_f)}{y_{f,p}^e} \quad (61)$$

$$= -\beta_{n_f,1} \left(1 - \frac{\gamma_f}{u_f^e} \frac{y_{f,d}}{k_f} - \delta_n \frac{\gamma_f}{u_f^e} \frac{n_f}{k_f} \right) \quad (62)$$

²⁷ 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.

$$= -\beta_{n_f,1} \left(1 - \frac{\gamma_f}{u_f^e} (\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f}) - \delta_n \frac{\gamma_f}{u_f^e} v_f \right) \quad (63)$$

$$u_f^e = \beta_{n_f,1} \left(\gamma_f (\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} + \delta_n v_f) - u_f^e \right) \quad (64)$$

Similarly, by definition of v_f and by Eqs. (8) and (59), we have:

$$\dot{v}_f = \hat{n}_f - \hat{k}_f \quad (65)$$

$$= \frac{1}{n_f} (y_{f,p} - y_{f,d}) - \delta_n - \hat{k}_f \quad (66)$$

$$\dot{v}_f = \frac{y_{f,p}}{k_f} - \frac{y_{f,d}}{k_f} - (\hat{k}_f + \delta_n) v_f \quad (67)$$

$$= \frac{u_f}{\gamma_f} - (\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f}) - (\hat{k}_f + \delta_n) v_f \quad (68)$$

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

$$\dot{d}_x = \frac{\dot{D}_x}{p_f k_x} - d_x (\hat{p}_f + \hat{k}_x) \quad (x \in \{e, f\}) \quad (69)$$

After inserting Eqs. (28), (29), (30) and the definition of π_x , we obtain:

$$\dot{d}_x = \frac{i_x}{k_x} - \frac{\Pi_{x,u}}{p_f k_x} - d_x (\hat{p}_f + \hat{k}_x) \quad (70)$$

$$= \frac{i_x}{k_x} - \frac{\Pi_x + p_f \delta_x k_x - \Pi_{x,d}}{p_f k_x} - d_x (\hat{p}_f + \hat{k}_x) \quad (71)$$

$$= \hat{k}_x - \frac{\Pi_x - \Pi_{x,d}}{p_f k_x} - d_x (\hat{p}_f + \hat{k}_x) \quad (72)$$

We can then insert (26) and (27) into this equation to get:

$$d_e = \hat{k}_e - (1 - \Delta) \pi_e - d_e (\hat{p}_f + \hat{k}_e) \quad (73)$$

$$\dot{d}_f = \hat{k}_f - \pi_f + \Delta \pi_f^e - d_f (\hat{p}_f + \hat{k}_f) \quad (74)$$

Given $o f_b := \frac{O F_b}{p_f k_f}$ and Eq. (39), we have:

$$\dot{o} f_b = \frac{O \dot{F}_b}{p_f k_f} - o f_b (\hat{p}_f + \hat{k}_f) \quad (75)$$

$$= \pi_{bu} - o f_b (\hat{p}_f + \hat{k}_f) \quad (76)$$

We can also transform equation (12) into:

$$\frac{k_f}{\gamma_f} u_f = \frac{k_f}{\gamma_f} u_f^e + \beta_{n_f,2} \left(\eta \frac{k_f}{\gamma_f} u_f^e - k_f v_f \right) \quad (77)$$

$$u_f = u_f^e + \beta_{n_f,2} \left(\eta u_f^e - \gamma_f v_f \right) \quad (78)$$

Given $u c_x := \frac{U C_x}{p_x}$ and Eq. (14), we further have:

$$U C_e = \frac{\gamma_e W}{\alpha_e u_e} + \epsilon_e p_e + p_f \frac{\gamma_e \delta_e}{u_e} \quad (79)$$

$$u c_e = \frac{\gamma_e}{u_e} \omega_e + \epsilon_e + \frac{\gamma_e \delta_e}{P_e u_e} \quad (80)$$

and

$$U C_f = \frac{W}{\alpha_f} + \epsilon_f p_e + p_f \frac{\gamma_f \delta_f}{u_f} \quad (81)$$

$$u c_f = \omega_f + \epsilon_f p_e + \frac{\gamma_f \delta_f}{u_f} \quad (82)$$

With $\pi_e := \frac{\Pi_e}{p_f k_e}$ and $\mathcal{T}_e := \frac{T_e}{p_e}$, Eq. (19) becomes:

$$\pi_e = \frac{P_e u_e}{\gamma_e} (1 - u c_e - \mathcal{T}_e) - r d_e \quad (83)$$

Similarly, Eq. (23) leads to:

$$\pi_f^e = \frac{u_f}{\gamma_f} (1 - u c_f) - r d_f \quad (84)$$

Using Eq. (59), we can also rewrite Eq. (20) as:

$$\pi_f = \frac{p_f y_{f,d} - p_f y_{f,p} \left(u c_f + \frac{\gamma_f}{u_f} r d_f \right)}{p_f k_f} \quad (85)$$

$$= \mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + \kappa_{w,f} + \kappa_{c,f} - \frac{u_f}{\gamma_f} u c_f - r d_f \quad (86)$$

