A successful assessment of the economic impacts of ecological transition policies in the EU requires the European Commission to broaden the range of its modelling tools

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Abstract

This paper presents a nuanced exploration of the current economic models used by the European Commission, highlighting their required complements in the context of ecological transition policies in the European Union, such as the European Green Deal. It emphasises the need for and value of incorporating a broader range of complementary modelling tools and models that illuminate aspects often abstracted in conventional approaches. This would permit to anticipate more adequately the impacts of the environmental crisis, environmental policies and transition strategies, and to assess their economic consequences. The authors discuss the theoretical and operational challenges faced by current models (*New Keynesian* DSGE and EEE-CGE types) and suggest alternative empirical modelling approaches developed in academic and public institutions. The aim of this work is both to provide an exhaustive review of complementary operational models in collaboration with their research teams, and to prioritise model development and guide discussions towards more effective policy recommendations. By integrating additional and complementary models having comparative advantages in addressing specific policy questions, this paper argues that the inventory of modelling tools of the European Commission could be enhanced. This paper makes a case for a more diversified, holistic and robust approach to economic modelling, to make them more capable of supporting the design of efficient, feasible, fair and socially acceptable ecological transition strategies. It also calls for an institutional convergence and interdisciplinary dialogue between modelling teams to improve tools and to provide effective and systemic guidance to policymakers in the EU.

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Content

Section 1 - Introduction

Our contemporary societies are marked by a major environmental, social, economic, geopolitical polycrisis, characterised by a multitude of risks and challenges that pose an existential threat to complex social organisations, both worldwide and in Europe. This multidimensional crisis encompasses not only the well-known risks associated with anthropogenic climate change (IPCC, 2021), often at the centre of discussions over the environmental crisis due to potentially devastating long-term damage such as sea-level rise, extreme weather events, or lethal heat-humidity combinations (Mora et al., 2017). Indeed, other planetary limits, such as biodiversity loss (IPBES, 2019; Ceballos & Ehrlich, 2023), soil degradation (Ferreira et al., 2022, on European Mediterranean region), disruption of biogeochemical cycles and dwindling freshwater resources, are just as worrying. Some of these phenomena are already having a retroactive impact on our economic systems, such as the increasing cost of natural disasters and climate change adaptation, with reported economic losses from disasters estimated at $2.98 trillion globally between 2000 and 2019, with climate-related disasters accounting for 77% of the total losses (UNDRR, 2020), and with negative effects of climate change on health in Europe, like extreme weather events, from flooding to heatwaves (EEA, 2017, 2023)[1]. These planetary limits are interdependent and their transgression can have profound repercussions on Europe's food security leading to increased reliance on food imports (FAO, 2021), as well as on energy, health and water security, but also on socio-economic stability (Rüttinger et al., 2015; Van Ginkel et al., 2020).

Faced with the scale of the polycrisis, it is becoming imperative to bring about a profound transformation of Europe's economy. Such structural transformation cannot be achieved by isolated measures or one-off interventions. It requires a massive overhaul of the continent's economic and energy systems, placing sustainability, resilience and equity at the heart of every decision. The success of this enterprise will depend, among others, on the availability and the quality of integrated economic and environmental modelling tools. These models can be used to anticipate the various effects of alternative environmental policies, and to assess the costs and benefits of specific measures or more global transition strategies.

The goal of this article is to take stock of the economic models currently used by the European Commission to treat such issues. The article aims at (i) providing a detailed list of the challenges faced by these models, especially in the light of the ecological transition; (ii) presenting already existing theoretical and operational complements and alternatives to these models, together with their scientific ecosystem. Through this, our goal is to facilitate generative incrementation of current modelling tools, to help them rise to the challenge of designing an efficient, feasible, macroeconomically stable and socially acceptable ecological transition.

Following **Section 1,** which introduces and sets the goal of this work, **Section 2** advocates diversification of modelling tools, taking the example of community practices for

[1] *"Extreme weather events like storms, heatwaves and flooding accounted for 85,000 to 145,000 human fatalities across Europe, over the past 40 years. Over 85% of those fatalities were due to heatwaves. Economic losses from weather and climate-related extremes in Europe reached around half a trillion euros over the same period."* (EEA, 2023).

model comparison in the climate sciences, and presents the relevant modelling ecosystem of the European Commission. The theoretical classes of models are exposed, together with their uses. The main models of interest are introduced. **Section 3** draws up a list of modelling challenges faced especially in the context of modelling scenarios for a systemic European ecological transition, and how the European Commission's models partially address them. **Section 4** proposes a series of existing consistent complements developed in the academic sphere as well as in public institutions, and the teams of researchers developing them, in order to complete the necessary responses to these challenges. **Section 5** then concludes. It calls for an interdisciplinary and collaborative dialogue between research teams - both academic and institutional - and for the institutional convergence of these different tools. Such endeavour is highly desirable to provide efficient guidance to public decision-makers in driving the ecological transition required by the European Union.

Section 2 - On the European Commission's economic-environment-energy modelling ecosystem

2.1 On model diversity and the incrementation of modelling tools within a scientific community: the case of climate sciences

Models play a central informational role in the development of public policy by democratic institutions and public decision-makers. The European Commission, with its various Directorates General ("DGs", e.g. ECFIN, CLIMA, ENER, TRADE, COMP, etc.) and the Joint Research Centre (JRC, providing technical support), makes extensive use of them both for policy making and evaluation, and economic forecasting[2]. The existence of several DGs and the JRC, with both common models and specific models and their own teams of researchers and modellers, is underpinned by the principle of diversity. Furthermore, the fact that the diversity of models adds to predictive accuracy is widely documented (e.g. Hong & Page, 2004; Guerrien & Jallais, 2009; Garnett et al., 2009; Page, 2007; 2010). As Scott Page (2010) puts it in a very simple way: ***Crowd of Models' Accuracy = Average Model Accuracy + Model Diversity***.

A possible epistemological counter-argument for this diversification of modelling tools, although recognized as relevant to dealing with the complexity of reality, is that it would imply that "anything goes", as Gräbner and Strunk (2020) explain. The limits and impediments to scientific diversification have long been addressed by its own advocates (e.g. Polanyi, 1962). Indeed, diversification must never imply a reduction in scientific rigour (Hodgson et al., 1992). This requires clear and active communication within the scientific community (Dow, 2004), with spaces for constructive exchange and collaborative dialogue. This is entirely possible, as the climate sciences demonstrate. Indeed, modelling is at the heart of the climate sciences, in particular through the General Circulation Models (GCMs) used to simulate the Earth's climate. The GCMs integrate models of the atmosphere, ocean, ice caps and land surfaces, which are then coupled (Ocean circulation, atmospheric circulation and coupling - AOGCM). These are extremely complex, large-scale models, often with hundreds of thousands of equations and parameters, which offer a very high level of granularity and realism. Yet, the need to compare models and their results was felt very early in this scientific community. The **Coupled Model Intercomparison Project (CMIP)[3]**, organised since 1997 under the aegis of the World Climate Research Programme (WCRP) of the World Meteorological Organisation (WMO), has been centralising and standardising this process ever since. The first element is the standardisation of databases, so that differences in results are only due to differences between models. The second element is the systematic and transparent comparison of models, functional forms, results and robustness, to enable continuous incrementation of collective modelling in a dialogue between research teams. The case of climate sciences thus offers an example of best community practice in comparing modelling tools to improve the quality and effectiveness of these tools in understanding and predicting complex phenomena.

[2] Hence, we do not discuss models used by the European Central Bank (which have already been extensively commented - see for example the Targeted Review of Internal Models (TRIM) internal project report of 2021) or other EU institutions.
[3] See for example CMIP Phase 5, Taylor et al. (2012).

2.2 On the European Commission's modelling ecosystem

Although the portfolios of some DGs do not explicitly refer to environmental and energy issues (e.g. the one of DG ECFIN (Economic and Financial Affairs), as specified on the European Commission's "Economic research" website), they generally do *de facto* in the current context. For example, the primary focus of DG ECFIN's research activities *"is to support policy making" (Ibid.)*. Indeed, the European Commission has set, at the heart of the European Green Deal, various environmental objectives for the EU. These were reaffirmed through the first European Climate Law proposed by the European Commission on March 4, 2023[4]. This latter translates the goal of reaching climate neutrality by 2050 into a legal obligation. It also affirms the intermediary objective of reducing net GHG emissions by 55% below 1990 levels by 2030 (the "fit for 55" plan), which ought to be achieved through the 8th Environment action program to 2030. Such objectives require a massive, structural transformation of the European economy, both supply- and demand-side.

What is more, the European Green Deal, next to climate neutrality by 2050, also sets as joint objectives *"economic growth decoupled from resource use"* and a transition with *"no person and no place left behind"*. Such objectives require a substantial amount of forward-looking analysis and modelling, all the more so in a framework of multilateral cooperation. For example, on March 6, 2020, the European Commission submitted the "Long-term low greenhouse gas emission development strategy of the European Union and its Member States" to the United Nations Framework Convention on Climate Change (UNFCCC), after receiving the long-term national decarbonization strategies of its member states. These must now be provided every 10 years (the next occurrence being 2029). They obviously deal with decarbonization but also, "to the extent feasible", with the socio-economic effects of the decarbonisation measures, the aspects related to macro-economic and social development, health risks and benefits. The Commission is also responsible for providing member states with "the state of the underlying scientific knowledge" when drawing up their long-term strategies, and for assessing whether each strategy is in line with EU objectives and targets.

Modelling tools are naturally mobilised for this vast task. Several DGs use various models to analyse and predict the evolution of the numerous economic and environmental variables of interest, and to model the impact of multiple public policies (e.g. taxes, subsidies, quotas and ETS...) on the different sectors of the European economy.

Obviously, there are many different sectoral models within the European Commission and its various departments and DGs. We will therefore restrict ourselves here to a small number of models, which are "general" macroeconomic models but include environmental and/or energy dimensions too. This will allow us to discuss more broadly the classes of models from which they derive. Thus, we will not refer to the large suites of sectoral models used (in partial equilibrium as well as in general equilibrium) such as, for example, RunDynam

[4] The European Commission set out in November 2018 a vision for a low-carbon European economy by 2050, aligning itself with the Paris Agreement to limit global warming to 2°C. The European Parliament has validated this GES-neutral approach with two resolutions, one in March 2019 on climate change and one in January 2020 on the European Green Deal. The European Council also validated this approach in December 2019.

(Recursive Dynamic Model - a general equilibrium model used by DG TRADE to analyse scenarios for international trade policies) or EEMM (European Electricity Market Model - a dynamic multi-market sectoral partial equilibrium model used by DG ENER for simulating the European electricity wholesale market). All these models, their uses and their affiliation to one or more DGs are referenced in MIDAS (**Modelling Inventory and Knowledge Management System of the European Commission**). This restriction also stems directly from our topic of analysis: as economists, we are less interested here in the detail of the energy/climate/environment modules than in the impact of economic core modelling on simulation results, and in the interaction of this core with these modules.

Two main theoretical classes of models are covered here, with different but complementary objectives: **Dynamic Stochastic General Equilibrium (DSGE)** models and **Computable General Equilibrium (CGE)** models. These two classes of models have emerged from the academic literature of recent decades and are widely used by international institutions (e.g. IMF, World Bank, ECB, US Federal Reserve and national public institutions). They are first and foremost *economic* models, which generally do not include energy and natural resources *a priori*. The main model of interest in this class is **QUEST3, a New Keynesian (NK) DSGE**, together with several of its variations[5], developed by DG ECFIN and used, according to MIDAS, by DGs CLIMA, EMPL, REGIO (Regional and Urban Policy), RTD (Research And Innovation), and TAXUD (Taxation And Customs Union).

DG ECFIN, next to QUEST3, has also developed the Global Multi-country (GM) model in cooperation with the JRC. Also a NK DSGE, built on estimated versions of QUEST3 and inheriting most of its structure, it is used for open economy analyses, involving the "Rest of the World" and the USA.

Finally, the **"General Equilibrium Model - Economy, Energy, Environment" (GEM-E3)**, a dynamic recursive CGE model developed by the JRC in cooperation with academic institutions, is used by DGs CLIMA, ENER, ENV and TAXUD to study the microeconomic aspects and macroeconomic impacts of energy, climate and air quality policies, particularly taxation and its distributive effects, on the various economic sectors.

These models can be supplemented by an energy and environment module. This allows to study the interactions between the economy, energy and the environment, as well as the potential impact of policies in these areas, with for example the E-QUEST variant, where energy production and energy use are disaggregated at sectoral level. Thanks to this module, the variance in emission intensities, as well as climate change mitigation policies and the analysis of their costs and benefits, can be examined.

In the following subsections, we will briefly present the classes of theoretical models to which those models belong, as well as their uses. The specific structure of the models of interest is then exposed.

[5] These range from highly aggregated versions with Bayesian estimation, in cooperation with the JRC, for estimating and decomposing the impact of shocks on business cycles, to multi-sector disaggregated models with different member states for studying of public policies, e.g. a version focused on endogenous innovation (QUEST3 R&D, Roeger et al. (2022)).

2.3. Brief theoretical description of DSGEs and CGEs

As mentioned above, two main types of model are used: DSGEs and CGEs. Let us start by pointing out that there are no "standard" DSGEs or CGEs (this is particularly true for DSGEs, as CGEs can be found in stylized form in advanced textbooks for graduates). Each institution generally develops its own variants of these models. We will therefore attempt to refer both to the historically "canonical" models and to the models currently in use. While DSGEs and CGEs are both based on General Equilibrium modelling[6] (following the seminal work of Frisch, Johansen, Leontief, Chenery, Von Neumann and Scarf in the 1950s and 1960s), they have their differences and do not respond to the same needs and issues.

DSGEs are a more recent category of economic models, used to analyse economic fluctuations and economic policies. They were developed in the wake of the RBC (Real Business Cycle) models and in response to Lucas' (1976) critique of the lack of a priori invariance of agents' behaviour in the face of public policy, nowadays with more and more New Keynesian rigidities and frictions. DSGEs are hence characterised by the use of "microfoundations". That is, they are based on the optimal microeconomic behaviour (i.e. rational maximisation under constraints) of representative economic agents such as households and companies. In a DSGE model, agents make decisions based on their expectations about the future, and these decisions influence macroeconomic variables such as output, employment, consumption, investment and inflation. DSGE models also incorporate exogenous random shocks (hence the stochastic character) that can affect the economy, such as technology, productivity, demand or monetary policy shocks. These shocks are modelled as stochastic perturbations of the model's equations, and may have persistent effects on the economy due to the model's dynamics. DSGE models are solved numerically and calibrated or estimated using economic data, often in a Bayesian fashion. Although DSGE models are a widely used tool for economic analysis, they have been criticised, particularly in terms of their ability to capture economic reality and predict financial crises. The criticisms pointed at the absence of a number of variables of interest (e.g. banks and private debt) in most DSGEs, but also at the model's presupposed framework (general equilibrium and market clearing).

A DSGE model often considered canonical is the one of Smet and Wouters (2007), published as an ECB working paper and estimated in Bayesian fashion on European data. These models come from generations of small-scale monetary business cycle models with a *"New Keynesian"* coloration, in the sense of adding frictions, rigidities and sticky prices and wages, asymmetric access to financial markets, market imperfections and agent heterogeneity, leading to different transitory and long-term results (notably a short-term non-neutrality of money and room for expansionary policies). This coloration is becoming increasingly widespread since Christiano et al. (2005), for example through heterogeneous agent models (see e.g. Gali & Gertler (1999), and Gali (2018)). For a recent review of DSGEs with numerous references, see Lindé, Smets & Wouters (2016).

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

CGE models are economic models used to simulate the impact of changes in economic policy, technology or other external factors, either on the economy as a whole or on specific sectors. Mainly developed since the 1970s at the World Bank, these models examine how supply and demand interact in different markets to determine prices and quantities of goods and services. CGE models are characterised by a detailed representation of the economy, including a disaggregation into several sectors, agents and markets. They take into account the interactions between these, whether in terms of flows of goods between sectors or in terms of elasticities of substitution. In a CGE model, the economy is represented by a set of equations describing production, consumption, exchange and price formation. Economic agents, such as households, firms and government, are modelled as optimizers who make decisions based on prices, income and technological constraints, again based on the theory of rational behaviour. CGE models are solved by finding the set of prices and quantities that balance supply and demand in all markets, taking into account government policies and external shocks. They are generally based on a "base year" calibration, where everything is assumed to be in equilibrium for this initial period. A CGE model is first benchmarked with disaggregated data from the Input-Output (IO) tables of the national accounts through Social Accounting Matrices (SAM). Technical and behavioural relationships linked to general equilibrium theory are then added to the model[7]. Unlike DSGEs, CGE models usually are recursive and do not include forward-looking intertemporal optimization, and if they do, they cannot always be solved intertemporally. They were originally static, but are becoming increasingly dynamic. CGEs still have their own limitations, notably due to the complexity of their calibration, sometimes *ad hoc*, and the need to make assumptions about agent behaviour and technology. For an example of a canonical dynamic recursive environmental CGE model, see for example ENV-Linkages of the OECD (Chateau et al., 2014).

2.4. Uses and purposes of DSGEs and CGEs

DSGE models offer a very high level of aggregation and stylization of economic agents, variables and phenomena. They are mainly used to study economic fluctuations, as well as monetary and fiscal policies and their impact on the former. They serve to make macroeconomic forecasts on economic aggregates such as unemployment, general inflation, economic growth or the rate of change of wages. By doing so, they heavily rely on calibration and Bayesian estimation. Based on an intertemporal optimization framework on the part of representative agents, DSGEs also aim to derive an "optimal" trajectory for public policies. They are widely used by central banks, financial institutions and public Treasuries to formulate monetary and budgetary policies, as well as for forecasting. In the context of the ecological transition, DSGEs are either used to study the impact on growth, consumption, production and investment of environmental policies, including taxes, subsidies and regulation, or to deduce "optimal" emission and carbon cost trajectories. Macroeconomic fluctuations in those models are

[7] Actually, one can think of a CGE as a traditional Input-Output model, onto which is grafted General Equilibrium à la Walras / Arrow-Debreu with price rather than quantity adjustment, optimization behaviours, and elasticities representing preferences and technologies.

triggered (only) by "exogenous shocks" and the optimal reactions of agents under constraints to these shocks.