With $\kappa_{w,f} := \frac{c_{w,f}}{k_f}$, we obtain, by combining Eqs. (6) and (34):

$$c_{w,f} (p_e \epsilon_{\text{cons}} f(P_e) + p_f) = (1 - s_{F,w}) W \cdot L \quad (87)$$

$$c_{w,f} = \frac{(1 - s_{F,w}) \omega_f}{P_e \epsilon_{\text{cons}} f(P_e) + 1} \alpha_f (L_f + L_e) \quad (88)$$

$$c_{w,f} = \frac{(1 - s_{F,w}) \omega_f}{P_e \epsilon_{\text{cons}} f(P_e) + 1} \left(y_{f,p} + \frac{\alpha_f}{\alpha_e} k_e \right) \quad (89)$$

$$\kappa_{w,f} = \frac{\omega_f}{P_e \epsilon_{\text{cons}} f(P_e) + 1} \left(\frac{y_{f,p}}{k_f} + \frac{\alpha_f}{\alpha_e} \mathcal{K}_e \right) \quad (90)$$

$$\kappa_{w,f} = \frac{(1 - s_{F,w}) \omega_f}{P_e \epsilon_{\text{cons}} f(P_e) + 1} \left(\frac{u_f}{\gamma_f} + \frac{\alpha_f}{\alpha_e} \mathcal{K}_e \right) \quad (91)$$

Similarly, with $\kappa_{c,f} := \frac{c_{c,f}}{k_f}$ and Eqs. (26), (27), (40), Eq. (43) becomes:

$$\kappa_{c,f} = (1 - s_c - s_{F,c}) \left(\Delta \pi_f^e + \mathcal{K}_e \Delta \pi_e + r (d_f + \mathcal{K}_e d_e) - \pi_{bu} \right) \quad (92)$$

Furthermore, by combining Eqs. (4), (6) and the definition of u_e , we obtain:

$$u_e = \frac{\gamma_e}{(1 - \epsilon_e)} \left(\frac{e_f + c_{w,e} + c_{c,e}}{k_e} \right) \quad (93)$$

$$= \frac{\gamma_e}{(1 - \epsilon_e) \mathcal{K}_e} \left(\frac{\epsilon_f u_f}{\gamma_f} + \frac{c_{w,e} + c_{c,e}}{k_f} \right) \quad (94)$$

$$= \frac{\gamma_e}{(1 - \epsilon_e) \mathcal{K}_e} \left(\frac{\epsilon_f u_f}{\gamma_f} + \epsilon_{\text{cons}} f(P_e) (\kappa_{w,f} + \kappa_{c,f}) \right) \quad (95)$$

Let us divide both sides of Eq. (22) by k_e . It gives:

$$\frac{i_e}{k_e} = \beta_{i_e} \left(\frac{k_e^T}{k_e} - 1 \right) + \delta_e \quad (96)$$

$$\hat{k}_e = \beta_{i_e} \left(\frac{u_e}{u_e^T} - 1 \right) \quad (97)$$

Finally, we combine Eqs. (37) and (41) to have:

$$r^T = r_{CB} + \lambda_{r,T} \frac{\mu_b (D_f + D_e) - O F_b}{\mu_b (D_f + D_e)} \quad (98)$$

$$r^T = r_{CB} + \lambda_{r,T} \frac{\mu_b (d_f + \mathcal{K}_e d_e) - o f_b}{\mu_b (d_f + \mathcal{K}_e d_e)} \quad (99)$$

C.6. Reduced form model

The reduced form model is the set of differential equations:

$$\dot{\mathcal{K}}_e = \mathcal{K}_e (\hat{k}_e - \hat{k}_f)$$

$$\dot{P}_e = P_e (\hat{p}_e - \hat{p}_f)$$

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

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

$$\dot{\lambda}_f = \lambda_f \left(\hat{k}_f + \frac{v_f}{u_f} - \alpha_0 - \alpha_1 \lambda - \widehat{POP} \right)$$

$$\dot{\lambda}_e = \lambda_e \left(\hat{k}_e - \alpha_0 - \alpha_1 \lambda - \widehat{POP} \right)$$

$$\dot{u}_f^e = v_f$$

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

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

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

$$\begin{aligned} \dot{r} &= \beta_r (r^T - r) \\ \dot{of}_b &= \pi_{b,u} - of_b (\hat{p}_f + \hat{k}_f) \end{aligned}$$

with the following intermediate variables:

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

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

$$GDP = I_e + I_f + C_{w,f} + C_{c,f} + C_{w,e} + C_{c,e} \quad (100)$$

$$\frac{GDP}{p_f} = i_e + i_f + c_{w,f} + c_{c,f} + (c_{w,e} + c_{c,e}) \mathcal{P}_e \quad (101)$$

$$\frac{GDP}{p_f k_f} = \mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) (\kappa_{w,f} + \kappa_{c,f}) \quad (102)$$

We also have, when combining equations (6) and (34):

$$(1 - s_{F,w}) W \cdot L = c_{w,f} (p_f + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) \quad (103)$$

$$\frac{W \cdot L}{p_f k_f} = \frac{\kappa_{w,f}}{(1 - s_{F,w})} (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) \quad (104)$$