CGE models, on the other hand, are disaggregated, multi-sector models, designed to study the production and trade of each sector and the interdependencies within the economy. Often very broad, they are used to assess the impacts of changes in economic, fiscal (especially taxes and subsidies), commercial, environmental and technological policies. Those impacts are studied on each sector and on the economy as a whole, together with the potential distortions and direct and indirect effects arising from them. By using national accounting data through Social Accounting Matrices (SAM), CGEs can study the allocative and redistributive effects of policies on households and businesses. They can also endogenize technology, to study its determinants, or to study how technology itself is a determinant of growth and structural change. In fact, CGEs have a much more positivist approach (i.e. more descriptive than normative) than DSGEs, due to the higher degree of precision in their description of the economy, and the emphasis they place on the multiple constraints of time, technology, etc. But they are built on the application of economic theory, they do not test it, involving its share of normativity. Their aim is not to deduce optimal dynamic policies, but to study the impact of *ad hoc* policies on the economy. In an environmental context applied to CGEs since the 1990s, those models can be used to study the specific impacts of a tax-type policy, and are used to compute the social cost of complying with the Kyoto Protocol (externality CGEs). Those impacts can be on the concerned sector or, through substitution elasticities, on other sectors, as well as on endogenous technological evolution or on the consumption of different resources.

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

2.5. Focus on the considered models of the European Commission

One of the two main DSGEs used by the EU Commission for the eurozone, modelled as an open economy with monetary and fiscal policies, is QUEST3 (Ratto, Roeger & in 't Veld, 2009; Burgert et al., 2020). The variant of interest is the E-QUEST model (Varga, Roeger & in 't Veld, 2022). It integrates energy and emissions with a disaggregation by sector and by energy source, in a multi-region framework. QUEST3 is a New Keynesian (NK) microfounded model. Unlike in most CGEs and IAMs, this implies the presence of frictions on the good, labour and financial markets, as well as a framework of imperfect and monopolistic competition à la Dixit and Stiglitz (1977) and household heterogeneity (two representative agents, one Ricardian[8] - the “rational one” - and one “hand-to-mouth”, i.e. liquidity-constrained, because they do not have access to financial markets).

E-QUEST aims at comparing climate policy scenarios for achieving the EU's net-zero target for 2050. In particular, it contrasts carbon taxation with direct regulation, playing the role of an IAM. It distinguishes between "clean" and "dirty" capital-energy bundles. Besides, it adds to QUEST3 a sectoral energy-input substitution to describe the transition from "dirty" to "clean"

[8] In the sense of the Barro-Ricardo equivalence.

sources. Although lacking the level of disaggregation of a CGE model, the presence of seven sectors in E-QUEST permits the analysis of the energy composition and interdependencies of the different sectors. Technical progress is not endogenous, but is generated by an exogenous growth rate of energy efficiency and learning by doing. Ricardian Agents' investment and savings decisions are the results of a forward-looking intertemporal optimization problem, with agents anticipating future environmental policies. The model is calibrated on the World Input-Output Database (WIOD). According to its sensitivity analysis, its results depend substantially on the elasticity of substitution between the clean and dirty capital-energy bundle and on the exogenous rate of technological and energy innovation (Varga et al., 2022).

The GEM-E3 model (Capros et al., 2017), a CGE, is part of a suite of environmental models, with the output scenarios of some models being the input of others to guarantee a form of internal consistency. **Figure 1** presents the structure of this suite of models. It comprises four blocks: Economy, Energy and Environment for the traditional EEE, with the environment block broken down into emissions/air pollution and land use/agriculture.

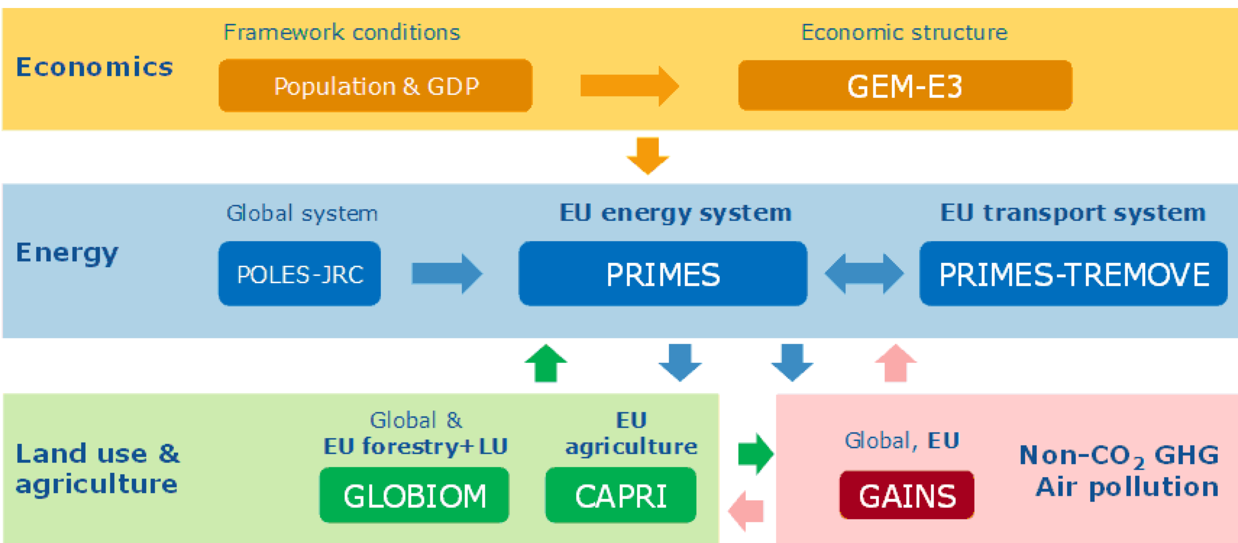

Figure 1: Structure of the suite of environmental models comprising GEM-E3. Source: European Commission

GEM-E3 is the starting model of the suite. It is a dynamic and recursive CGE, disaggregated at member state level and representing the rest of the world in its different regions. It incorporates both goods and environmental flows. GEM-E3 is multi-sectoral, with 30 to 31 sectors and 10 energy sources, represented by endogenous bilateral trade flows (an input-output table coupled with demand and supply equations and market clearing mechanisms). It is based on agents with myopic expectations, which optimise their objective functions (well-being for households, cost for firms), taking into account the emissions produced by economic activities. The basic framework is a competitive market allowing endogenous Walrasian equilibrium pricing, not only in the good and labour markets, but also between energy demand and supply, in the capital market (**Figure 2**) and between emissions and abatement costs. Still, extensions of the model allow for the introduction of imperfect competition frameworks (e.g. Nash-Cournot competition on quantities). It also includes private debt through the savings-investment determination and surplus/deficit. The elasticities of substitution between production factors (capital, labour, energy, etc.) have proposed values ranging from 0.2 to 1.7. They determine a large part of the model's results.

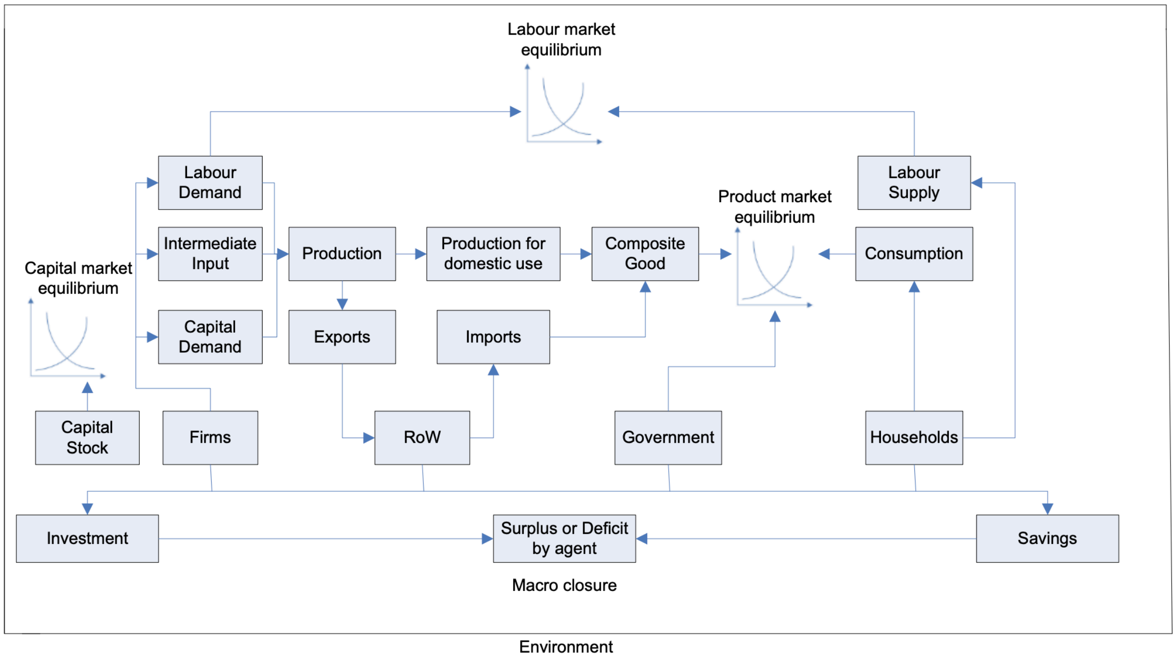

Figure 2: Structure of the GEM-E3 model (Capros et al., 2017).

JRC's GEM-E3 is then coupled to an energy block consisting of three models: PRIMES (Price-Induced Market Equilibrium System), a partial equilibrium model which simulates the energy system of the EU and each member state; PRIMES-TREMOVE, a dynamic system of multi-agent choices under several constraints simulating the evolution of demand for passenger and freight transport by transport mode; and POLES-JRC, a global energy model representing the whole energy balance, from trade of energy commodities and primary energy supply to the various end-use demands.

The Energy block itself interacts with the two environmental blocks. Forestry and agriculture are represented by the GLOBIOM and CAPRI models, while GAINS treats the emissions aspect. GLOBIOM is a global recursive dynamic partial equilibrium model for the bio-energy, forestry and agriculture sectors; CAPRI is a partial equilibrium model focused on the agricultural sector; finally, GAINS is an IAM for GHG emissions but also non-CO2 emissions, i.e. other air pollutants. GEM-E3 and E-QUEST are among the main public ecological transition modelling tools developed by and for the European Commission.

Finally, in the context of macroeconomic analysis, the European Commission uses another NK-DSGE to complement QUEST3, the GM (Global Multi-country) model. Even if the GM model has not been used so far for the analysis of environmental policies (while including oil and gas), it seems relevant to mention it, given the importance of international trade, exchange rates, financial flows and more generally cross-border flows in the context of the ecological transition. Built as a development of QUEST3, the GM model was originally intended to study research questions involving international trade and financial flows at Euro Area-level, and then at European country-level. Such research topics included the determinants of European countries' current account balances and the impact of these balances on each other (see the seminal paper by Kollman et al. (2014) for the German current account). The GM model, estimated in a Bayesian manner, places emphasis on international economic issues, such as international trade dynamics and financial flows. The GM2 version includes the Europe Area (EA) and the "Rest of the World (RoW)". The GM3 version covers the Euro Area, the USA and the “Rest of the World” (Kollman et al., 2016), and it has been used to perform GDP growth forecast decomposition by the European Commission since 2015 (e.g. European Commission, 2017). Finally, the GM3-EMU (for Economic and Monetary Union) versions apply to individual Euro Area countries in relation to the rest of the Euro Area and RoW (Albonico et al., 2019). Kept at a relatively low level of complexity to decrease the computational burden compared with QUEST3, GM is used to assess the impact of shocks and policies. It is particularly useful for examining the spillover effects of policies from one country to others, a critical aspect in a globalised economy. More generally, GM is used for a wide range of policy analyses, including global trade policies, international financial regulations and global economic shocks like oil price changes or financial crises, or the macroeconomic effects of central banking policies such as quantitative easing (Hohberger et al., 2019).

At the heart of all these models is the intertemporal optimization of households' welfare in monetary terms, i.e. their consumption (or the deviation of consumption from a baseline as a result of a policy). Thus, the criterion for comparing different policies (in this case, environmental policies) is mainly the comparison between the evolution of welfare (i.e. the present discounted value of consumption) according to each policy, and according to the baseline scenario, using a counterfactual simulation. They lead to diverse results in terms of the impact of achieving decarbonization targets, ranging, *very generally speaking*, from a small welfare-reducing trend in decarbonization for GEM-E3, to an almost non-significant negative impact on output for E-QUEST (without taking into account the economic costs of avoided climate damage or the potential growth effects of "green" investments). Furthermore, the inclusion of heterogeneous agents leads to distributional effects, and generally points towards a more regressive character of regulation, compared to a carbon tax with distributional recycling of tax revenues.

This overview of the current macroeconomic models used to design and steer the ecological transition highlights the important use of both DSGE and CGE models by the EU Commission. The ensuing sections delve into the challenges faced by such models and show how the current EU Commission’s models partially respond to these. Then, a range of existing complementary models developed in academic and public institutions is presented, showcasing the efforts of various research teams and exploring potential avenues for enhancing the economic modelling of the EU's ecological transition.

Section 3 - Challenges faced by economic models in the light of the ecological transition

Although useful for the design of economic and environmental policies, and for economic forecasting, the model classes presented in **Section 2** face certain theoretical, methodological and practical challenges. Those limitations may be non-trivial in the context of continental ecological transformation, and all the more in the context of an economy that is becoming re-embedded in the environment. The aim of this section is therefore to present a constructive summary of these challenges, which have been underlined by regular users and designers of these model classes. The partial response of the EU Commission's models to these challenges is presented in parallel. We also point out how those issues are becoming more problematic when faced with the challenge of modelling the ecological transition. **Section 4** will subsequently present diverse solutions through modelling tools already designed by different teams of researchers.

It should be pointed out that the aim of this work is **not to highlight doctrinal oppositions, but rather to objectify elements that have a direct impact on modelling results, on their relevance** for the design of public policies, and which limit the practicality of those models. What follows is therefore first and foremost an operational, pragmatic discussion.

A large number of criticisms, well documented, have long been levelled at both DSGE and CGE models, including by leading researchers, practitioners, users and developers, among others for their failure to forecast and predict financial and economic crises like the GFC of 2008. With regard to the DSGEs, Vines and Wills (2018) conducted a survey in the framework of the Rebuilding Macroeconomic Theory Project, asking leading macroeconomists to describe how the canonical New Keynesian DSGE models could be rebuilt following the 2008 crisis. Their findings confirmed the need for a change in macroeconomic theory, implying a more pluralistic discipline[9]. By way of significant examples, Olivier Blanchard (2016), former IMF chief economist, in an article entitled "Do DSGE Models Have a Future?" considers them to be *"seriously flawed"*, due to i) assumptions that are not only unrealistic but also in conflict with empirical knowledge about firms and consumers, whether for the Euler equation or Calvo pricing (in the aggregate demand and forward-looking price adjustment equations); ii) major problems of calibration and (now mostly Bayesian) estimation; iii) problems of use for normative purposes, particularly in terms of welfare functions and the optimality of trajectories and policies; and iv) the inability to communicate to the reader the results of policies and distortions introduced on a really heavy algebraic structure, and the proper causality. He concludes by recommending that DSGEs become less *"insular"* and less *"imperialist"* and need to be integrated into a much broader and complementary ecosystem of economic models[10]. In his view, *ad hoc* aggregate equation models and structural equation models (e.g. Blanchard & Bernanke, 2023) have an important role to play, both upstream and downstream.

[9] *"Achieving these objectives requires changes to all of the behavioural equations in the model governing consumption, investment, and price setting, and also the insertion of a wedge between the interest rate set by policy-makers and that facing consumers and investors." (Ibid.).*

[10] *"(...) the profession (and again, this is a note to the editors of the major journals) must realize that different model types are needed for different tasks."* (Blanchard, 2016, p.3).

Narayana Kocherlakota (2018), former President of the Minneapolis Fed, argues that in an institutional and public policy design framework, macroeconomic evaluation, to be of any practical value, should be based on a regression-based approach with past macroeconomic data rather than on putative structural models. Mankiw (2008), Solow (2010), D. Romer (2015), P. Romer (2016) and Stiglitz (2018) make similar and complementary criticisms. It addresses the problems of forecasting and even simulating financial and economic crises. They identify problems caused by rational expectations (making those models to be estimated sometimes more *ad hoc* than previous macroeconometric equation models). These classes of models, they claim, favour analytical coherence of a specific and chosen theory, generally at the detriment of their relevance for studying reality and recommending policies, even if the trend is towards a better empirical fit and more realistic assumptions in New Keynesian Macroeconomics.

Similarly, CGE models are better suited for applying economic theory than for testing it - what is referred to as the “bridge perspective” by Bergman (2005). However, they are still based on strong, normative theoretical choices, such as the general equilibrium framework, where perfect flexibility of prices and quantities ensures the existence of an equilibrium. So CGEs also tend to provide a normative vision of economic mechanisms and even of possible economic policies, instead of testing them. This is all the more important since, as the literature review by Ji et al. (2022) shows, *"reflections on environmental policy instruments have shifted from command-based to market-based"*, and that *"CGE model promotes the shift"*. Nevertheless, it should be noted that recent CGEs gradually include the possibility of imperfect competition, disequilibria and involuntary unemployment. In this respect, a macro-micro assessment of the 2030 Climate Target Plan of the EU Green Deal by the JRC, using heterogeneous households and micro-data with GEM-E3 shows that a regulation-based policy scenario is complementary to and can perform as well as price-based / market-based ones (Temursho et al., 2020)[11].