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

$$\Omega = \frac{\frac{\kappa_{w,f}}{(1 - s_{F,w})} (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e))}{\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) (\kappa_{w,f} + \kappa_{c,f})} \quad (105)$$

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

$$\Pi = \frac{\pi_f + \delta_f + r d_f + \mathcal{K}_e (\pi_e + \delta_e + r d_e)}{\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) (\kappa_{w,f} + \kappa_{c,f})} \quad (106)$$

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

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

$$1 - \Omega - \Pi = \frac{\frac{\mathcal{K}_e \mathcal{P}_e u_e}{\gamma_e} \mathcal{T}_e}{\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) (\kappa_{w,f} + \kappa_{c,f})} \quad (107)$$

The consumption share C is:

$$C = \frac{(\kappa_{w,f} + \kappa_{c,f}) (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e))}{\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) (\kappa_{w,f} + \kappa_{c,f})} \quad (108)$$

And investment rate I is the fraction of GDP that is not allocated to consumption:

$$I = 1 - C \quad (109)$$

$$= \frac{\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f}{\mathcal{K}_e (\hat{k}_e + \delta_e) + \hat{k}_f + \delta_f + (1 + \mathcal{P}_e \epsilon_{\text{cons}} f(\mathcal{P}_e)) (\kappa_{w,f} + \kappa_{c,f})} \quad (110)$$

Appendix D. Alternative, supply-driven version of the TEMPLE model

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

$$y_{e,p} = y_{e,d} := y_e \quad (111)$$

$$y_{f,p} = y_{f,d} := y_f \quad (112)$$

The constraint (111) was already enforced in the demand model from Appendix C. However, constraint (112) is new and implies the loss of one degree of freedom. This has three main consequences. First, there are no inventories in the supply-driven model and Eqs. (8)–(12) do not apply. Second, the value of u_f is fixed and equal to one. Third, the investment i_f of final goods firms is not determined anymore by Eq. (25). Instead, it is defined as the residual of Eq. (112):

$$y_{f,p} = y_{f,d} \quad (113)$$

$$\frac{k_f}{\gamma_f} = i_e + i_f + c_{w,f} + c_{c,f} \quad (114)$$

$$i_f = \frac{k_f}{\gamma_f} - i_e - c_{w,f} - c_{c,f} \quad (115)$$

D.1. Reduced form of the supply-driven model

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

$$\dot{\mathcal{K}}_e = \mathcal{K}_e (\hat{k}_e - \hat{k}_f)$$

$$\dot{\mathcal{P}}_e = \mathcal{P}_e (\hat{p}_e - \hat{p}_f)$$

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

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

$$\dot{\lambda}_x = \lambda_x (\hat{k}_x - \alpha_0 - \alpha_1 \lambda - \widehat{POP}) \quad (x \in \{e, f\})$$

$$\dot{d}_x = \hat{k}_x - (1 - \Delta) \pi_x - d_x (\hat{p}_f + \hat{k}_x) \quad (x \in \{e, f\})$$

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

$$\dot{of}_b = \pi_{b,u} - of_b (\hat{p}_f + \hat{k}_f)$$

with the following intermediate variables:

$$\pi_{b,u} = \beta_b (\mu_b (d_f + \mathcal{K}_e d_e) - of_b)$$

$$uc_f = \omega_f + \epsilon_f \mathcal{P}_e + \gamma_f \delta_f$$

$$\pi_f = \frac{1}{\gamma_f} (1 - uc_f) - r d_f$$

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

Table 4
Results of the calibration — variables.

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 ($\frac{2017\text{US\$}}{\text{GJ}}$)
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_e^f	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
v_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^f	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.
$\kappa_{e,f}$	–	–	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

$$\kappa_{c,f} = \frac{1 - s_c - s_{F,c}}{1 + \mathcal{T}_{c,f}} (\Delta \pi_f + \mathcal{K}_e \Delta \pi_e + r(d_f + \mathcal{K}_e d_e) - \pi_{b,u})$$

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

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

$$\hat{p}_e = \beta_{p_e} (\mu_e uc_e + \mathcal{T}_e - 1)$$

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

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

$$\hat{k}_f = \frac{1}{\gamma_f} - (\mathcal{K}_e (\hat{k}_e + \delta_e) + \delta_f + \kappa_{w,f} + \kappa_{c,f})$$

$$\lambda = \lambda_f + \lambda_e$$

$$\hat{p}_f = \beta_{p_f} (\mu_f uc_f - 1)$$

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

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

Appendix E. 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 Appendix C.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.²⁸ 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 4 and 5 describe the results of the calibration. Table 4 refers to the model's variables at steady-state (both the variables which have an associated differential equation and the intermediary variables). Table 5 refers to the model's parameters. For each variable and parameter, the lower and upper bounds are given, as well as the data source used for defining this range of admissible values (if no bounds are given, it means that a value was directly imposed based on the data source). Then, the value obtained after calibration is presented. Finally, a brief description of the variable or parameter is given,²⁹ as well as its unit if it is not dimensionless. Note that the reduced form model was built such that practically all variables and parameters are dimensionless.