It is important to emphasise that macroeconomic research, like any scientific discipline, is constantly evolving, and it is clear that the models involved are also moving forward. More and more frictions and rigidities (nominal, real, financial) are added; the frameworks of pure and perfect competition are relaxed, and heterogeneity among agents is introduced (such as with HANK models, Galí-Gertler-type models, or in our case, E-QUEST); the assumptions of perfect rationality are gradually replaced by bounded rationality (e.g. Beqiraj et al, JRC, 2018); and financial markets and market beliefs are sometimes added (e.g. Annichiarico et al., 2022). These are partial and encouraging responses to some criticisms and the research program expansion called for, for example, by Stiglitz (2018). But, although positive, these transformations and additions are only partial and thus insufficient, especially in light of the current economic and environmental situation. In the following pages, we will thus attempt to review the challenges faced by the main classes of economic modelling tools, and the partial answers provided by the EU Commission’s models under consideration.

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[11] Price-based policies, if they include redistribution, can offset the potentially regressive nature of regulation-based policies by offering compensation for lost income (Levinson, 2019). Otherwise, the price instrument will also be regressive, as the tax will be passed on to the consumer, as the poorer classes will have a higher carbon content in their expenditure and a low price elasticity of demand for carbon products in the event of low substitutability.

3.1. Output gap framework

- ***Usual challenges and shortcomings faced by CGEs and DSGEs***

Standard DSGE and CGE models are based on constrained intertemporal optimization by households and firms[12]. Economic variables, notably output and employment, naturally converge towards structural ("natural") rates. Generally speaking, variations outside these values are only temporary (zero or very short time for original RBC type models, short or medium time for NK-type models à la Gali & Gertler, 1999). In this case, the temporary rise in production, the "output gap", is caused solely by the misinterpretation of inflation by producing agents, which is understood not as general but idiosyncratic (specific to the producers' asset). Producers will perceive a decrease in the relative price of their output, and will therefore invest and hire less, decreasing output and employment and thus closing this output gap. Thus, the output gap is defined as the difference between the real GDP of a country and the potential GDP that would be attainable if all production factors were used at "normal" capacity utilisation, i.e. at non-inflationary levels. Once firms have liquidated the overcapacity, equilibrium values are restored - the only difference being a higher general price level (the "Island parable", Phelps, 1969). Thus, economic policies tend to have no effect at all on real variables for RBCs, and no effect in the long term for NK DSGE, with an impact only on inflation. There is virtually no room for expansionary economic policies, or only temporary and for monetarist reasons (Sargent & Wallace, 1975). The fiscal policy has as its sole aim to stabilise the debt-to-GDP ratio towards the target and limit fluctuation of fiscal deficit, in alignment with the Stability and Growth Pact. Generally, fiscal consolidation is deduced from the output gap, a policy that has already led to weak domestic demand in Europe and output (Fatás & Summers, 2018; Fatás, 2020), as fiscal consolidation is pro-cyclical (DeLong & Summers, 2012)[13].

Yet, the ecological transition, given its cost, the necessary economies of scale, the complementarities, the degree of risk capital to be overcome and the amount of capital stranding envisaged, can only call for an interventionist state and an active fiscal policy, as the European Green Deal assumes. It is essential for modelling tools to be able to represent and assess such active policies. Moreover, the assumed optimising behaviour implies that every available resource in the economy is employed (100% capacity utilisation rate), which means that an increase in green investment implies crowding out of investment in other sectors (higher price of capital). This also leads to more negative effects on GDP. However, capacity utilisation data for the European manufacturing sector (Eurostat), for example, show a utilisation rate of 80% to 85%, with stable trends alongside fluctuations linked to the economic cycle. On the other

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[12] To be precise, the CGEs of interest increasingly exhibit intertemporal optimization behaviour, but are generally not capable of being solved intertemporally. They (including GEM-E3) are therefore solved in a time forward manner with adjusting dynamics.

[13] In the EU, the European Commission uses an output gap model as the core of its fiscal surveillance of member states. However, there is a self-prophetic effect of pessimistic estimates of potential outputs, particularly after crises, for example that of 2008, following which estimates were very pessimistic and which, through negative loops, led to fiscal consolidation and austerity policies, partially confirming the pessimistic estimates and leading to increasing public debt-to-GDP ratios instead of reducing public debt through the negative impact on output (Fatás & Summers, 2018; Fatás, 2020). This confirms the pro-cyclical and self-defeating nature of fiscal consolidations (DeLong & Summers, 2012).

hand, southern member states have a lower utilisation rate. This calls into question the output gap approach and the assumption of an optimised use of resources, and therefore the consequences of green investments.

Despite being a theoretical construct which is not observable (or, at least, whose structural parameters' identification remains questionable), the output gap is generally still at the core of macroeconomic modelling. However, New-Keynesian models, which are more and more widespread, relax this lack of effectiveness of economic policies over the long run, by introducing a set of more realistic assumptions: price viscosity, nominal and real rigidities, imperfect information and markets, liquidity constraints (e.g. Galí et al., 2007), as well as a Taylor rule for monetary policies, restoring the role of expansionary policies at least in the short term.

- ***Contributions of the considered models of the European Commission***

E-QUEST, a New-Keynesian DSGE, uses a Taylor rule for monetary policies, recognizing the short-term non-neutrality of these policies[14]. What is even more interesting is its exploration of fiscal policies (in line with QUEST3), generally little studied in DSGEs in favour of monetary stabilisation policies. The frictions, asymmetries and rigidities included in NK-DSGE, coupled with non-Ricardian households (cf. **3.5**), enable it to represent long-run effects of fiscal policies (including an increase in government spending), with a permanent effect on real output. See Burgert et al. (2020) for a recent version of QUEST3 with extended policy analysis, where increased government spending leads to higher output and where public investment crowds in private productive investment in the medium term. In E-QUEST, the modelled fiscal policies include carbon tax, regulation, consumption tax, recycling tax revenues, capital taxation and clean subsidies. Nevertheless, the authors acknowledge that the policies discussed are budgetary-neutral policies to reach the net-zero emission targets. Thus, the model does not seek to study *"possible growth effects of a green investment action plan, as promoted by the European Union's Green Deal"* (Varga et al., 2022). This central issue is yet to be explored.

3.2. Equilibrium framework and Say's Law

- ***Usual challenges and shortcomings faced by CGEs and DSGEs***

Standard macroeconomic modelling, including CGEs and DSGEs, is based on an equilibrium framework, not as a result but as an assumption (market clearing, fixed point, growth steady state, rational expectations). Blanchard (2018) puts forward as a *"widely believed proposition"* with *"a wide agreement"* that *"Macroeconomics is about general equilibrium*". This framework, in addition to eliminating numerous real dynamics, prevents the modelling of a central and fundamental empirical fact: fluctuations that are endogenous to the economic

[14] Note that E-QUEST, although using the output gap framework, derives it from a production function, making it possible to obtain a more satisfactory proxy, i.e. the deviation of the use of production factors from its long-term trend (see Denis et al. (2002) for this practice).

system, in the absence of exogenous shocks. Indeed, macroeconomic variations in those models are not endogenous but caused by exogenous shocks, real or monetary (productivity, technology, oil shock, changes in agents' preferences, unexpected monetary policies, etc.), and their propagation, as DSGEs focus on equilibria that are stationary linear fluctuations caused by those shocks. Therefore, macroeconomic fluctuations can be seen as the optimal response of the private sector to those shocks under constraints. This approach, beyond its lack of realism and the *ad hoc, ex-post* nature of the assumed shocks (cf. **Appendix B.1**) also prevents the modelling of persistent financial crises and economic recessions (e.g. massive and long-term unemployment). Eventually, DSGEs postulate from the outset (or adopt assumptions that necessarily lead to the built-in property) that there is a unique equilibrium, which is moreover locally stable — so that small exogenous shocks do not prevent the economy, after a small deviation, from returning back to the original steady state[15]. By contrast, most of the specialised literature on General Equilibrium Theory from the 1990s' has shown these postulates to be only exceptionally valid (Giraud, Kleman & Souffron, forthcoming). All these remarks are nonetheless widely documented empirically. It is therefore not excessive to require a model, especially within an institutional framework, that allows for i) crises (with persistence and hysteresis) and ii) endogenous, out-of-equilibrium fluctuations, even without exogenous "productivity shocks", such as the Goodwin model (1967), and the debt-augmented one (Keen, 1995; see Bovari et al, 2018, 2019, for an ecological extension). In addition, the possibility of multiple self-reinforcing equilibria could be an interesting framework, raising the question of equilibrium selection through public policies which push the system to one or another basin of attraction - see the MEADE (Multiple-Equilibrium And DiversE)[16] paradigm proposed by Vines and Wills (2021), following their survey of macroeconomists.

Even if some recent CGEs allow for imperfect competition and involuntary unemployment, most CGEs assume perfect price and quantity flexibility, which guarantees full utilisation of production factors at all times since the base year. Prices are market-derived and ensure the existence of an equilibrium. By construction, Social Accounting Matrices satisfy Walras Law. Assuming equilibrium and market clearing in those CGE models amounts to postulating Say's Law i.e. that demand always adjusts to match exactly the level of output in the economy. Such an assumption has been broadly questioned (Shaikh, 2016) and empirically contested, namely in the aftermath of the 2008 crisis (Yellen, 2016), and in terms of relevance (Kornai, 1971). Moreover, Say's Law implies that the economy always operates at full capacity

[15] We can question the ability of a highly complex socio-economic system to provide an efficient market outcome without problems of market and price incompleteness, particularly in phases of high uncertainty leading Pareto-suboptimality to be the rule (even in terms of second best, cf. Geanakoplos & Polemarchakis, 1986).

[16] As Sandbu put it in the Financial Times (28th January 2021) about the MEADE paradigm, *"a focus on multiple equilibria is transformative. The standard model, smooth and self-rectifying as it is, invites economists to see their role as identifying marginal policy changes to improve trade-offs, speed up the pace at which the economy returns to its natural equilibrium, and even nudge that equilibrium itself to a slightly better place. Once we acknowledge multiple equilibria, and that the economy can jump from a good to a bad state or vice versa, it becomes clear that by far the most important policy question is equilibrium selection: how to get the economy out of a self-reinforcing bad state, or prevent disruptions that tip it out of a good state."*

(CGEs assume capital is fully utilised in the baseline scenario). Investments related to the green transition can only displace or “crowd-out” other economic activity in the model, making it deviate from the optimal path and thus resulting in economic costs or losses. This is a highly contested conclusion, since additional green spending is expected to benefit the economy, by allowing to employ previously idle resources (Dwesar et al., 2022a).

Models should therefore allow imbalances between supply and demand, with dynamic fluctuations. Such relaxation of Say's Law can be achieved by integrating inventories (see for example Grasselli & Nguyen-Huu, 2015, 2018; Taylor, 2004). As a corollary, such inventories would make it possible to analyse stocks and industrial (over- or under-)capacities, and refine the analysis of the risks of inflationary tensions specific to each sector. This is especially relevant in the context of ambitious ecological plans like the Green Deal, which can lead to important tensions on productive capacities (Jacques et al., 2023).

- ***Contributions of the considered models of the European Commission***

The New-Keynesian nature of E-QUEST implies a combination of nominal and real frictions, the presence of non-Ricardian households, imperfect competition and endogenous labour supply and demand with endogenous wage setting. This makes it possible to obtain public policy results less distorted by the general equilibrium framework, even while maintaining Say’s law and optimisation behaviours. Unlike most CGEs and the main Integrated Assessment Models (IAMs) that rely on perfect competition, E-QUEST gives economic policies a greater role, namely thanks to spillover integration and fewer self-stabilising or negative feedback (e.g. there is no crowding out of public spending, while GEM-E3 assumes that each investment linked to decarbonization crowds out investment in other productive sectors, leading to an increase in the price of capital and therefore negative economic consequences). Thus, the results of optimal decarbonization policies to meet GHG emission reduction targets, under conditions of recycling tax revenues into subsidies for green capital, lead to a very low expected output reduction compared to the baseline (not considering the role of green investment on growth). Such output reduction is deemed *"hardly significant given the scale of the energy transition"* (Varga et al., 2022). As for GEM-E3, although its main framework is that of perfect competition, it also offers the possibility of including imperfect competition à la Nash-Cournot, and Principal-Agent wage bargaining (à la Shapiro-Stiglitz) allowing for an "involuntary" (equilibrium) unemployment rate, and not just voluntary unemployment. Yet, the lack of endogenous fluctuations and the issue of equilibrium’s uniqueness are not addressed by E-QUEST or GEM-E3.

3.3. Neutrality and exogeneity of money

- ***Usual challenges and shortcomings faced by CGEs and DSGEs***

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

Moreover, considering money as exogenous overlooks the critical role that financial institutions play in money creation, allocation of credit, and thus in influencing economic cycles (cf. next section). A vast literature shows the endogeneity of money, including based on empirical demonstrations (e.g. Bank of England, McLeay et al, 2014; Werner, 2014; Werner, 2016 by Granger's causality). Banks do not need to collect savings in order to lend them out, and the literature tends to show that their ability to issue credit is not constrained by the central bank's money supply through a "money multiplier". In fact, commercial banks obtain money from the central bank on demand, at the rate set by monetary policy. A tradition of models have been integrating money-creating banks where they pre-finance investments (e.g. Jakab & Kumhor, Bank of England, 2015) and integrating short and even long term non-neutrality of money, and can be seen as monetary extensions of Solow's growth model (Van der Ploeg, 1985; Gertler & Kyotaki, 2011; Costa-Lima et al 2014; Dossetto & Giraud, 2023 for non-neutrality without the need for rigidities).

- ***Contributions of the considered models of the European Commission***

Regarding GEM-E3, its main structure differs from traditional CGEs. It is common for standard CGEs with financial capital to have the "allocation of savings" as a core concept. Accordingly, investment equals savings, via a market for loanable funds linking lenders in funds (agents in surplus) and borrowers of funds (agents in deficit). This implies a crowding-out effect, as the state becomes a competitor to the private sector for financing. GEM-E3, on the other hand, proposes a money market through a "World Bank" in charge of collection and allocation. It includes an option in which the money supply is adjustable, and therefore endogenous (hence not just determined by interest rates)[17], which is in line with the current knowledge on money and banking. However, this option remains often unused, in favour of the exogenous approach (e.g. Fragkos & Fragkadakis, 2022; Kriegler et al., 2024). In addition, the market clearing

[17] A comparison of European macroeconomic scenarios of energy efficiency was carried out between GEM-E3 and E3ME (Pollitt et al., 2017). One of the major differences obtained was the financial constraints in GEM-E3, leading to more pessimistic results, whereas E3ME chose an endogenous structure for money. A new comparison, including the (optional) endogenous character of money in GEM-E3 could be relevant to study the drivers of the remaining differences.

framework and the numerous automatic closures within CGEs, including in GEM-E3, diminishes the interest and effects of the endogenous representation of money.

Regarding E-QUEST, it does not explicitly include banks, financial systems or money, but does include monetary policy through a Central Bank that sets interest rates according to the Taylor rule (Taylor, 1993) and includes non-neutrality through rigidities. It should also be noted that E-QUEST is a DSGE of the European Commission, not the ECB, and is therefore primarily concerned with fiscal policies. But, as Dossetto and Giraud (2022) show, the relaxation of Say's Law (cf. *supra*) seems necessary to allow true integration of money, through the filling of imbalances between savings and debts by the issuance of new bank credits and therefore by money creation. Indeed, in the case of Say's Law combined with accounting equalities, the situation is equivalent to that where companies borrow "money" in the form of household savings and vice versa, which could quite easily be replaced by a consumer good and therefore by numéraires (Pottier & Nguyen-Huu, 2017).

3.4. Private debt and financial instability

- ***Usual challenges and shortcomings faced by CGEs and DSGEs***

The economic role of private debt, credit emission and financial markets, both in investment and in financial crises, has been widely documented (cf. work by Fisher, Minsky (1977, 1986) or Kindleberger and Aliber (1978)), from the Japanese stagnation to the 2008 GFC (Koo, 2008). High levels of private debt in the non-financial sector and rapid credit expansion can lead to financial instability and are good predictors for it (*inter alia* Claessens et al., 2012; Drehmann et al., 2012; Gourinchas & Obstfeld, 2012; BIS, 2014; IMF, 2017; Gertler & Gilchrist, 2018; BIS, 2022). They reinforce macroeconomic cyclicality, especially from the moment when real income is insufficient to repay the leveraged loan (the so-called "Minsky moment"), for example during asset bubbles (In't Veld et al., 2011). Thus, models that integrate private debt can better analyse the implications of debt accumulation and deleveraging processes on economic stability.

However, including private debt is not sufficient when such inclusion is performed in a general equilibrium framework where, by construction and assumption, stabilisers lead to market clearing, capital readjustment and therefore to the drastic reduction of modelling possibilities of financial crisis results. There is a need to include reinforcing feedbacks in the financial sector and amplification mechanisms which lead to out-of-equilibrium dynamics and therefore to massive financial crises and recessions (e.g. Krugman, 2009). Such additions are necessary if one wishes to simulate the post-2008 recession. For instance, a few New Keynesian models were modified to include not only private debt, but also further additions like a debt-limit and the deleveraging effect of shocks (Krugman & Eggerston, 2010), or monetary transactions and the possibility for default so that monetary policy can affect the real output even with fully flexible prices (Giraud & Pottier, 2016). By doing so, they show the risk of the impact of rapid deleveraging on the emergence of Fisherian debt deflation (Fisher, 1933), a liquidity trap and a savings paradox. A Keynesian multiplier also emerges naturally from the Krugman and Eggerston's model. This calls for models to take into account financial assets and their counterparts, not just real assets. These assets must be modelled as stocks, and not only flows (e.g. mortgage-based, ABS, naked CDS, etc.). This requires an integration of the financial mechanisms and drivers of these imbalances, notably banks' probability of default (PD), non-performing loans (NPL), investors' balance sheets, pure speculative assets and a distinction between real resources and financial assets, as there is sometimes a confusion between them (cf. *infra*)[18]. The intrinsic link between money and debt has been all the more exemplified in recent years by Quantitative Easing (QE) policies, and have led to proposals for "green QE" which would be worth testing and analysing in appropriate models (Dafermos et al., 2018).

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

Finally, integrating money and private debt would also prevent confusion in the interpretation of the "savings equal investments" equation as pertaining to financing whereas it actually tracks resource flows (Borio & Disyatat, 2015; Taylor, 2004). Indeed, traditional interpretation of the equation often fails to distinguish between financial savings (gross financial flows) and real savings (deferred consumption for future investment in real assets, implying the existence of inventories and stocks). It overlooks the role of the financial sector in creating credit, which can influence investment independently of real savings. Incorporating financial flows and private debt into economic models clarifies the distinction between savings and investment (Lindner, 2015; Taylor, 2016). It emphasises that investment can be financed

[18] As Werner (2016) put it, *“one of the implications of this study is that it does not make much sense to build economic theories of the financial sector, if these are not based on institutional (and accounting) realities. The role of accounting and law in economics should be increased, both in research and in the teaching of economics. This includes the role of national income accounting and flow of funds information (...), which have to be reconciled with those records of the banks. These are not only the central settlement bureau, a kind of clearing house or bookkeeping centre for the economic system (Schumpeter and Nichol (1934), p.124), but also the creators and allocators of the money supply. The reflection of empirical bank reality within theories and textbooks surely must become the new normal' in finance and economics.”*

through credit creation, which does not depend on prior savings (Kajab & Kumhof, 2015). This perspective aligns with the endogenous money theory, which posits that banks create money through lending, and, as we have seen, in order to integrate money it requires integrating money means relaxing Say's Law to allow the issuance of bank credit and therefore money to fill the savings/debt imbalance.

- ***Contributions of the considered models of the European Commission***

DSGEs and CGEs generally include private debt, while imposing a cross-cutting constraint requiring repayment in all cases (sometimes in the form of a "transversality condition"). This explicitly prevents the occurrence of Ponzi schemes and asset bubbles that must occur by other financial frictions. GEM-E3 integrates a well-developed financial system with different types of assets, and a World Bank that handles market clearing (rates can be endogenous to enable closure). The financial behaviours depend on optimal portfolio theory, and there is just a primary capital market. E-QUEST incorporates debt and financial frictions through liquidity-constrained households. Besides, the most recent versions of QUEST3 additionally include credit-constrained households. Nevertheless, despite the additions of some particularly well-developed New Keynesian models such as those mentioned above, a limitation still arises from the exogenous nature of the shocks creating the linear stationary fluctuations and from the stabilisers leading to market clearing and readjustments. Despite the presence of financial frictions, financial market imperfections and liquidity constraints in the New Keynesian literature, which often lead to an amplification of the effects of non-financial shocks (e.g. Bernanke et al., 1999; Christiano et al., 2014), there is a de facto exclusion of non-linear, non-stationary and endogenous phenomena linked to financial crises (cf. Galí, 2017). As explained by Galí, *"those phenomena include the economic and financial boom that often precedes financial crises, with a gradual build-up of financial imbalances leading to an eventual "crash" characterised by defaults, sudden-stops of credit flows, asset price declines, and a large contraction in aggregate demand, output and employment. By contrast, existing models of "financial crises" generally trace the latter to a large exogenous shock that impinges on the economy unexpectedly and triggers a large recession, possibly amplified by a financial accelerator mechanism embedded in the model."* (*Ibid.*).

3.5. Representative agent and rational expectations

- ***Usual challenges and shortcomings faced by CGEs and DSGEs***

Another important feature of DSGE and CGE models is their optimization behaviour. Indeed, they are based on constrained optimization by an agent representative of the economy (in the sense of Lucas, 1977, and Kydland & Prescott, 1982). The aim of this construction is to have a model that is robust to structural change in the economy, when macro-econometric models estimated on past time series may not be valid after such a change. It follows that, in the case of optimization, whatever the shock, agents will always optimise their situation, maximising the use of resources at any period. Beyond the fact that this assumption may be questionable in terms of realism, it does not seem appropriate to consider that any model other than those using optimization would be "*ad hoc*" and therefore “inferior” or “useless”. Optimization is itself difficult to model in a robust way (implying the need to model the desire for property ownership, laziness, more or less capital accumulation, etc., all the more so in an intertemporal way, the point of Euler’s equation). Macro-econometric models may not robust be to structural changes indeed (such as the Phillips curve of recent decades, cf. Ratner & Sim, 2022), but this can be decided, analysed and adapted on a case-by-case basis.

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

Generally, this representative agent has rational expectations[19], i.e. perfect foresight in mean (except for stochastic unexpected shocks), since the rational expectation "revolution" (Muth, 1961; Lucas, 1977) that led to the generalisation of this vision in the construction of agents' expectations. However, in addition to the vast empirical, psychological and econometric literature contributing to show that agents do not have rational expectations[20], the theory illustrates the fundamentally unstable nature of the latter in the presence of non-linear dynamics à la Solow (Cass & Stiglitz, 1969[21]; Guesnerie (2005) on eductive instability and coordination failures). Furthermore, we need to distinguish between two elements: i) the epistemic ability of agents to perfectly forecast in stochastic average and conditional on available information, and ii) the ability of agents to act on variables, e.g. for households that would anticipate future inflation perfectly, to negotiate better nominal wages perfectly to fully preserve their real wages. Even if i) were valid, this would in no way imply the validity of ii). For example, in the current inflationary context, despite relatively correct expectations of consumption price index trends on the part of households, their capacity for wage bargaining is limited, as the Phillips curve has flattened out in the last years (Ratner & Sim, 2022; Borio et al., 2023). Finally, rational expectations may be seen as eliminating the dynamic character of even a multi-period model in discrete time, since backward induction may just double the number of equations in a single period.

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[19] Nonetheless, in numerous CGEs, like GEM-E3, representative agents are myopic, which is not necessarily a more satisfactory approach.
[20] *Inter alia* Lovell (1986), Pesaran (1987), Manski (2004), Guesnerie (2005), Evans et al. (2013), Kirman (2021), D’Haultfoeuille et al. (2021)...
[21] It shows that a rational expectation inflation path is not locally stable, as any mistake by any agent in the formation of expectations will lead to another path, leading to a generic failure of agent coordination on this path.

However, expectations do play an economic role (e.g. failure of the 1981 French “Mauroy’s plan”, anchoring of inflation expectations, mimetic behaviour and instabilities on financial markets, sunspots à la Cass and Shell (1983)...). Keynes had *“animal spirits”* at the heart of his work. There is a whole range of mobilizable expectations (adaptive, or "error-in-the-variable" à la Muth (1985), which Muth introduced to go beyond the rational expectations he himself criticised). Finally, many of the results attributed to rational expectations are in fact the result of the combination of rational expectations and the Walrasian general equilibrium structure of the model (assumed existence of "natural" values, market clearing, etc.). The problem is probably not so much the (rational) expectations as their object: rational expectations are always mobilised with an output gap framework, market clearing, natural rates, etc. Conversely, if the agents of the economy believe that the economy is Keynesian... then they will behave accordingly, and the economy will be Keynesian - besides, the more rational the expectations, the higher the Keynesian multiplier (Neary & Stiglitz, 1983). We can therefore think of expectations not as a "rational" divinatory exercise, but as agents' modes of representation of the economy, and their partially prophetic impact (e.g. Hommes & Sorger, 1998, with their “consistent expectations”). Moreover, the coupling with the Ricardian hypothesis implies a neutralisation of fiscal policies - agents reduce their consumption by the same amount in intergenerational anticipation of future taxes to pay it back. Such hypothesis is empirically contested (Stanley, 1998; Wroblowsky, 2007) or at least nuanced (Nickel & Vansteenkiste, 2008). This hypothesis holds mainly thanks to (or because of) the *ad hoc* optimisation framework (Ricciuti, 2001), together with the added problem of publication bias (D’Andrea, 2022).

Some models now integrate bounded rationality, as well as suboptimal and heterogenous forecasting power of agents, with heuristics (e.g. Deak et al., 2017). Nevertheless, the intertemporal optimization goal of agents, even in a framework of bounded rationality, leads to a smoothing of the impact of economic shocks, through a modification of the capital stock seen as extremely flexible and able to be reallocated intertemporally to achieve the desired return, which can underestimate the impact of negative economic shocks (for example, underestimating the impact of capital stranding in the case of ecological transition). To overcome this problem, Heterogeneous Agents New Keynesian (HANK) models aim to replace the aggregate Euler's Equation (IS curve) with more modern theories of consumption and saving (e.g. "buffer stock" model), with a diversity of households (and sometimes firms), which are heterogeneous ex-ante and ex-post, with incomplete financial markets and imperfect risk sharing among them. It allows to relax the Ricardian hypothesis and intertemporal optimising behaviour hypothesis through hand-to-mouth agents, as empirical work tends to show that consumption has a weak sensitivity to real rate changes and strong, very heterogeneous responses to transitory income changes. See Alves et al. (2022) for a review of HANKs and Kaplan et al. (2018) for the importance of heterogeneous agents’ responses in the transmission mechanism of monetary policy[22]. However, the complexity of HANKs added on the NK DSGE

[22] The heterogeneity of agents and their behaviour, beyond realism, is an important element as it can undermine policy model analyses, for example of standard NK DSGE results, as optimal monetary policies and distributional effects are affected by this heterogeneity and differences in expectations (e.g. Gasteiger, 2014, 2017; Di Bartolomeo et al., 2016).

structure leads to important computational issues, as *"solving for the equilibria requires the use of nontrivial computational techniques, given the need to keep track of the distribution of wealth, and the hurdles arising from the presence of occasionally binding borrowing constraints. The reliance on numerical techniques for the analysis of those models often presents a challenge when it comes to understanding the mechanisms underlying some of the findings, and may thus limit their use in the classroom or as an input in policy institutions"* (Debortoli & Galí, 2017).

- ***Contributions of the considered models of the European Commission***

In GEM-E3, households are defined as a single group (i.e. a single representative household is modelled) and agents have myopic expectations (i.e. their future planning is based on current prices). E-QUEST, on the other hand, includes heterogeneity in terms of representative agents, with two classes of households. One class is forward-looking Ricardian, anticipates the future climate-related policy, has full access to financial markets and can therefore smooth its consumption in the face of shocks and the burden of policies (e.g. carbon taxes) to avoid welfare reduction. The second class is liquidity-constrained, is not forward-looking and consumes its disposable income each period (i.e. "hand-to-mouth"). This differentiation has an impact on the degree of regressivity of climate-related policies. It provides a preliminary insight into the role, for example, of the distribution of Pigouvian tax revenues on vulnerable households unable to smooth their consumption. Moreover, the JRC issued several works (Beqiraj et al., 2016, 2018) integrating boundedly rational agents whose expectations are based on heuristics, and heterogeneity in horizons (short-sighted or long-horizon forecasters).

3.6. Substitutability in production functions and increasing returns to scale

- ***Usual challenges and shortcomings faced by CGEs and DSGEs***

Economic models generally build on production functions, which take production factors as inputs (mostly capital and labour) and give production level as output. If standard models generally do not include energy into production factors, energy plays a fundamental role in the economy, which can also be conceptualised as a dissipative structure requiring energy and material flows to sustain itself (Herbert et al., 2023)[23]. If energy is rarely mentioned as a factor of production, often hidden as a residue of capital, it is included in current economic-energy-environment models usually through a nested KLME (Capital, Labour, Material, and Energy) production function. Nevertheless, three problems seem to be emerging: the low energy elasticity of GDP by construction due to cost-sharing, the high substitution elasticities between production factors derived from estimates and calibration, and the place of increasing returns to scale.

[23] Empirical literature tends to show that energy and GDP co-integrate, and that there is a causal relationship in Granger's sense from energy to GDP taking into account the other factors of production (Lee & Chang, 2008; Stern, 2011 with a VAR; Giraud & Kahraman, 2014), even if energy intensity per output unit is historically declining (Gales et al., 2007; Stern, 2011).

With regard to the first issue, one of the properties of production functions and the firm's profit maximisation program is that, in the case of perfectly competitive markets, with constant returns to scale (i.e. where the production function is homogeneous of degree 1) and without externality, output elasticity of each production factor should equal its cost share in the production[24]. Thus, when primary energy is a factor of production, the cost-share property, although implicit in the construction of the models, implies that the elasticity of energy with respect to GDP should be between 0.08 and 0.1 on average (Giraud & Kahraman, 2014), corresponding relatively well to the share of energy costs in developed countries over the last few decades. There is no a priori reason why this relationship should be robust, i.e. that technological characteristics depend directly on price factors. In this case, if the price of energy were suddenly to fall as a result of production innovation (e.g. nuclear fusion), or the discovery of new exploitable reserves, and lead to a fall in the cost share, there would be no a priori reason to consider that the dependence of production (GDP) on energy would suddenly diminish (see the rest of the subsection for the alternative hypothesis of constant returns). A number of works have estimated the GDP elasticity of energy (e.g. Csereklyei & Stern, 2015; Burke & Csereklyei, 2016), but little work has been done on the energy elasticity of GDP, with causality in Granger's sense. Ayres et al. (2013), Kümmel et al., (2008), Kümmel (2013), and Giraud & Kahraman (2014) all find much higher elasticities than the cost share offers. Preliminary estimation work seems necessary to build these relationships, so as not to underestimate the energy dependence of economic activity and therefore overestimate the ease of the energy transition. Moreover, the relaxation of the cost-share theorem is compatible with the maximisation of profit and temporal utility if appropriate technological constraints on production inputs are taken into account, in particular by adding shadow prices due to technical constraints on factor prices (*Ibid., Ibid., Ibid.*), which is an avenue worth exploring.

A second issue directly concerns the degree of substitutability between inputs in production functions (i.e. the ability to compensate for one factor of production with another while maintaining the same level of production). Those functions are generally of the Cobb-Douglas type or CES (Constant Elasticity of Substitution) type, with different elasticities of substitution (named “eos” hereafter) between production factors. The Cobb-Douglas form implies an eos of 1. It means that a constant level of production can be maintained while substituting production factors on a one-to-one basis. The CES allows to introduce values different from 1. The empirical literature tends to refute a unit value for the elasticity between labour and capital, but rather points to a value strictly below 1 in both the short and long term (e.g. Knoblach et al., 2020; Luoma & Luoto, 2010; see **Appendix B**). Maybe a more important issue is the substitutability between energy and other production inputs in nested CES production functions. Generally speaking, the value of these eos parameters have a critical impact on the transition trajectories obtained from the models: trivially, the higher the eos, the easier it is to transition, the less costly it is, and the smaller the negative impact on GDP. Indeed, high eos indicates an ease to replace the productive apparatus with a “clean” one, thus implying a low degree of path dependency for the system. This is in line with one of the common criticisms against large scale CGEs: the fact that, from a certain scale, we no longer know what determines the trajectory, whether public policy or the choice of certain parameters’ values).

[24] See e.g. Giraud and Kahraman (2014) for a formal presentation.

This ties in with Pindyck's (2017) criticism of the arbitrary calibration within the IAMs of parameters that are nonetheless crucial to the model's dynamics and results (e.g. damage functions, climate sensitivity, discount rates…)[25]. At the very least, simulation of different trajectories through ranges of parameter values and through probability density functions should be explicitly presented to express the underlying uncertainty (e.g. Bovari et al., 2019). Finally, substitutability implies the ability to reshape the technological production structure. However, it could be argued that while there is considerable scope for substitution in the choice of technology, once the productive investment has been made, the productive combination becomes complementary due to the fixed capital. This is the idea of a "Putty-Clay" structure (see **Appendix A.3.**), implying path dependency.

A third challenge, linked to the cost-share theorem, is to take into account increasing returns to scale, whereas production functions assume constant returns. Such constancy is required for the return of capital and labour to correspond to their marginal productivity by Euler's theorem on homogeneous functions, but also for the existence of a program of profit maximisation by firms. However, as Stiglitz and Stern (2023) point out in detail, the real world and production are above all made up of increasing returns, and this is all the more true in the context of the ecological transition, which concerns infrastructures and industrial sectors. Such sectors are heavy and highly capital-intensive, and therefore include elements that are partly fixed costs - not to mention the significant increasing returns in technological innovation (induced innovation, scaling up of technologies...). Moreover, the downward trend in the cost of renewable energies and the presence of scale complementarities in energy production and distribution networks, public transport and recycling - the famous *"grid"* - confirm the significant increasing returns. The impact of such returns on the macroeconomic loop, for aggregate models, is significant. For example, under-investment in R&D slows down innovation and economic development. It thus slows down the return on R&D itself, causing low-level traps (Stiglitz, 1994).