In the last rows of Tables 4 and 5, neither lower nor upper bounds are given, nor a data source. Indeed, the values of the last variables and parameters are simply deduced from the other ones through the steady-state conditions, to which we add the following identities:

$$\frac{\alpha_f}{\alpha_e} = \frac{\lambda_e}{\lambda_f} \frac{u_f}{\gamma_f} \frac{1}{\mathcal{K}_e} \tag{116}$$

$$\omega_e = \omega_f \frac{\alpha_f}{\alpha_e} \frac{1}{\mathcal{P}_e} \tag{117}$$

Moreover, the values of some of the last parameters are only loosely constrained by the steady-state conditions. In that case, we choose them

²⁸ Used only for the amount of private debt: "Private Debt Non-Financial sector (All sectors, Market value, Percentage of GDP, and Adjusted for breaks)".

²⁹ In which the abbreviation "f.g." is used to refer to the final goods subsector.

Table 5
Results of the calibration — parameters.

Parameter	Min	Max	Value	Source of range of values	Description (Unit)
\overline{POP}	–	–	0.011	Penn World Table 10.0	Global pop. growth rate
r^n	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
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. $\left(\frac{MJ}{2017US\$}\right)$
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. $\left(\frac{2017US\$}{GJ}\right)$
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_e	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 $\left(\frac{GJ}{2017US\$}\right)$
\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
$\lambda_{r,T}$	–	–	0.018	–	Param. in banks target int. rate
ϵ_{cons}	–	–	0.0024	–	Technology parameter from Eq. (6)
a_0	–	–	1.06	–	Param. of func. $f(\cdot)$ from Eq. (6)
a_1	–	–	3.2	–	Param. of func. $f(\cdot)$ from Eq. (6)
a_2	–	–	0.84	–	Param. of func. $f(\cdot)$ from Eq. (6)

a value by trial and error, which ensures realistic dynamics to the model. Finally, the function $f(\cdot)$ from Eq. (6) is assumed to be of the form:

$$f(\mathcal{P}_e) = a_0 \left(\frac{a_1}{\mathcal{P}_e} + a_2 \right) \tag{118}$$

The values of a_1 and a_2 are calibrated based on the IEA data tables, the Penn World Table 10.0 and BP (2020). The value of a_0 is computed based on the calibrated values from Tables 4 and 5. The values of a_0 , a_1 and a_2 are given in Table 5.

Appendix F. Modelling 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 Eqs. (3) and (5), we have:

$$e_f = \epsilon_f y_{f,p} \tag{119}$$

$$y_{f,d} = i_e + i_f + c_{w,f} + c_{c,f} \tag{120}$$

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

$$e_f = \epsilon_f y_{f,p} \tag{121}$$

$$\approx \epsilon_f y_{f,d} \tag{122}$$

$$\approx \epsilon_{f,i_e} i_e + \epsilon_{f,i_f} i_f + \epsilon_{f,c_f} (c_{w,f} + c_{c,f}) \tag{123}$$

$$\epsilon_f \approx \epsilon_{f,i_e} \frac{i_e}{y_{f,d}} + \epsilon_{f,i_f} \frac{i_f}{y_{f,d}} + \epsilon_{f,c_f} \frac{c_{w,f} + c_{c,f}}{y_{f,d}} \tag{124}$$

$$\epsilon_f \approx \epsilon_{f,i_e} \frac{i_e}{y_{f,d}} + \epsilon_{f,i_f} \frac{i_f}{y_{f,d}} + \left(\theta_g \epsilon_{f,c_f,g} + \theta_s \epsilon_{f,c_f,s} \right) \frac{c_{w,f} + c_{c,f}}{y_{f,d}} \tag{125}$$

where we defined

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

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

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

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

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

Table 6
Energy and capital intensities: calibrated values for the year 2019 and projected constant rates of change for the period 2019–2060.

Parameter	Value	Source	Description (Unit)
ϵ_{f,i_e}	5.07	EXIOBASE and PWT 10.0	En. intens. of en. cap. stock. prod. $\left(\frac{\text{MJ}}{2017\text{US\$}}\right)$
ϵ_{f,i_f}	2.80	EXIOBASE and PWT 10.0	En. intens. of f. g. cap. stock. prod. $\left(\frac{\text{MJ}}{2017\text{US\$}}\right)$
$\epsilon_{f,c_f,s}$	3.67	EXIOBASE and PWT 10.0	En. intens. of f.g. prod. for cons. $\left(\frac{\text{MJ}}{2017\text{US\$}}\right)$
$\epsilon_{f,c_f,s}$	1.15	EXIOBASE and PWT 10.0	En. intens. of f.g. prod. for cons. $\left(\frac{\text{MJ}}{2017\text{US\$}}\right)$
θ_g	0.189	EXIOBASE and PWT 10.0	Share of goods in final consumption
θ_s	0.811	EXIOBASE and PWT 10.0	Share of services in final consumption
$\hat{\epsilon}_{f,i_e}$	-0.0169	EXIOBASE and PWT 10.0	Constant rate of change of ϵ_{f,i_e}
$\hat{\epsilon}_{f,i_f}$	-0.0059	EXIOBASE and PWT 10.0	Constant rate of change of ϵ_{f,i_f}
$\hat{\epsilon}_{f,c_f,s}$	-0.0096	EXIOBASE and PWT 10.0	Constant rate of change of $\epsilon_{f,c_f,s}$
$\hat{\epsilon}_{f,c_f,s}$	-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 5	Cap. intens. of en. prod. $\left(\frac{2017\text{US\$}}{\text{GJ}}\right)$
γ_{re}	223.05	Eq. (132)	Cap. intens. of r.e. prod. $\left(\frac{2017\text{US\$}}{\text{GJ}}\right)$
γ_{nre}	24.98	Eq. (133)	Cap. intens. of n.r.e. prod. $\left(\frac{2017\text{US\$}}{\text{GJ}}\right)$
ϵ_e	0.082	Table 5	En. intens. of en. prod.
ϵ_{re}	0.087	Dupont (2021)	En. intens. of r.e. prod.
ϵ_{nre}	0.104	Eq. (134)	En. intens. of n.r.e. prod.

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

As explained in Section 3.2.3, 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 6. The rate of degrowth of ϵ_{cons} is computed in a similar way and also presented in Table 6. Finally, thanks to Eq. (125), the evolution of ϵ_f can be deduced from the energy intensities defined above.

Now that we detailed the energy intensity of the economy and modelled 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):

$$y_{e,p} = y_{nre,p} + y_{re,p} \tag{126}$$

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

$$\chi = \frac{y_{re,p}}{y_{e,p}} \tag{127}$$

$\chi = 3\%$ in 2019; the transition is completed once $\chi = 1$. We can thus rewrite equation (126) as:

$$y_{e,p} = y_{nre,p} + y_{re,p} \tag{128}$$

$$= (1 - \chi) y_{e,p} + \chi y_{e,p} \tag{129}$$

Similarly, if we define the capital and energy intensities of respectively non-renewable (γ_{nre} , ϵ_{nre}) and renewable (γ_{re} , ϵ_{re}) energy production, we have:

$$\gamma_e = (1 - \chi) \gamma_{nre} + \chi \gamma_{re} \tag{130}$$

$$\epsilon_e = (1 - \chi) \epsilon_{nre} + \chi \epsilon_{re} \tag{131}$$

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

$$\gamma_{re} = \frac{1}{\text{EROI}_{re} \epsilon_{f,i_e} \delta_e} \tag{132}$$

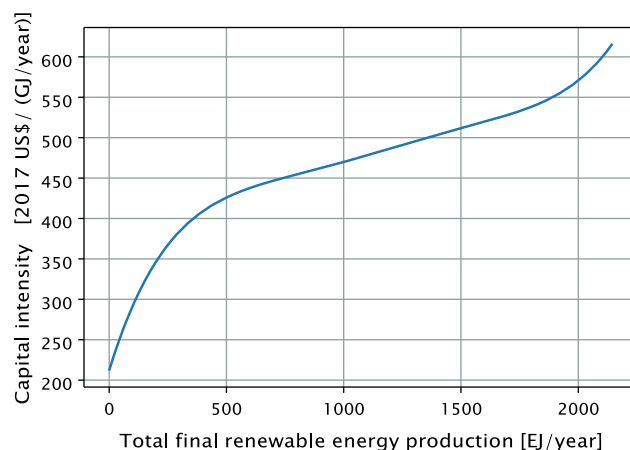


Fig. 9. Capital intensity of renewable energy production worldwide γ_{re} as a function of total renewable energy production $y_{re,p}$.

In this formula, ϵ_{f,i_e} allows to transform the embodied energy from the EROI into final goods and $\frac{1}{\delta_e}$ is the lifetime of the energy capital stock³⁰

After replacing in Eq. (132) EROI_{re} by the EROI curves from Dupont et al. (2018, 2020), we obtain the capital intensity curve depicted in Fig. 9.³¹

³⁰ Note that we use ϵ_{f,i_e} and not ϵ_f in Eq. (132). This is a notable refinement compared to Dupont et al. (2021b) and Dupont (2021). This improvement implies that γ_{re} takes a much lower value (less than half the value computed by using ϵ_f in place of ϵ_{f,i_e}). Thus, our refined computations compared to Dupont et al. (2021b) and Dupont (2021) imply that the energy transition is much less costly than modelled in these papers.

³¹ 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.

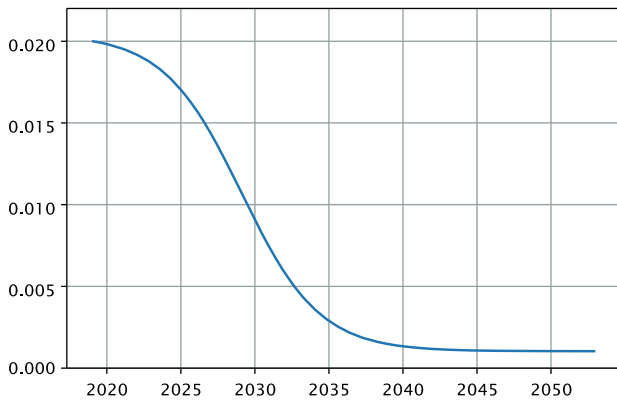


Fig. 10. Imposed decrease for the parameter κ_{f0} from Eq. (25) in the “slow growth” scenario.