This also has an impact on the role of the public sector and on the general equilibrium framework underlying most of DSGE and CGE models. Indeed, the presence of returns to scale and, more broadly, of non-convexities in the economy (production sets and others) justifies an important role for the public sector and public investment: these non-convexities induce multiple market failures, since the Walrasian properties and optimality in the sense of Welfare Theorems are dependent on convexity assumptions (Lipsey & Lancaster, 1956; Cornet, 1988; Bonnisseau & Cornet, 1988): fixed costs and therefore monopoly risk, important externalities (Starret, 1972). The impossibility of profit maximisation, multiplicity of sub-optimal equilibria or oligopolistic and low-level equilibrium indicate *"that a sufficiently strong set of public actions could unleash a dynamic move away from the low-level equilibrium to a different, better equilibrium"* (Stiglitz &

[25] In addition, the possibility itself to estimate production functions and the values of the substitution elasticities is questioned, and may not be robust (Shaik 1974; Felipe & McCombie, 2005, 2010; Cserekly ei et al., 2016). This estimation is derived more from tautological accounting identities and statistical artefacts than from technological relationships (Felipe & McCombie, 2010). Besides, the reality also implies non-technological and institutional determinants (Knoblach & Stöckl, 2020).

Stern, 2023). Similarly, economies of scale play an important role in reducing the cost of low-carbon technologies (Verdolini et al., 2018). All these considerations are absent from a framework of constant returns with market clearing, where the state can afford to be passive and simply invest according to a fixed share of GDP (the usual approach in models where there is a public sector). There is full justification for multiple roles for the state, especially in the context of the European Green Deal, which implies regulation as well as proactive and massive public investment and coordination (see e.g. Mazzucato (2013) on the *"Entrepreneurial State"*).

- ***Contributions of the considered models of the European Commission***

Both E-QUEST and GEM-E3 integrate energy as a factor of production, through nested KLME production functions. E-QUEST, using a nested CES function, differentiates value-added and intermediates, and then capital and labour, but also general (non-energy) capital, and "clean" and "dirty" capital-energy bundles. In the "dirty" bundle, fuel-intensive capital is combined with fossil fuel, while in the "clean" bundle, electricity is required to use the corresponding electricity-intensive capital. For example, the proposed eos is 1 for general capital and capital-energy composite, 6 for clean and dirty capital/durable-energy composite, and 1 for labour and capital composite. The sensitivity analysis led by the authors (Varga et al., 2022) - a best practice that ought to be generalised - highlights that some specific parameters have a crucial impact on the results. This is especially the case for the assumed elasticity of substitution between clean and dirty energy, although this parameter is calibrated to historical trends identified by other studies (Weyant (2000) and Webster et al. (2008) for technological change; intermediate value of the values used by Acemoglu et al. (2012) for the eos and clean and dirty capital-energy bundle). The estimation problems raised above concerning substitution elasticities may also apply to these studies. In short, the higher the eos, the easier it is to transition, the less costly it is, and the smaller the negative impact on GDP, neglecting the technological constraints in the transition process. The authors of QUEST3 also acknowledge the high sensitivity of the results to the autonomous energy efficiency improvement (AEEI). This is an exogenous rate that represents technological progress alongside a learning-by-doing productivity improvement for green capital production - which in a way corresponds to increasing returns. GEM-E3 faces the same issue, the model's results being highly sensitive to the chosen eos values and to technical change rates (the FIT version of the model now also allowing for a semi-endogenous learning-by-doing technological progress, implying some economies of scale, cf. Fragkos & Fragkiadakis (2022)). These issues clearly call for this parametric uncertainty to be taken into account (cf. **Appendix A**) and for standardised and harmonised, robust empirical estimation work and meta-analyses. As Varga et al. (2022) put it, *"there remains considerable uncertainty (...) concerning these factors"*.

3.7. Inequalities

- ***Usual challenges and shortcomings faced by CGEs and DSGEs***

Inequalities in contribution to ecological degradation and in exposure to environmental damage need to be taken into account, as well as the differentiated distributional effects of climate-related public policies. Including these inequalities when modelling the ecological transition is essential for policy design, goal achievement and social acceptability (e.g. Douenne & Fabre 2020, 2022). Growing income inequalities can drive the economy towards non-desirable long-run equilibria (Giraud & Grasselli, 2021) and lead to economic and social instability, and can directly affect - or be affected by - environmental policies. For example, subsidies for renewable energies may disproportionately benefit affluent households, who can afford the initial co-investment. Similarly, the carbon tax on firms may be passed on to selling prices and therefore proportionately more on the purchasing power of low-income classes, whose share of spending on carbon-intensive goods and services is higher than that of the affluent classes. Finally, capital stranding and changes in employment resulting from the ecological transition are likely to have differentiated welfare impacts, which need to be taken into account, especially as the European Green Deal pledges to *"leave no-one behind"*[26]. Moreover, an institutional literature demonstrates the interconnection, both between European regions and within countries, between populations with lower socio-economic conditions and the higher exposure to environmental degradation (WHO, 2019; EEA, 2017, 2019; Ganzleben & Kazmierczak, 2020). One should note that integrated assessment models (IAM) incorporating intra-regional inequalities (e.g. the Nested Inequalities Climate Economy (NICE) model (Dennig et al., 2015) which is based on Nordhaus's Regional Integrated Model of Climate and the Economy (RICE model, Nordhaus & Sztorc, 2013)) lead to a social cost of CO2 and therefore an "optimal" price of CO2 that is strictly higher than those without inequality. However, the usual models do not generally offer a high degree of precision in terms of the redistributive effects of social and fiscal policies, even though they attempt to measure and evaluate welfare and the impact of policies on the latter. It is nonetheless essential to explicitly model different income groups and differences in terms of concrete economic position (and not only in terms of access to liquidity), to assess the distributional effects of any given economic policy, or to better represent the role of income distribution and propensity to consume on i) economic activity (Kalecki, 1954); ii) the (un)stability of the economic system (Giraud & Grasselli, 2021); iii) household debt accumulation (Stiglitz, 2012). It is also important to represent intra-group inequalities, as for example progressive inter-group policies (e.g. Pigou-style carbon taxes with income redistribution) can sometimes lead to an increase in these intra-group income inequalities (horizontal equity is often less taken into account in welfare analysis than vertical equity, see for example Fischer & Pizer, 2019). While canonical CGEs and DSGEs do not represent agents' heterogeneity, initial advances have been made in attempting to incorporate inequalities, mainly in DSGEs (with HANK, Heterogeneous-Agent New Keynesian Models, going beyond DSGEs with 2 types of households, e. g. Lee, 2021 on the distributive impact of

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[26] The European Union commits to provide *"a high level of protection and improvement of the quality of the environment"* (Treaty of Lisbon, 2007)

Quantitative Easing)[27]. Yet, such advances still seem insufficient in view of the economic role of inequalities and of the important distributional impacts of environmental damage and green policies.

- ***Contributions of the considered models of the European Commission***

In GEM-E3, there is a distribution of income through the Social Accounting Matrix (SAM), but only between the different types of agents (households, firms, public sector, external sector, national banks and a World Bank) and between production factors (the profit and wage shares). There is no differentiation of income within each class of agents. Moreover, households in the GEM-E3's SAM are a single social group (single representative household). The distributional effects of policies are therefore only between the types of agents in the national accounts. Nonetheless, it should be noted that the NAVIGATE project[28] (Kriegler et al., 2023) expanded GEM-E3-FIT in their study to represent ten income classes in EU member states. In E-QUEST, inequalities and different income/wealth groups are not explicitly modelled, but two proxies attempt to gain initial insights into inequalities and distributive effects: i) a differentiation of labour demand and supply between three skill levels: low-, medium- and high-skilled, with an elasticity of substitution set at 1.7 (from Acemoglu and Autor, 2011); ii) the differentiation of households into two types as previously described, a Ricardian with access to financial markets, and a liquidity-constrained unable to protect themselves from the policy burden by accessing financial markets. The second household type are therefore more vulnerable to the welfare reduction associated with climate-related policies, as they cannot redirect their savings from investment to consumption. Varga et al. (2022) show that regulation disproportionally hurts the liquidity-constrained households, and that carbon taxation, if applied in combination with the recycling fiscal revenues, can significantly mitigate households' welfare loss linked to the ecological transition (without mentioning the potential growth effects of green investments). A fine-tuned integration of inequalities seems all the more important in the context of general equilibrium modelling, the aim of which is to study the progressive or non-progressive nature of policies (e.g. the progressivity of environmental taxes in the case of redistribution of the captured income)[29].

3.8. Damage functions

- ***Usual challenges and shortcomings faced by CGEs and DSGEs***

If there is indeed an impact of the economy on the environment, there is also feedback from the environment to the economy (IPCC, 2022), a principle formalised in the concept of

[27] HANKs attempt to build a correspondence between behaviour and socio-economic classes, where "hand-to-mouth" agents have low liquidity and high marginal propensity to consume, and middle classes build precautionary saving to stay away from credit limit - even if their wealth distributions do not necessarily correspond neither to the savings nor to the capital of the top deciles.

[28] Next generation of AdVanced InteGrated Assessment modelling to support climaTE policy making.

[29] And, more generally, to study redistribution-dependent policy transmission, as emphasised by Auclert (2019) for example on monetary policy transmission.

"damage functions", at the heart of Integrated Assessment Models. While debates on the impact of a temperature anomaly corresponding to +°5C at the end of the century (i.e. the IPCC's RCP8.5 scenario) lead to different predictions (from about -1% to -5% of world GDP for the most optimistic (e.g. Nordhaus & Sztorc, 2013) to -80% for the most pessimistic (e.g. Dietz & Stern, 2015), none is zero (cf. Howard & Sterner, 2017, for a meta-analysis). Moreover, the more realistically these functions are constructed, i.e. with convexity of effects, feedback not only on production but on productive capital and therefore on growth, and catastrophic and extreme climatic events, the more pessimistic the results, and the higher the social cost of carbon[30] and the optimal carbon tax. This issue is crucial in terms of public policy design and of the budgetary and fiscal capacity to implement them: failure to take into account or underestimate these major uncertainties in terms of damage can lead to suboptimal efforts (Pindyck, 2013). It also raises the question of the type of policy: the only policies tested are often mitigation policies, and not adaptation policies, which will nevertheless be necessary (IPCC, 2022) as acknowledged by the European Commission through the creation of the Climate-ADAPT platform. An integrated assessment work should necessarily and presumably always integrate environmental feedback, both for forecasting and public policy design. What is more, the climate damages should be modelled as sector-specific and bottom-up as possible, since aggregate functions struggle to provide reliable estimates of these damages (see Woillez et al. (2020) on the non-ergodicity of damage functions).

Generally, the fundamental criterion to compare simulated policies in models is a purely economic one, the change in "welfare". This single objective is expressed in monetary terms (often with consumption as a proxy) and is very partial, with its computation relying on normative discount rates, i.e. with a marked preference for the present (see **Appendix B.5**). An alternative to this, however, without over-complexifying the model, is to test the robustness of "optimal" scenarios, by integrating other criteria, and investigating whether the results are viable for these dimensions too. For example, at a global level, Ferrari et al (2022) test the scenarios of the RICE model (the regionally disaggregated DICE model) on different objectives (welfare for economic, temperature for climate, cross-country inequality for social) to find a "compromise" scenario where each dimension is not necessarily maximised as it would be independently, but lies within viable ranges. This generally leads to lower emissions than in simple "optimal" welfare scenarios. Finally, if cost can be measured by DSGEs and CGEs, it is more complex to measure co-benefits of climate policies such as avoided financial instability or improved balance thanks to reduced fossil fuels imports. The complementary models proposed in **Section 4** attempt to measure these co-benefits for inclusion in the trade-off (Dafermos et al., 2018; Gourdel et al. 2022). Similarly, the authors of E-QUEST, while comparing price-based policies (e.g. carbon pricing) and regulation-based ones, acknowledge that standard macroeconomic models cannot capture the potential benefits of regulatory policies, e.g. the acceptability linked to their perception compared to the one of a carbon tax.

[30] The social cost of carbon (SCC) measures the external cost of carbon combustion, with all its externalities on society. The carbon tax is thus the taxation of carbon at its full price, the SCC. See Pindyck (2013) for a systematic critique of the arbitrary, *ad hoc* nature of Integrated Assessment Models (IAMs) and the resulting SCC.

- ***What about the considered models of the European Commission?***

It should be noted that there are no environmental feedback effects i.e. economic damages induced by environmental degradation in public versions of E-QUEST so far. Instead, impacts of climate policy are evaluated according to a baseline without damage[31] (the authors state that this is left to future model extensions and that they examine the role of damage functions in a forthcoming extension of the model). E-QUEST focuses only on the direct economic impact of green policies, while assuming that the Rest of the World (excluding the EU) does not implement climate policies: *"overall, the scenarios have limited effects on GHG emissions in the rest of the world. [...] two counteracting effects result in an almost unchanged aggregate emission from the rest of the world."* (Varga et al., 2022). Nevertheless, despite the absence of damage functions, the authors state that their result *"is relative to a baseline without accounting for the economic cost of climate change. If no action is taken, the economic costs of climate change will increase over time, especially in the second half of this century, becoming substantial (...). Mitigation policies at a global level could avoid these damages and yield net output gains."* (Varga et al., 2022).

Surprisingly, environmental feedback effects are neither present in the suite of models centred around GEM-3E. Damage estimates in GEM-E3, derived from global warming, rain acidification and air quality, come from another interdisciplinary project, ExternE for Externalities of Energy (EU Commission, DG Research and Innovation, 2005), last updated in 2005 to our knowledge. This project estimated the damage caused by energy production and consumption in the USA and many European countries. A highly relevant element is the inclusion of cross-border effects. However, this damage only concerns energy production and consumption. Other dimensions of environmental degradation ought to be taken into account, such as biodiversity (cf. **Appendix B**). Above all, even if some damages with their monetary valuation are included, these do not impact the structural determinants of growth, thus there is no full feedback loop.

The European Commission's models, however, could make use of the results of the successive JRC PESETA projects (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis - see Ciscar et al. (2011, 2014, 2018) for the previous ones, the current one under development being PESETA IV). These projects include the simulation of physical climate damages with monetary (e.g. Value of Statistical Life) and non-monetary metrics. The economic impacts based on environmental trajectories are calculated with a static CGE (constant GDP and population). In PESETAs I-III, the impacts of climate change are represented on the current economy, without taking into account feedback on productive capital and hence on long-term economic growth[32]. In comparison, the ACP (American Climate Prospectus) uses a dynamic approach for climate impacts on capital accumulation (see Ciscar et al. (2019) for a detailed comparison).

[31] It uses PRIMES energy simulations and the WIOD dataset to compute emission intensities.
[32] With the exception of coastal and river flooding.

3.9. Feedback of energy and other resources as production constraints

- ***Usual challenges and shortcomings faced by CGEs and DSGEs, including the considered models of the European Commission***

Both E-QUEST-3 and GEM-E3 couple their economic module with an energy module giving a more (GEM-E3) or less (for E-QUEST-3) detailed description of the energy production system. This is essential for analysing the dynamics of the energy transition, but the integration is only one way: the energy module can inform on the energy price, but there is no feedback on the economic module in terms of potential constraints on production (by assuming that resources will always be available). Indeed, due to high substitutability values of inputs in production functions (see **Section 3.6** above) and since the energy module only impacts the economic module through the energy price, the feedback loop from the energy sector onto the rest of the economy is not complete, not taking into account the accessibility of resources modulo price. Indeed, the accessibility of fossil energy resources (oil, gas, coal) is measured through the Energy Return On Investment (EROI), the ratio of the energy produced to the energy used in the process of producing it. This ratio is steadily decreasing (Court & Fizaine, 2017; Brockway et al, 2019), as the resources that are easiest to extract are generally exploited first. A related concept is that of net energy, i.e. energy production net of the energy required by the energy sector itself. The impact of the decreasing EROI and net energy available for society is generally overlooked in economic models, even in integrated assessment models, even though this constitutes a major risk which should be taken into account in transition planning (Delannoy et al., 2023).

Besides, models must take into account the stocks and flows of matter and physical resources other than energy. Both the economic system and the ecological transition depend on a number of resource flows whose extraction, production and import capacities vary and must be endogenised. An overlooked issue in economic modelling - but otherwise largely documented - is the availability of metals and minerals (Court & Fizaine, 2015; Meinert et al., 2017; Vidal et al., 2019). Some of them are vital for the ecological transition and recognized as a potential bottleneck for the implementation of the European Green Deal (IEA, 2021; Pulido-Sánchez et al., 2022). Thus, the integration of economic models into a larger bio-physical system is lacking, while the European Union is in a risky position in terms of resource availability (Auzanneau, 2020; Auzanneau et al., 2022).

3.10. International trade, finance and flows

- ***Usual challenges and shortcomings faced by CGEs and DSGEs, including the considered models of the European Commission***

It is essential to dispose of one modelling tool having an open-economy framework, especially given the interdependence between the European Union and the rest of the world in terms of trade, resource, energy and financial flows. This is all the more relevant in the context of the European Green Deal, dependent on and impacted by bilateral material flows, exchange rate and current account constraints, and given the cross-border effects of policies such as carbon taxation, which can entail important impacts on countries outside of the EU (e.g. fossil fuel reserve stranding for Southern exporting countries).

For example, GEM-E3 proposes an international trade framework. It bases its bilateral trade flows on the Armington hypothesis (1969), representing the imperfect elasticity of substitution between goods from different countries as a standard assumption. Total demand in each country is optimally allocated between domestic and imported goods according to this imperfect elasticity of substitution. However, this relationship has no reason to be fixed, and may well be dynamic. Moreover, there are very few econometric estimates of these elasticities, e.g. Shiells and Reinert (1994). As an answer, the Global Multi-Country (GM) model (Albonico et al., 2019) adds endogeneity, as the elasticity of substitution can be influenced by productivity shocks or changes in trade conditions. But as GM is not oriented towards environmental policy analysis (while still including oil and gas), it lacks resource constraints and physical phenomena in the RoW such as declining EROIs or variation in agricultural production and yield, which must be taken into account in terms of physical interdependence.