As explained in Section 3.3, this curve must finally be multiplied by the corrective factor $(1 + \frac{\chi}{\rho})$ 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 6, 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 formulae:

$$\gamma_{nre} = \frac{\gamma_e - \chi \gamma_{re}}{1 - \chi} \tag{133}$$

$$\epsilon_{nre} = \frac{\epsilon_e - \chi \epsilon_{re}}{1 - \chi} \tag{134}$$

Once the values of γ_{nre} and ϵ_{nre} have been computed for the year 2019, the evolution of these parameters up to the year 2060 can be obtained by assuming that they evolve proportionally to $EROI_{nre}$, the aggregated EROI of fossil fuels:

$$\gamma_{nre} = \gamma_{nre}(2019) \frac{EROI_{nre}(2019)}{EROI_{nre}} \tag{135}$$

$$\epsilon_{nre} = \epsilon_{nre}(2019) \frac{EROI_{nre}(2019)}{EROI_{nre}} \tag{136}$$

$EROI_{nre}$, in turn, is a function of the total cumulated non-renewable energy production since the year 2019, as explained in Section 3.2.2. This function takes the following form (x being the cumulative production since 2019, in exajoules):

$$EROI_{nre} = 1 + 6.50 \times e^{-0.00002 \cdot x} \tag{137}$$

Overall EROI of the energy system

Next to the point of use EROI used above, the EROI of the entire energy system or of the (non-)renewable energy sub-system can also be computed. This system’s EROI is defined as the total energy produced, divided by the energy inputs of the energy (sub-)sector. These energy inputs can be separated into direct energy inputs and energy embodied into the capital stock. Using Eq. (2), this translates into:

$$EROI_{sys} = \frac{y_{e,p}}{\epsilon_e + \epsilon_{f,ie} k_e \delta_e} = \frac{1}{\epsilon_e + \epsilon_{f,ie} \frac{\gamma_e}{u_e} \delta_e}$$

And similarly:

$$EROI_{sys,re} = \frac{1}{\epsilon_{re} + \epsilon_{f,ie} \frac{\gamma_{re}}{u_e} \delta_e}$$

$$EROI_{sys,nre} = \frac{1}{\epsilon_{nre} + \epsilon_{f,ie} \frac{\gamma_{nre}}{u_e} \delta_e}$$

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 3.3, 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 Eq. (25) is not constant anymore, but decreases in a sigmoid way, as shown on Fig. 10. 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 Eq. (25). This scenario enables us to discuss the impact of economic growth on the energy transition.

Appendix G. Results of the supply-driven version of the model

Fig. 11 gives the simulation results obtained with the supply-driven version of the model for the scenario of a rapid global energy transition compatible with the 1.5 °C objective of the Paris Agreement. These results are extremely similar to the ones of the demand-driven version of the model, presented in Section 4.

Appendix H. Sensitivity analysis

The results of the sensitivity analysis described in Section 5.2 are displayed in Fig. 12 and Fig. 13. For concision, only the results for the investment rate and the inflation in final goods price are shown. In Fig. 12(e), the variation of the investment rate is small so all curves are overlapped.

We also carry out sensitivity analyses on the adjustment speeds. First, we play with $\beta_{pf,1}$ and $\beta_{pf,2}$, 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 $\beta_{pf,1}$ and $\beta_{pf,2}$ must respect the following condition at $t = 2019$:

$$\beta_{pf,1} (\mu_f u_{cf} - 1) + \beta_{pf,2} \left(\eta \frac{u_f}{\gamma_f} - v_f \right) = 0.019$$

Fig. 14 displays the corresponding simulations’ results.

Second, we modify the value of $\beta_{nf,1}$, 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 $\beta_{nf,1}$ appears in the following equations of the reduced-form model (see Appendix C.6):

$$\dot{u}_f^e = v_f$$

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

$v_f = 0$ at $t = 2019$ so changing the value of $\beta_{nf,1}$ has no impact on the initial steady-state. Fig. 15 shows the simulation results obtained when varying the value of $\beta_{nf,1}$. We observe that for lower values of $\beta_{nf,1}$, 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.

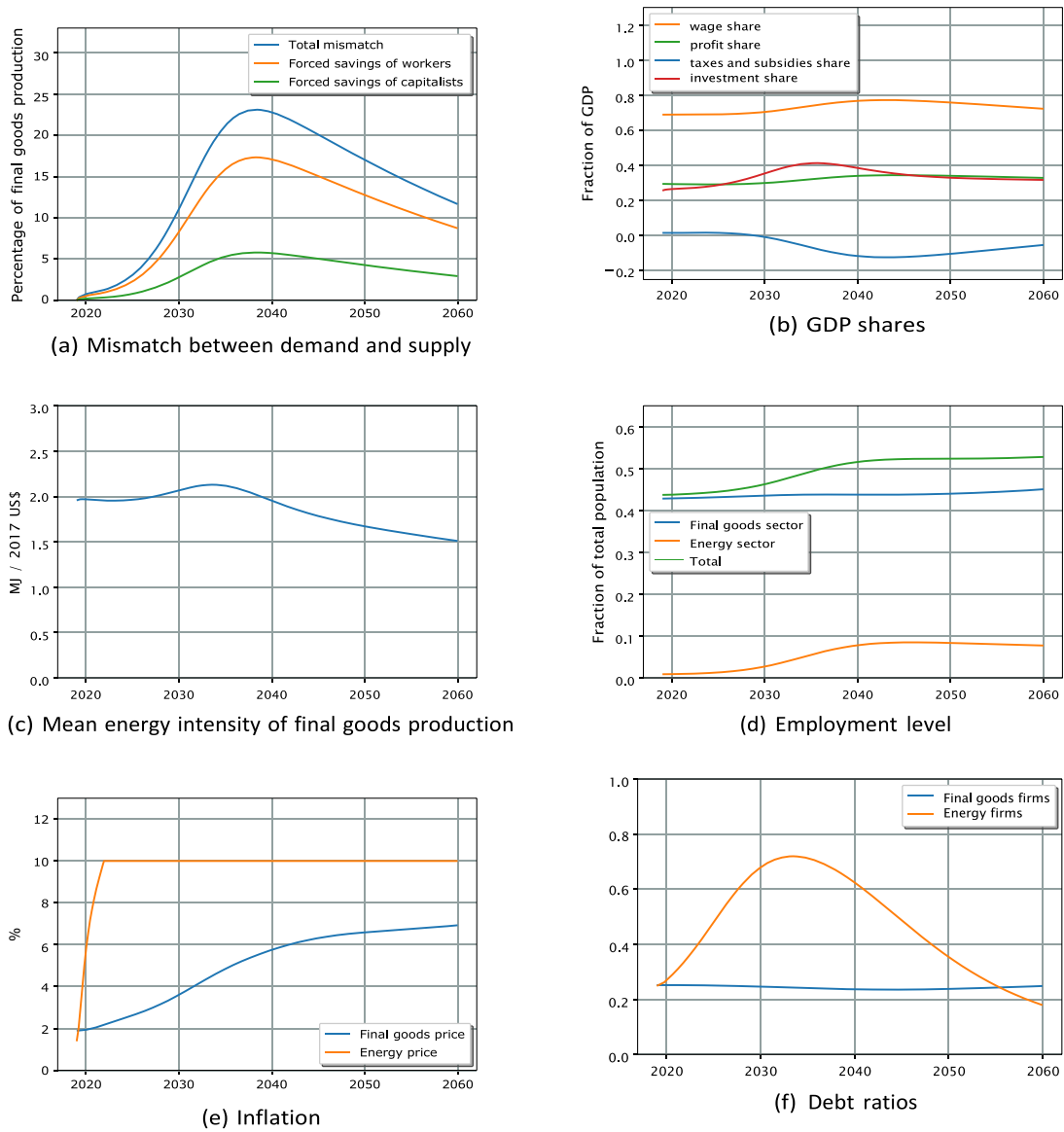
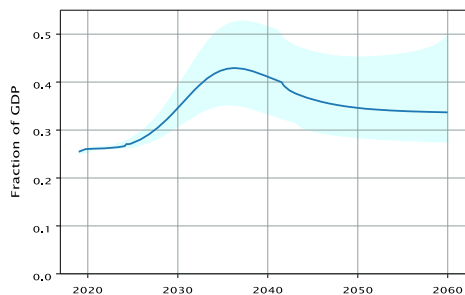
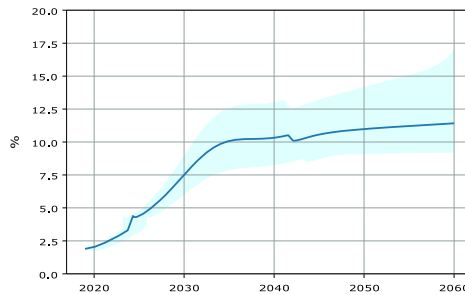


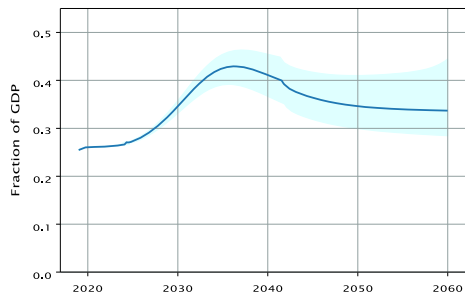
Fig. 11. Simulated macroeconomic dynamics of the energy transition under the scenario of a rapid energy transition, obtained with the supply-driven version of the model.