Above all, the main obstacle to capturing international mechanisms seems to be an assumption about the interactions between current account dynamics and financial flows. Firstly, GEM-E3 proposes two options: either a fixed current account and an endogenously determined interest rate (a rise in energy costs in the domestic country cannot be offset by a shift towards imports, and the interest rate therefore rises), or a flexible current account and a fixed interest rate. But both can vary, and need to be endogenous together. More generally, these models are based on a simplification that confuses financial flows and real resources in the accounting equation "Current Account = Savings – Investments" (Borio & Disyatat, BIS, 2015), and therefore between current account and net financial flows, at the heart of the intertemporal view of current account. Imports and exports represent real flows, different from net financial flows.[33] Thus, *"contrary to a common view, current account patterns are largely silent about the role a country plays in international borrowing, lending and financial intermediation - aspects that must be at the core of the understanding of any financial crisis."* (*Ibid.*). For example, the private productive sector of a country with a trade deficit can theoretically finance itself through its banking system, by issuing credit *ex nihilo* (even though such money creation has an effect on inflation, exchange rates, and creates other challenges). Thus, in GEM-E3, the borrowing/lending is in real terms simply the balance of trade, preventing a realistic and analytical representation of international financing mechanisms.

Beyond the distinction between trade flows and financial flows (calling into question the role given to the "global saving glut" (Bernanke, 2005) in inducing very low interest rates and in fuelling credit expansion in countries with a current account deficit (Borio & Disyatat, BIS, 2011)), the agents holding the debts are also an issue. Following QUEST3, in the GM model only the RoW bond is traded internationally (RoW agents can only invest in domestic bonds

[33] Part of the representation of the economy's financial structure in models is often to ensure the macroeconomic closure of the S – CA = I condition.

while European households can invest both in national and foreign bonds, equivalent to the reduced form of a world bank lending domestically and abroad in RoW. This creates a bias in favour of European investors that can distort the analysis of capital flows and reactions to economic and financial policies. Similarly, limiting investment options for RoW agents could lead to underestimating the risks of financial contagion and economic interdependence between Europe and the rest of the world, thus altering interest rate dynamics. Finally, about 95% of Japan's sovereign debt is held by Japanese nationals (so if need be, the Central Bank of Japan can refinance the State), while about 60% of France's and 30% of Italy's public debt is held abroad. The breakdown of debt between domestic and foreign ownership is important. The more domestic the ownership, the less the question of sustainability depends on a simple threshold, but also on other parameters specific to the domestic macroeconomic situation, and therefore possibly leading to more fiscal space. Foreign debt indeed "matters more" than domestic debt (Gros, 2013). For example, the adjustment variable during a crisis is less the budget deficit than international balances, particularly in cases where foreign creditors are unwilling to provide additional resources and external debt must be serviced[34]. This is all the more relevant since it seems that supply of foreign funds is not a monotonic increasing function of the interest rates, but is affected by sudden rise of risk premia and credit rationing (*Ibid.*).

3.11. The need for a multi-sectoral approach and cross-sector dynamics, both for goods and capital

- ***Usual challenges and shortcomings face by these model classes***

Standard DSGEs usually simplify the economy into a limited number of sectors or, in some extreme cases, represent the economy as a single representative sector, producing one type of good with one type of capital. They thus lack a comprehensive multi-sector framework and intersectoral dynamics. Nonetheless, an ecological transition will impact different sectors in different ways. Without a multi-sectoral approach, there is a risk of missing out both on the carbon-intensive sectors that will suffer the most from capital stranding and job losses, and on the green sectors that will benefit in terms of growth and job gains. The risks of shortages, supply constraints and inflationary pressures are also likely to be underestimated. Finally, the technological options, energy intensity and carbon intensity specific to each sector need to be taken into account.

About CGE modelling, even if one of its core principles is to have a high level of disaggregation, the interactions between sectors are generally too simple, based on substitution elasticities often derived from a simple calibration. Moreover, the presence of multi-sectoriality implies neither the presence of heterogeneous capital (i.e. multi-sectoriality of production but not of productive capital), nor the explicit presence of the inter-sectoral dynamics that would devolve from it. Yet, intersectoral interactions and dynamics are complex. Such complexity can span for

[34] It should be added that the pressure for state support for foreign-owned private debt in the event of a crisis is obviously less strong than for domestically-owned debt, as demonstrated by the Icelandic banking crisis of 2008.

example from joint production systems to bidirectional and cyclical supply chains (where upstream sectors depend on intermediate goods produced by downstream sectors), as conceptualised by economists like Sraffa (1960) and Pasinetti (1980). These dynamics are crucial for understanding the ripple effects of economic policies and shocks across different sectors, where changes in one sector can have significant and non-linear impacts on others.

In addition, those requirements apply not only to goods but also to capital, as the question of the energy and CO2 intensity of productive capitals is crucial, and as the Cambridge controversy (cf. Robinson, 1953; Samuelson, 1966) showed us that real aggregate capital (mixing lands, factories and computers) does not have a *meaning*, especially in the aggregate production function (see Harcourt (2012) for a review of this important controversy). For example, Farmer and Wendner (2004) show that the definition of capital and the way it is aggregated lead to very different results in dynamic CGEs, depending on whether capital aggregation is based on fixed shares or is derived, or whether capital is heterogeneous. In the context of the ecological transition, Lennox and Parrado (2015) show the limitation of CGEs by the fact that carbon-free energy technologies are generally embodied in capital goods, while usual CGE models cannot capture capital-embodiment of sector-specific technologies. As Lennox and Parrado (2015) explain, "*aggregating productive sectors and investment goods eliminates channels whereby specific technological changes are embodied in specific capital stocks*".

Thus, there is a need for models to incorporate a multi-sector framework that comprehensively covers both production aspects (like productive capacities, technological mixes, energy efficiencies, resource intensities) and macroeconomic elements (such as investment behaviours, profit rates, labour market dynamics, and sector-specific inflationary trends). This approach is essential for developing effective institutional planning and investment policies.

Finally, the temporality of the ecological shift is an important issue in terms of scenario building. While capital accumulation is modelled as the sum of each year's investments, there are delays between investments and the finalisation of the productive capital (from 6 months to 10 years), so between I and ΔK (Kalecki, 1935; Matsumoto & Szidarovszky, 2011)[35]. It is never taken into account while crucial, and can lead to bifurcations and radically different scenarios and trajectories. On the role of time and path dependency in EEE modelling, see the multi-sector IMACLIM-R model of the CIRED (Sassi et al., 2010)[36].

- ***Contributions of the considered models of the European Commission***

Unlike standard DSGEs, E-QUEST offers sector-based disaggregation to address climate-related measures targeting clean and dirty sectors, with a seven-sector framework, including a plurality of capital goods. E-QUEST encompasses two energy provider sectors

[35] An insight already present in the seminal RBC paper of Kydland and Prescott (1982), rightly named "Time to Build and Aggregate Fluctuations".
[36] More generally, Grandmont (1977), and Champsaur and Deleau (1990).

(fossil fuels and electricity) and three capital producing sectors (fossil fuel-intensive capital, electricity-intensive capital, and non-energy related capital). The rest of the economic activities are further divided into two sectors depending on their emission intensity. The purpose of such a breakdown is to study the impact of the burden of emissions' reduction on multiple sectors, not only on the energy sector. While the authors acknowledge that this first level of disaggregation is lower, either in regional or sectoral terms, than the input-output interdependence constructs of CGEs such as GEM-E3, it nonetheless allows to describe initial primary transmission mechanisms.

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In conclusion, we attempted to draw up a list of challenges faced by economic modellers working on the ecological transition. The models currently used by the European Commission on this subject bring some innovations, adaptations, and partial answers to those common challenges. We argue that a diversification of models' classes can lead to more comprehensive and systematic responses to the challenges presented in this section. This is also due to the fact that, as Dow (2021), Storm (2021) and Blanchard show, New Keynesian extensions and additions to CGE and DSGE are applied on an already existing structure, leading to limits in the scope of additions, complexity and tractability. Models with a different core structure therefore seem to have all their place to complement the macroeconomic models currently used by the EU Commission.

What is more, the introduction of non-linearity into the analysis of reality greatly reduces the possibilities for modellers to apply optimal control methods (Châtelain & Ralf, 2020; Pottier, 2014). Faced with this, as the former chief economist of the Bank of England, A.G. Haldane, reminds us (Haldane & Turrell, 2018), there is an imperative for humility and openness, collective and interdisciplinary work, cooperation and dialogue, diversification and mobilisation of existing resources - and there are plenty of them, in institutions as well as academic laboratories.

The following section aims to present such complementary modelling tools and their welcome added-value, with contacts and direct contributions from the research teams responsible for them. A few additional challenges are presented in **Appendices A** and **B** (e.g. climatic and economic uncertainty, estimation and calibration issues, inclusion of services, etc.). See also Giraud and Valcke (2023a,b) for a comprehensive call for a research program on macroeconomics and the environment in the face of current scientific challenges.

Section 4 - Complementary and alternative contributions

It was underlined in the previous section that there are many challenges and limitations to the macroeconomic modelling of the ecological transition by CGE and DSGE models, widely documented in the literature. It has also been shown that the models currently used by the European Commission provide a partial response to them. These challenges can be summarised as follows:

1. Output gap framework;
2. Equilibrium framework and Say's Law;
3. Neutrality and exogeneity of money;
4. Private debt and financial instability;
5. Representative agent and rational expectations;
6. Substitutability in production functions and increasing returns to scale;
7. Inequalities;
8. Damage functions;
9. Feedback of energy and other resources as production constraints;
10. International trade, finance and flows;
11. The need for a multi-sector approach and cross-sector dynamics, both for goods and capital

Robustness to criticisms:	1	2	3	4	5	6	7	8	9	10	11
DEFINE	✔	✔	✔	✔				✔	✔		
DSK	✔	✔	✔	✔	✔			✔			
E3ME	✔	✔			(✔)	✔	✔			(✔)	✔
EIRIN	✔	✔	✔	✔	(✔)	✔	✔			(✔)	
ESTEEM										✔	✔
EUROGREEN	✔	✔	✔	✔			✔				
GEMMES	✔	✔	✔	✔		(✔)		✔		✔	(✔)
MEDEAS						✔		✔	✔		✔
WILIAM	✔	✔	✔	✔	(✔)	✔	✔	✔	✔		✔

Table 1. List of advanced alternative models. A check mark indicates that the model is robust to the corresponding critique from **Section 3**. A check with brackets indicates that the model is partially robust to the critique. The listed models present an important variety of sizes and scopes.

Hence, research teams have been working around Europe at designing alternative macroeconomic models which bring contributions in response to those needs and requirements. In particular, the perspective of the ecological transition and of the numerous associated challenges has fostered the development of a very dynamic community of researchers in the field known as *Ecological Economics*. Several empirical models of this field have now reached a sufficient level of maturity to be directly employed by the European Commission, in complement to the currently used DSGEs and CGEs. **Table 1** draws up a list of such empirical models, assessing for each model its robustness to the critiques from **Section 3**. Those models present an important variety of sizes and scopes. **Table 2** then lists the scientific literature related to these empirical models and gives the contact of the authors who developed them and are ready to collaborate.

Model	**Scientific literature**	**Corresponding author**
DEFINE	Dafermos et al. (2017, 2018) Dafermos & Nikolaidi (2019, 2021, 2022) George & Dafermos (2023)	yannis.dafermos@soas.ac.uk
DSK	Lamperti et al. (2018, 2019, 2020, 2021) Lamperti & Roventini (2022)	francesco.lamperti@santannapisa.it
E3ME	Dwesar et al. (2022b)	hb@camecon.com
EIRIN	Monasterolo & Raberto (2018, 2019) Gourdel et al. (2022) Ranger et al. (2022) Gourdel & Monasterolo (2022) Dunz et al. (2023)	i.monasterolo1@uu.nl
EUROGREEN	D'Alessandro et al. (2020) Cieplinski et al. (2021)	simone.dalessandro@unipi.it
GEMMES	Yilmaz & Godin (2020) Woillez & Espagne (2022) Truong et al. (2023) Yilmaz et al. (2023) Godin et al. (2023)	godina@afd.fr
MEDEAS	Nieto et al. (2020a) Nieto et al. (2020b) Capellán-Pérez et al. (2020) Blas et al. (2018) Álvarez-Antelo et al. (2018)	jaime.nieto.vega@uva.es inigo.capellan@uva.es
WILIAM	LOCOMOTION project reports	inaki.arto@bc3research.org inigo.capellan@uva.es
ESTEEM	Magacho et al. (2023a) Magacho et al. (2023b)	magachog@afd.fr godina@afd.fr

Table 2. List of advanced alternative models. For each model, the related scientific literature is given, together with the contact of the authors.

In the following paragraphs, the models presented in **Table 1** are further detailed. The families of models to which they belong are described, and each model is characterised in terms of its specific features, aim and scope.

4.1. Stock-Flow Consistent modelling

A class of models has developed that addresses several of the shortcomings listed in **Section 3**: the Stock-Flow Consistent (SFC) models. SFC models have their roots in the development of the flow of funds analysis by Copeland (1952). They emerged as a structured theory following the work of Nobel prize James Taubin (Backus et al., 1980). Since the financial crisis of 2008 especially, SFC modelling has grown into a blossoming literature (Caverzasi & Godin, 2015). Even more interestingly, SFC models have for several years now been widely used as a tool of macroeconomic analysis for the ecological transition (Svartzman et al., 2019; Carnevali et al., 2019). SFC models are characterised by two main elements: a distinct accounting framework and behavioural equations. The accounting framework is based on a set of matrices that reproduce the balance sheets and transactions of each of the sectors that make up the economy. The behavioural equations, in turn, model all the transactions that are not directly determined by the accounting structure of the economy. The main advantage of SFC models is that they ensure the overall consistency of the modelled economy[37]: the outputs of one sector are always the inputs of another sector, and similarly the liabilities of one sector are always the assets of another sector (Godley & Lavoie, 2007; Jacques et al., 2023)[38].

The two first points of criticism detailed in **Section 3** (**output gap framework; equilibrium framework and Say's Law**) are intrinsic to the optimization, equilibrium framework of DSGEs and CGEs. As explained, the related challenges, although understood and tentatively dealt with, cannot be fully addressed while staying in such a framework. On the contrary, the primary reliance of SFC models on an accounting framework gives to this class of models a rather positivist approach to the economy. Their behavioural equations describe macro-trends in the economy or dynamic behaviours of economic agents. They do not rely on any equilibrium assumption or on systematic optimization and can represent fluctuations endogenous to the economic system, instead of being triggered by exogenous shocks. This allows SFC models to be robust to our two first points of criticism. Then, the two following critiques made in **Section 3** (**real economy model, neutrality and exogeneity of money; absence of private debt and financial instability**) stem from the limited treatment of the monetary and financial systems in

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[37] The difference between the Stock-Flow Consistent accounting framework and Social Accounting Matrices (SAMs, the usual accounting frameworks of CGEs) is that the latter generally do not include financial assets, private debt and money, focusing solely on the real economy. While SAMs include information about transactions (flows), they do not focus explicitly on the accumulation of stocks (like wealth, debt, assets), hence introducing a static (for SAM) versus dynamic (for SFC, with historical time) difference.

[38] In addition, some SFC models (e.g. cf. Dafermos et al., 2017) also introduce Georgescu-Roegen's flow/fund distinction (1971, ch. 9; 1979; 1984) which is a core principle of ecological economics. "*The stock-flow resources (non-renewable energy and material resources) are transformed into what they produce (including by-products), can theoretically be used at any rate desired and can be stockpiled for future use. The fund-service resources (labour, capital and Ricardian land) are not embodied in the output produced, can be used only at specific rates and cannot be stockpiled for future use. Crucially, these types of resources are not substitutable: they are both necessary for the production process.*" (Dafermos et al., 2017. See also Mayumi, 2001; Daly & Farley, 2011). This helps to refine the understanding of the role of each physical element in the productive process - and also to differentiate their destruction in the context of damage functions and negative feedback from the environment on these resources.

most DSGEs and CGEs. SFC models, on their part, were developed with the specific aim to allow finance, the real economy and the interactions between the two to be represented in a single framework, and thus to overcome such challenges (Godley & Lavoie, 2007).

An advanced, empirical SFC model is the EIRIN model (Monasterolo & Raberto, 2018, 2019). It was specifically developed to analyse the direct and indirect impacts of climate risks, green fiscal and finance policies on the real economy and on finance. EIRIN is an open economy model composed of a limited number of heterogeneous agents and sectors of the real economy, public and private finance. Agents are heterogeneous in terms of sources of income and wealth, access to financial markets, access to capital, skills and GHG emission intensity. Thanks to this, the distributive effects of green policies are assessed in terms of income inequality and wealth concentration (Monasterolo & Raberto, 2018). Agents are endowed with behavioural decisions based on empirical information and heuristics. They formulate decisions based on adaptive expectations. Firms' investment decisions are endogenous and based on expected production plans and the Net Present Value (NPV), optimising their expected return. Agents and sectors interact through a set of real markets (including labour, energy, services, tourism, capital goods, consumption goods, raw materials, etc.) and financial markets (green/brown bonds, equity, loans) thus allowing to assess the impact of both endogenous and exogenous climate related shocks. The way how productive firms progressively shift their investments from brown to green assets, in reaction and in anticipation of several types of public policies, is explicitly modelled. Besides being robust to the first four points of criticism of **Section 3**, to address **inequalities** and to integrate the role of **agents' expectations** in economic phenomena, EIRIN also addresses the modelling issues related to **substitutability of inputs in production functions**. The EIRIN model includes a Leontief production function with no substitution between labour, capital and raw materials (encompassing fossil fuels). This allows to better account for path dependency and to incorporate the importance of the firms' investment decisions on the short- and medium-term. Having raw materials and energy sources (fossil fuels and renewables) that enter the production function and the NPV further allows the model to assess how resource and carbon- intensive production and consumption affects the performance of the economy. EIRIN has already been applied by several central banks and international financial institutions to complement standard macroeconomic approaches in the assessment of the impacts of climate risks in the economy and finance. These include the analysis of the double materiality of climate risks in the euro area in collaboration with the European Central Bank (Gourdel et al., 2022a); the assessment of compounding COVID and climate physical risks in emerging markets and developing economies with the World Bank (Ranger et al., 2022; Dunz et al., 2023); the impact of cross-border climate risks on sovereign fiscal and financial stability (Gourdel et al., 2021; Gourdel & Monasterolo, 2022) within the G24-V20- Task Force on Climate Development and the IMF.

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

4.2. Inclusion of climate damages

At this point, two challenges from **Section 3** which have not been addressed yet are the ones on **damage functions** and **feedback of energy and resources as production constraints**. A model particularly robust to these critiques is the DEFINE model (Dafermos et al., 2017, 2018; Dafermos & Nikolaidi, 2019, 2021, 2022). DEFINE encompasses economic, monetary and financial stocks and flows on the one hand, and physical stocks and flows on the other hand, based on the laws of thermodynamics. The production functions are Leontief-type (**imperfect substitutability**). In addition to capital and labour, inputs to the production function include extracted materials, recycled materials and energy, with distinctive intensities depending on the type of capital (i.e. green capital vs. conventional capital). The environmental feedback loops on the economy are incorporated through different channels. First, a climate damage function is included, similar to the ones of standard IAMs. The difference here is that climate change does not impact production directly, but rather the resources used as factors of production. Second, the climate damage function does not only impact production, but also the different components of aggregate demand. Third, the exhaustion of natural resources (fossil fuels, minerals) used as factors of production in the model can result in supply constraints. The impacts of environmental degradation are therefore included both from a supply and demand perspective (Dafermos et al., 2017). The DEFINE model is then used to study the environmental, economic and financial impacts of numerous green policies, be it carbon taxes, green subsidies, green public investment (Dafermos & Nikolaidi, 2019), financial regulation tools for climate-related financial risks (Dafermos & Nikolaidi, 2021), a green quantitative easing programme (Dafermos et al., 2018) or sufficiency policies (Dafermos & Nikolaidi, 2022). Such policies are not analysed in a cost-benefit or optimisation perspective and no social discount rate is used. Instead, *"policies are evaluated based on their ability to achieve high well-being in a way that does not cause a collapse of the highly interconnected macroeconomic, financial and ecological systems (in both the short run and the long run)"* (Dafermos & Nikolaidi, 2019).

DEFINE's scope is currently global, but the model or some of its components could easily be adapted to the EU perimeter. A UK version of DEFINE is under development at the moment (George & Dafermos, 2023).

Moreover, the French Agency for Development (AFD) developed an advanced and highly detailed SFC model: the GEMMES model. GEMMES is an SFC model in continuous time. Drawing from the Goodwin-Keen model (Goodwin, 1967; Keen, 1995) and its ecological extension (Bovari et al., 2018, 2019), the GEMMES canonical model (Yilmaz & Godin, 2020) led to the development of various country-specific versions, for example for the case of Vietnam (Woillez & Espagne, 2022); Truong et al., 2023), Tunisia (Yilmaz et al., 2023) or Colombia (Godin et al., 2023). The GEMMES model represents a small, developing economy with an open financial account and flexible exchange rate. It allows to study how fluctuations in major financial centres can induce boom and bust episodes in such a small open economy, via portfolio flows and cross-border lending (Yilmaz & Godin, 2020). The accumulation of foreign exchange reserves and fluctuation of exchange rates are included in a robust way in the model, with clearly identified causality mechanisms, encompassing the **role of agents' expectations**. Real and financial flows are distinguished from each other and the interdependence between both is modelled. The GEMMES model therefore adequately answers the **international trade, finance and flows** critique from **Section 3**. GEMMES was also coupled with several biophysical models, namely crop production models under different climate scenarios (Yilmaz et al., 2023) and energy models (EnergyScope for Colombia and LEAP for Morocco & Vietnam - ongoing work). Moreover, Woillez and Espagne (2022) added to GEMMES, under different climate scenarios, various sectoral **climate damages** which are interconnected and lead to an aggregate damage which is higher than the sum of its parts. Thus, GEMMES has been extensively used to study how climate change and/or decarbonisation policies impact trade, resource, energy and financial flows. Importantly, GEMMES not only assesses the impacts of adaptation/decarbonisation policies, but also the impacts of the alternative ways to finance these. The GEMMES model considers transitions as processes of structural change, leading to disequilibrium dynamics (stranded assets, creative destruction, etc.). Thus, it uses procedural rationality and asymmetric information. The model also includes explicit aspects of tensions between economic actors, leading to temporary or permanent imbalances. Furthermore, GEMMES incorporates investment functions à la Bhaduri and Marglin (1990) which allow to model economies that can be driven by both supply and demand (profit rate and productive capacity utilisation rate, cf. Setterfield & Blecker, 2019). GEMMES has not been calibrated to an advanced economy so far, but its framework could be adapted and would provide relevant insights for the case of the EU.

4.3. Agent-based modelling

Thus, a number of advanced SFC models exist, several of which have been specifically designed or adapted to represent the EU economy. A drawback, yet, is that most SFC models stay at the aggregate level and do not model intra-sectoral flows (Caiani et al., 2016). In particular, the focus of SFC models on macro-tendencies renders them especially vulnerable to the Lucas critique. With this in view and thanks to the new perspectives opened up by advanced computing capabilities, another form of modelling has developed: agent-based modelling (ABM). It uses an entirely different language of autonomous agents, objects and environments rather than variables, functions and equations (Boulanger & Brechet, 2005). As explained by Caiani et al. (2016), ABM "*conceives the economy as a complex adaptive system populated by heterogeneous locally interacting agents*". ABMs are bottom-up macroeconomic models in the sense that the behaviour of actors at the micro-level, relative to the opportunities and thresholds fixed by the broader environment, brings about emergence of aggregate properties. They illustrate a major new development in both economic and behavioural modelling, allowing better ways to model non-equilibrium evolutionary economic phenomena based on empirical grounds (Stiglitz et al., 2016). As noted by Caiani et al. (2016): *"empirically, agent based macroeconomic models have proven to be capable of reproducing a significant number of micro and macroeconomic stylized facts ... often outperforming DSGE models"*. Besides, Colander et al. (2008) highlight how such empirical reconstruction of macroeconomics with agent-based computational modelling improves robustness of models to the issue of aggregation.

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

4.4. Multi-sector disaggregated complements

The six alternative models presented so far are all suitable complements to DSGEs, since their level of detail, scope and applications are similar in nature. However, none of these models focuses on representing **multi-sector**, disaggregated economy with its interdependencies, in the way that CGEs do[39]. The goal of the MEDEAS, then LOCOMOTION projects was to fill this gap. Those two research projects were funded by the European Union's Horizon 2020 research and innovation program and led to the development of the MEDEAS IAM, followed by WILIAM. MEDEAS is a system dynamics model, in the fashion of the pioneering WORLD3 model of Meadows et al. (1972). The main goal of MEDEAS is to provide a detailed, multi-sectoral model which endogenously accounts for biophysical constraints (**energy and resources**, namely). These constraints, such as the declining Energy Return On Investment (EROI) and geological availability of fossil fuels, as well as maximum potential of renewable energies, can heavily influence the production side of the economy, depending on the chosen transition scenario. Particularly, MEDEAS is based on the Ecological Economics framework, whereby the socioeconomic system's capabilities are shaped by the boundaries imposed by the wider biophysical system. Thus, energy availability determines the maximum potential economic growth. MEDEAS comprises 9 main modules: economy & employment, energy demand, energy availability, energy infrastructures and EROI, minerals, land-use, water, climate and social impact indicators. The economic module is based on a dynamic Input-Output (IO) framework, with a sectoral disaggregation into 35 industries. MEDEAS has been developed at three different scales: global (Nieto et al., 2020a; Capellán-Pérez et al., 2020), EU (Blas et al., 2018; Nieto et al., 2020b) and country-level (Alvarez-Antelo et al., 2018). Those three models are nested into each other, with a one-way integration: the parent models (World, EU) provide the child models (EU, country) with the constraints in terms of energy and materials availability deriving from regional or global dynamics. In the same way, CO_2 concentration and global temperature increase are determined by running MEDEAS-World. They are then taken as inputs by the EU and country models, based on which these models compute **heterogeneous climate damages** (Nieto et al., 2020a; Capellán-Pérez et al., 2020).

The LOCOMOTION project departed from the legacy of MEDEAS to develop the WILIAM model. In WILIAM, the economic model of MEDEAS was replaced by a dynamic econometric multi-regional Input-Output model. WILIAM comprises a high level of disaggregation of economic sectors (62 industries), households (60 types) and regions (35) and captures the mutual feedbacks between quantities and prices, and the interplay between consumer demand, induced investment, government and exports demand, on the one side, and

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

production and income generation and distribution on the other. The model has New Keynesian features, as markets are not generally cleared by the price mechanism, but effective demand under supply constraints determines the outcome for the different industries. The macroeconomic IO model in WILIAM is especially designed for incorporating feedback between the economy and nature, in particular **resources constraints** and **climate change impacts**. The core of the firms' submodule is a dynamic econometric input-output model which computes the production and demand factors (energy, materials, other intermediates, labour, and capital) required to satisfy the demand from the different agents. The regions are linked through trade flows, with trade shares defined through Armington elasticities, which enables the analysis of different configurations of supply chains (e.g., globalisation, near-shoring, or back-shoring). WILIAM covers 62 sectors, with a detailed representation of decarbonisation-related sectors such as mining industries, transportation sectors, and energy transformation industries. These sectors are linked to the bottom-up models of the WILIAM materials module (hydrocarbons and metals) and the energy module which includes energy transformation (electricity and heat, refining, hydrogen), buildings and transportation. These linkages include bilateral inter-module exchanges of physical and monetary variables. The households' submodule follows a heterogeneous-agent econometric approach covering 60 different types of households with a nested structure. For each household and region, the module computes the levels of consumption of durable goods, energy goods, transportation, and other non-durable goods on the basis of their preferences, income, financial situation and prices. This module is linked to the bottom-up models of buildings and transportation, with the expenditure in energy, transportation, and vehicles being a combination of the interaction between the aforementioned economic variables and some technological and behavioural variables coming from the bottom-up modules. The economic module is also linked to the land module (demand for food) and to the demographic module (number and types of households, income). Finally, the economic module is also linked to the financial, production and government sub-modules. The latter computes government revenues, expenditure, budget balance and debt. In the case of the government consumption and investment, the model covers 10 categories (health, education, defence, etc.). The level of detail of this module is essential to analyse scenarios in which national governments and the EU Commission would perform multiple green policy interventions. The multi-regional nature of WILIAM also allows to study how the EU's transition policies might affect other regions and, in turn, how evolutions in other regions might affect the EU.

Thus, the high level of detail of WILIAM and its representation of multi-sectoral and multi-regional interdependencies are comparable to those of CGEs, without falling into the shortcomings listed in **Section 3**. The final meetings of the LOCOMOTION project took place in September and October 2023. A detailed description of the WILIAM model is yet to be published in a peer-reviewed journal, but can already be found in the LOCOMOTION project reports. Furthermore, a "model analyser" (i.e. a user-friendly version of the model) is available online and targeted at policymakers for helping them to assess environmental, social and economic costs and benefits related to decarbonisation pathways and policies.

A model sharing several similarities with WILIAM is E3ME ("Energy-Environment-Economy Model for Europe"). E3ME is a global, multi-country, non-equilibrium model including detailed econometric equations. It was developed by Cambridge Econometrics, originally through a European Commission's research framework programme. E3ME models the close integration of the economy, the energy systems and the environment, with two-way linkages between the economy and energy system. It combines microfounded technological choices and innovations in a bottom-up way with a macroeconomic structure, allowing true **multi-sectoral disaggregation**, sector-specific energy intensities and intersectoral spillovers. The econometric specification of E3ME gives the model a strong empirical grounding. In particular, its harmonious bottom-up and top-down integration makes the model robust to the Lucas critique (or at least as much as possible, since there exists no macroeconomic model whose entire set of calibrated parameters are perfectly immune to that critique). E3ME uses a system of error correction, allowing short-term dynamic (or transition) outcomes, moving towards a long-term trend. The dynamic specification is important when considering short and medium-term analysis and rebound effects, which are included as standard in the model's results. E3ME represents 71 countries, 70 industrial sectors and 43 categories of household expenditure (Dwesar, I. et al., 2022b). Furthermore, as E3ME is a **simulation model without optimisation behaviour** (cf. Subsection **3.1**), it allows for the representation of the unused resources and productive capacities in the economy, reducing the risk of crowding out effects, while still representing potential constraints in the scenarios studied such as the total available workforce. The model is widely used in Europe and beyond for policy assessment, for forecasting and for research purposes. It was used by DG CLIMA, namely for the EU's Impact Assessment of the 2030 climate and energy package and for designing the EU's long-term strategy for achieving net-zero emissions. We argue that, in light of the previous sections, this model is becoming increasingly relevant and should be used more widely for designing economic policies in the context of the EU Green Deal. Besides, its authors are ready to incorporate supplementary financial features into the model, to make it even more relevant to the work of DG ECFIN.

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

4.5. On the use of macroeconomic models

The 9 models presented above are part of the blossoming research field of Ecological Macroeconomics (Delannoy, 2023). Most of them were developed with the specific aim of overcoming one or several of the challenges listed in **Section 3**. Yet, as can be seen from **Table 1**, none of these models is robust to all points of criticism. This is not an aim *per s*e. As Blanchard (2018) puts it, "*We need different types of macroeconomic models for different purposes. [...] No model can be all things to all people*". A model is developed to answer one or several specific policy questions. Given the complexity and variety of domains affected by the ecological shift, one cannot hope to dispose of a single, exhaustive tool to guide policy making in the green transition. Instead, a variety of models must be used, reflecting a plurality of views and methodologies. Indeed, the choice of models to inform decision-making is non-neutral, and will partially determine the outcome of the recommendations emanating from the models. Modelling choices can even be the object of political demands to change or reinforce seemingly innocent technical assumptions that will have an impact on the modelled results and retroact on political decisions (Heimberger et al., 2020)[40]. Some model structures and core assumptions naturally tend to favour market-based solutions over regulation-based solutions, and vice versa. Moreover, models are often complementary in terms of temporality. For example, a DSGE like E-QUEST might be preferred for analysis of short-term effects, while many of the models presented above will be favoured for medium- and long-term outcomes. Having a co-existence of alternative models is therefore key for environmental policy discussion. Existing examples of models diversification include the World bank, which jointly uses E3ME and MANAGE (a CGE model) for producing the Country Climate and Development Report for China (World Bank Group., 2022) or the TCFD, IMF and European Central Bank which released a series of technical papers using the EIRIN model (see *supra*).

[40] See for example Spain's pressure to change the Kalman filter used to calculate its NAWRU (non-accelerating wage inflation rate of unemployment) and therefore its "structural unemployment rate" by the European Commission (Dalton, 2013).

Section 5 - Model diversification: the need for collaborative dialogue and institutional convergence of ecosystems, and Conclusion

In the previous section, we presented a comprehensive review of alternative modelling tools, complementary to the ones currently used by the European Commission for addressing the methodological challenges raised in **Section 3**. This review demonstrated a need for a nuanced and holistic approach to economic modelling applied to environmental policy analysis and the ecological transition. By engaging in collaborative efforts with academic and public institutions developing these complementary models, and prioritising their development and inclusion, the European Commission can significantly enhance its capacity to anticipate and evaluate the economic impacts of environmental crises and policies. Furthermore, this paper advocates for a systemic research program and institutional convergence, emphasising the value of interdisciplinary dialogue. This collaborative and integrative approach is essential for providing policymakers with comprehensive and effective guidance, thereby ensuring that economic models not only reflect the complexity of ecological transitions, but also facilitate the production of nuanced policy recommendations. In essence, the diversification and enhancement of modelling tools as discussed in this paper are not merely academic exercises.

The current use of E-QUEST and GEM-E3 highlights the need for at least two broad categories of models. In light of the ecological transition, we would summarise these two categories as follows:

1. a highly aggregated model, able to perform integrated assessment work such as analysing macroeconomic fluctuations (requiring, all the same, at least a weakly multi-sectoral character), and with an environmental and ecological framework including energy and resource flows and stocks, and feedback through damage functions. This model would be used to study major investment and macroeconomic policies;

2. a highly disaggregated, highly multi-sectoral and multi-regional model, decomposing productive structure and interdependencies with empirically estimated elasticities and an endogenous bottom-up technological structure, which could be microfounded, while being connected to several specific and integrated environmental models. This model would be used to study taxation, subsidy, quota, regulatory, innovation, technological and sectoral policies. Environmental feedback can then be envisaged according to the vulnerabilities and exposures of each sector (including dependencies on the global supply chain).

E-QUEST, GEM-E3 and the considered model classes only partially fulfil this task, through the partial responses to the series of modelling challenges described in **Section 3**. We argued in **Section 4** that a series of alternative models should be used by the EU Commission, in complement to E-QUEST and GEM-E3, to better assess the economic consequences of ecological transition policies. These alternative models can be classified in the two categories mentioned above:

1. EIRIN, EUROGREEN, GEMMES, DEFINE, DSK
2. MEDEAS, WILIAM, E3ME, ESTEEM

These models could be used directly by the European Commission (requiring preliminary adaptations for some). Alternatively, some of their most innovative components highlighted in **Section 4** could be recuperated and used for the development of new modelling tools.