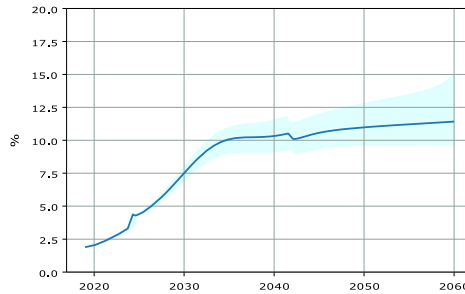
(a) Effect of γ_e on the investment rate



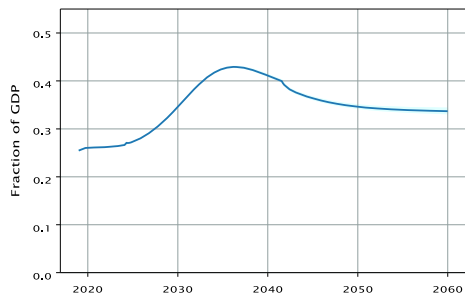
(b) Effect of γ_e on the inflation in final goods price



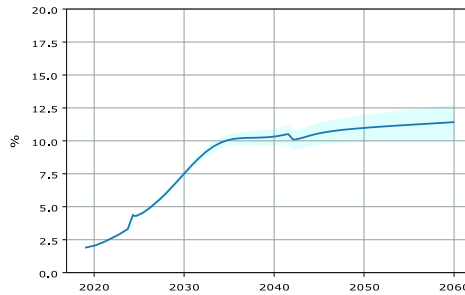
(c) Effect of the degrowth rate of the energy intensities on the investment rate



(d) Effect of the degrowth rate of the energy intensities on the inflation in final goods price

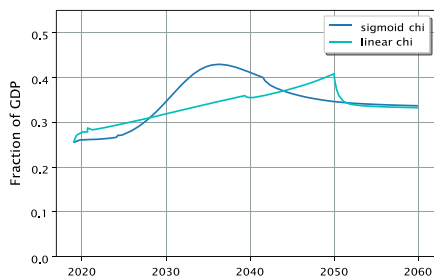


(e) Effect of population growth rate on the investment rate

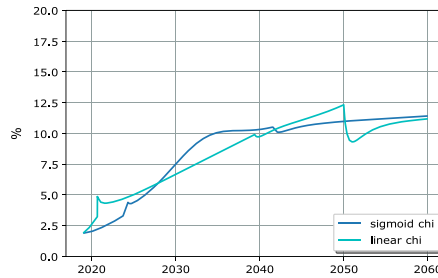


(f) Effect of population growth rate on the inflation in final goods price

Fig. 12. Effect of different parameters on the investment rate and on the inflation in final goods price.



(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. 13. Effect of different parameters on the investment rate and on the inflation in final goods price — continued.

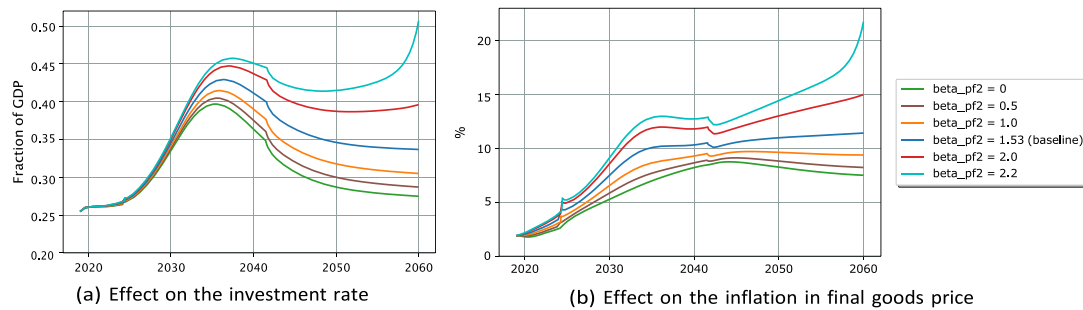


Fig. 14. Effects on the model's results of varying jointly the adjustment speeds for cost-push and demand-pull inflation in the final goods' price.

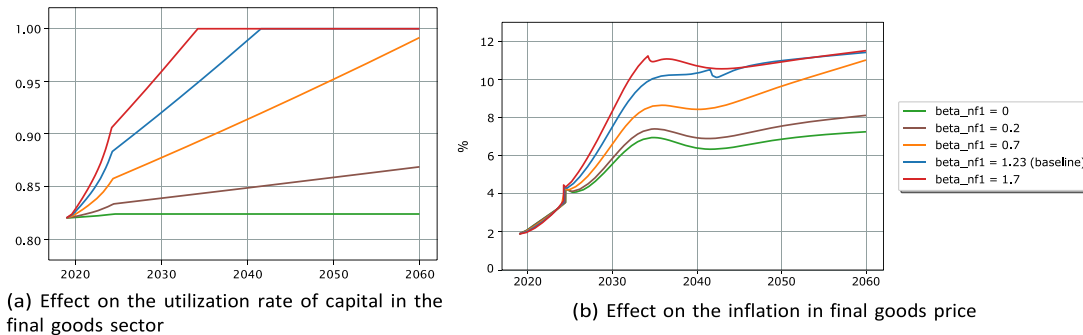


Fig. 15. Effects on the model's results of varying the adjustment speed for the utilization rate of the final goods firms' capital stock.

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