The analysis and design of European environmental policies require models with explicit and comprehensible causal mechanisms to effectively guide public policies and decision-makers' understanding. Public decision-makers themselves need causal traceability in order to anticipate the impact and reception of a given public policy. The reverse mechanism of integrated assessment modelling (IAM), which consists in deducing from the model a socially "optimal" scenario with an "optimal" social cost of carbon and carbon tax, no longer convinces public decision-makers today, due to the particularly normative nature of these models and their many implicit and abstract assumptions. Realism is therefore to be favoured over analytical coherence, not only from a scientific point of view but in order to win the confidence of the public and stakeholders - it is worthy to note that the most contributory and robust modelling approaches are not necessarily those with the highest degree of technicality (Summers, 1986; D. Romer, 2015) and, similarly, a high level of technicality, whether in algebraic formalism or theoretical refinement, does not necessarily imply a high level of realism. This communication challenge was already raised by Blanchard (2016) and Rivera et al. (2018). It comes together with a need for transparency in the choice of hypotheses, which must be made explicit. This is essential since the models of interest imply important theoretical choices (for example, whether or not there is a double dividend for the carbon tax, or whether or not there is a crowding-out effect for public borrowing and investment).

Underlying theoretical choices can present the risk of having models that, at a particular point in time, cannot by construction advocate for certain required economic policies (Truger, 2015). For example, in 2019, the European Commission calculated that Italy's production level in the same year was almost at its potential output level (with an output gap estimated at -0.2%), even though Italy had zero inflation and an unemployment rate of around 10%. The normative deductions from such an estimate were then recommendations for austerity and fiscal consolidation despite the totally contradictory empirical conditions (Heimberger, 2019). It is thus necessary for the European Commission to dispose of a variety of models grounded on alternative theoretical choices and to make sure that at least some of these models can advocate for policies in line with the objectives fixed by both itself and the European Parliament. In the context of the European Green Deal, this amounts to disposing of some models which can provide recommendations for European expansionary policy packages (Kerlero de Rosbo et al., 2024), with a clear causal justification for them. This paper therefore strongly argues for diversification, in line with the recent call of ECB chief Christine Lagarde (2024) at Davos: diversification of the model classes used and of the assumptions, to benefit from the specificities and comparative advantages of each class. This calls for dialogue between modelling research teams, whether academic or institutional. Such dialogue would ideally not just be in the sharing of models, but also in the construction of the models themselves. Scientific dialogue on the hypotheses to be validated would also harmonise model testing and comparison. Thus, this work is above all an invitation to scientific and institutional collaboration, in the service of better economic modelling tools, towards equipping the European Commission with the analytical capability to design and implement ecological transition policies that are economically sound, environmentally sustainable, and socially just. This endeavour, while challenging, is essential for the European Union to navigate the intricate and evolving landscape of ecological transition in the 21st century.

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Appendix A - Other desirable features for future models

See Giraud and Valcke (2023a,b) for a comprehensive research program in the face of current scientific challenges.

A.1. Climatic and economic uncertainty

A number of parameters of the economic and climate system are concerned by high uncertainty (Knutti et al., 2017), such as the magnitude of the long-term effect of climate change, the sensitivity of the climate to GHGs, the inertia of the climate system linked to carbon reservoirs and feedback mechanisms, the long-term profitability of investments and capital, technological innovation including "green" innovation (in contrast to the deterministic nature of the latter in the DICE, necessarily caused by rising temperatures) or even labour productivity growth, all with thick-tailed distributions (Weitzman, 2013). Nordhaus (2018) explicitly acknowledges the uncertain nature of some of its parameters by introducing, instead of a discrete value, a probability distribution. Bovari et al. (2019) pursue this approach with different PDFs. Similarly, the impact of fiscal and monetary policies and new financial instruments in the context of ecological transition is uncertain, both in terms of their objectives and the potential effects on growth, the stability of financial and credit markets, or inequality.

Monasterolo and Raberto (2018) develop a behavioural economic model incorporating this uncertainty (EIRIN). Gourdel et al. (2022): “study extent to which climate-adjusted financial risk assessment affects firms’ investment decisions in the low-carbon transition, and the realisation of the climate mitigation trajectories”

A.2. Capital accumulation or exogenous growth

The need to endogenize growth, as opposed to capital accumulation and exogenous productivity growth models, by integrating the impact of growth on increasing returns and productivity growth (Kaldor-Verdoorn’s law) and the role of technical progress without a hard deterministic character (e.g. autonomous technical efficiency change rate) but with relative dependence on investment (Romer, 1986; Aghion & Howitt, 1992) in a Schumpeterian logic, notably for green technological innovation. E-QUEST has an autonomous energy efficiency improvement rate, but also a learning-by-doing rate which is a form of endogenization[41]. EIRIN *“endogenizes green technology investments and displays their effects on the changes in green technology adoption and thus on the level of resource efficiency of the production process”* (Monasterolo & Raberto, 2018). E3ME microfounds technological change through a bottom-up process.

A.3. Capital Putty-Clay and path dependency

An interesting complement and balance between Leontief and Cobb-Douglas is the introduction of a constraint in firms' investment plans, which is path dependence, seemingly fundamental in a logic of ecological planning, massive investment and stranding capital management. It is possible to consider that capital is Putty before it is installed (i.e. machines

[41] QUEST3 R&D (Roeger et al., 2022) includes an endogenization through the share of spending and subsidies on researchers.

can be designed to be combined with a specific number of workers and quantity of resources), then Clay after it is installed, i.e. fixed and no longer modifiable, creating path dependency and irreversibility of the investment and the technical combination implemented (cf. Johansen, 1959; Akerlof, 1967; Akerlof & Stiglitz, 1969; Harcourt, 2012).

A.4. Regionalization and geographic disaggregation.

Adapting all parameters and behavioural equations to each country in the zone, not just a few parameters, cf. Blanchard's (2016) criticism of the presence of the same Calvo parameters in the Phillips curve for different countries. There is a need to develop a consistent integration of multi-sector and multi-region frameworks.

A.5. Integration of structural and regime changes, and evolution of the Phillips curve

The challenge is to integrate changes in the regime and structure of the economy, both European and national, e.g. the horizontalization of the Phillips curve due to a collapse in wage bargaining, unionisation rates, international competition, etc. (Borio et al., 2023; Lombardi et al. 2023). In traditional RBC/CGE, the Phillips curve is vertical in both the short and long term. In a NK DSGE, like in “Friedmanian” models, it is vertical only in the long term, for monetarist reasons of price adjustment time and frictions and rigidities. However, the evolution of conflicts in the distribution of value is at the heart of the Phillips curve, both in terms of the evolution of nominal wages and prices, and is still in existence, even if it is largely weakening towards a horizontal curve (Ratner & Sim, 2022, on a variation of Dixit-Stiglitz). Furthermore, this curve is non-linear and depends on the increasing or decreasing direction of economic activity (non-injective function, cf. Lipsey,1960; Nalewaik, 2016). Finally, such an approach will make it possible to analyse the role of company markups and markup setting in inflation phenomena beyond those of imports/energy (Lorenzoni & Werning, 2023a,b). The need for a sociological and institutional approach seems to be justified (Forder, 2014).

A.6. Inclusion of services

In developed countries, over 80% of GDP is made up of services (World Bank data). The development of services has been studied for a while (e.g. Baumol’s paradox) and has important impacts on the economy (Peneder et al., 2003; Ko & Rubalcaba, 2007). Yet, generally models only study production and trade of goods. It needs imagination in terms of capacity utilisation as there is no inventory of services. Moreover, services hide a lot of energy consumption, which needs to be taken into account.

Appendix B - Further modelling challenges to overcome?

B.1. Estimation, calibration and backtesting.

Estimation and parameterization in DGSE rely on a mixture of calibration and Bayesian estimation, which, according to Blanchard (2016), is *“not convincing”*. The first problem, not addressed by Blanchard but by Romer (2016) is the very large number of degrees of freedom allowed by “exogenous shocks” to explain macroeconomic and financial variations. Indeed, if these models can claim to capture a large number of macroeconomic fluctuations (including moments of order 2), this is partly due to the ontological and discretionary solution of explaining any fluctuation by a shock exogenous to the general equilibrium model, its propagation and the optimal reactions of optimising agents, an idea dating back to Frisch (1933). For example, Kollmann et al. (2014) assume 46 hypothetical shocks in their model of Germany from 1995 to 2013, *"as it appears that many shocks are needed to capture the key dynamic properties of macroeconomic and financial data."* (*Ibid.*, see also Smets & Wouters, 2007; Kollmann, 2013; and in’t Veld et al., 2014[42])[43].

For Blanchard (2016), estimating these models by whole system instead of equation by equation leads to having to estimate a very large number of parameters - which is impossible. This leads calibration to be sometimes arbitrary, without an empirical basis (Blanchard points for example at the calibration of the Calvo parameters, which determine the effect of unemployment on inflation in the Phillips curve - but one could more broadly question the parameters of production functions with high elasticity of substitution despite the inverse empirical literature). Parameters are estimated by Bayesian methods because, beyond the misspecification problems common to all estimation, the large number of parameters means that the likelihood function is generally flat, justifying such a method. But robust priors are often lacking, and *"what is estimated reflects more the prior of the researcher than the likelihood function"* (*Ibid.*). Moreover, DSGEs/CGEs are not robust to Lucas and Sargent's (1979) criticism of *ad hoc* relation-based macroeconometric models, despite the "cross-equation restriction", notably due to rational expectations, as the number of parameters to be calibrated arbitrarily multiplied (Romer, 2016)[44].

Thus, Kocherlakota (2018), as a central banker (Fed Minneapolis, has noted their uselessness and calls for a return to pre-New Classical Economics econometric regression estimates, coupled with sound theory to avoid ad hoc relationship and identification problems. One of the avenues of research is the backtesting method, i.e. building models on data and testing them with other data. This method comes from finance and can be in the form of "rolling" to avoid the separation period being arbitrary. Some models estimated by backtesting are particularly robust, even when compared with VARs (McIsaac, 2021). However, Bayesian estimation should not necessarily be rejected. For instance it has promising applications in the

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[42] It should be noted that, unlike estimated standard DGSEs, QUEST3 has no detrended data (e.g. through the Hodrick-Prescott filter or linear time trends) but is estimated by growth rates and nominal ratios.

[43] Also due to the fact that the large number of observables (time series) requires an even larger number of shocks to prevent stochastic singularity.

[44] See Lindé et al. (2019) for a recent review of misspecification and identification issues.

difficult construction of damage functions (e.g. Sairam et al., 2019, for a hierarchical bayesian model for flooding damages), or when applied with uncertainty bounds of the parameter estimation with confidence intervals (see Bailly et al., (2023) for a statistical analysis of model's predictions with a sieve bootstrapping approach).

B.2. Financing constraints

Including financing constraints is important (Godley & Lavoie, 2007). E-QUEST, following standard DSGEs and as a first step, includes agents that are liquidity constrained, i.e. they do not have access to financial markets and therefore cannot optimise their intertemporal consumption. Several important empirical brakes in finance and green finance have been discussed recently (e.g. Campiglio, 2016) such as credit crunch by banks exposed to brown assets, bond loan rationing spreads and the absence of green premium for green bonds on the markets etc... Taking financing constraints into account would lead to more realistic, more constrained scenarios and with a greater role and analysis visibility for the public sphere in terms of direct investment as well as financial regulation and draining private finance towards the ecological transition. Recent versions of QUEST3 push in this direction by offering credit-constrained households.

B.3. Capital-labour substitution

As for the elasticity of capital/labour substitution, even though the main meta-analyses report a value strictly below 1 in both the short and long term (e.g. Knoblach et al., 2020; Luoma & Luoto, 2010), it is generally fixed at 1 (Cobb-Douglas form), and the consequences of this homogeneity are that the remuneration of production factors corresponds to their marginal productivity and therefore to purely technological properties, not to socio-political and institutional contingencies despite the constant empirical variation in the share of wages and profits in the distribution of added value, with a trend and structural decline in the share of wages, to the benefit of the share of profits, dropping from 66.1% to 61.7% on average in most OECD countries between 1990 and the end of the 2000s (BIS, 2006; European Commission, 2007; IMF, 2007; OECD, 2012; ILO, 2012). This in addition to those unrealistic assumptions of substitutability between factors of production (capital being however dependent on labour even without its own production, cf. Wicksell effects). An independent determination of the share of profits and wages in the factorial distribution can be built in parallel with the production function (e.g. Goodwin, 1967).

B.4. Other environmental feedback loops and issues

There is a particular emphasis on the temperature anomaly, when other issues are also present: collapse of biodiversity (cf. IPBES numerous reports), increasing demand and reduction in the rate of extractive yield of materials and rare earths (Vidal et al., 2017, 2018; Court & Fizaine, 2017), decline in agricultural yields, increased risk of anthropo-zoonosis (Allen et al., 2017; Friedman, 2022) etc. PAGE and FUND-type IAMs incorporate damage functions for many phenomena. There is a need to take into account other planetary limits. Some IAMs have diversified damage functions, *inter alia* PAGE (Hope et al., 1993) and FUND (Anthroff, 2009).

B.5. Optimality, intergenerational inequalities and social discount rate

An element not addressed in this work is the measurement of welfare, a central element in policy evaluation. Indeed, CGEs, such as GEM-E3, calculate households' "well-being" in monetary terms and add them up, to simulate in a counterfactual way the variation in welfare due to the introduction of a policy, for example an environmental one, to offer choice criteria. DSGEs, such as E-QUEST, also study variations in welfare, implying a normative character on the construction of the welfare function and on the degree of preference for the present (as welfare is calculated as the present value of the change in consumption relative to baseline). Welfare here is not environmental, however, nor is the thinking that applies to it, as the authors of E-QUEST (Varga et al., 2022) explicitly consider, for example, that EU climate mitigation policies can only have a limited impact, in terms of orders of magnitude, on global GHG emissions, and could even stimulate extra-EU imports and hence production outside the EU, leading to higher emissions in the abroad sectors, with the two effects possibly neutralising each other and leading to a very low net result. They therefore do not use Ramsey-style social discounting and are thus “agnostic” on the subject. In CGEs, the emissions trajectory is an exogenous objective, and economic policies are used to achieve these objectives, with the model measuring the associated economic impacts.

However, other categories of models, the integrated assessment models (IAMs, e.g. DICE-type), and more broadly any model attempting to compute a dynamically "optimal" carbon tax or carbon cost, are fundamentally normative in character, due to the need to use a criterion to derive these optimal trajectories. This criterion is based on the mechanism of social discounting: the costs and benefits of any policy, as well as wealth, are discounted temporally, i.e. they have less and less value in the future. Trivially speaking, the further in the future generations lie, the less they matter at time t, which then impacts the "optimal" policies prescribed and their resulting trajectory in terms of consumption, production and emissions. This calculation is based on a discount rate applied to the various variables, including environmental damage, to take into account the opportunity costs of the ecological transition. This optimal discount rate ϱ is often based on Ramsey's (1928) equation:

$$\varrho = \delta + \sigma \cdot g$$

Where δ is the "rate of pure preference for the present” (our collective perspective on the future) which is a normative ethical choice devoid of any economic analysis and which could be zero. g is the (expected) rate of economic growth. σ is the elasticity of marginal well-being (utility) due to change in consumption and thus the aversion to intergenerational inequalities. The subtlety here is that this aversion implies that present generations feel unequal to future generations because, since growth g is assumed to be positive, future generations will be richer than we are, and optimality therefore implies policies favouring our generations and reducing the value of future environmental damage. This is based on assumptions of long-term growth. The combination of these three factors (δ, σ, g) generally leads to a discount rate ϱ resulting in a discounting of investments in the ecological transition, all the more so when some authors propose that ϱ should take the value of the market rate of return (e.g. Posner & Weisbach, 2010)[45]. However, Stern (2006) reminds us that a positive rate implies the possibility of letting humanity's living conditions collapse. Fleurbaey and Zuber (2013) gives a set of reasons why the result of the Ramsey equation should be negative and therefore imply a preference for future generations, notably because of a risk of sudden decline in GDP due to resource constraints and to negative environmental feedback, not only on output but also on productive capital (Dietz & Stern, 2015). Thus, future generations would be poorer than present ones as a result of the damage, reversing the role of the inequality aversion parameter σ, an idea already anticipated in Schelling's conjecture (Schelling, 1995). We should at least be cautious in the face of uncertainty about future long-term growth (Gollier, 2002; Gollier & Weitzman, 2010). As for Weitzman (1998, 2011), he shows through his "Dismal Theorem" that we cannot have insurance discounting reasoning in a situation of radical uncertainty and thick-tailed distribution in terms of environmental catastrophes. See Pindyck (2013) for a critique of the arbitrary nature of the discount rate in AMIs and the high sensitivity of the Social Cost of Carbon deduced from it.

Beyond the justification for using a negative discount rate, we can consider that this normative dimension of cost-benefit analysis is in fact a competence of political institutions and public decision-makers in a democratic framework. Such decisions should not be left to modellers, who are simply supposed to enlighten public decision-making with their quantitative and prospective tools. The short-term imperatives of investment and ecological transition are now well documented, and public decision-makers are aware of them. Rather than going into a philosophical debate over the value of the discount rate, it is possible to abandon this discount rate altogether, in favour of a purely descriptive and positivist approach of the economy (Stern, Stiglitz & Taylor, 2022), based on based, for example, on the medical consequences of environmental degradation. Public decision-makers and researchers can set desired outcomes, or at least outcomes that must be avoided (e.g. catastrophic consequences, large uninhabitable zones, etc.). This would be done preferably by democratic means. Emission trajectories can then be retroactively computed, modulo the uncertainty of climate sensitivity parameters, to obtain the required carbon cost trajectory and policies. The process then becomes a combination of socio-political compromise and scientific forecasting.

Another method proposed by Pindyck (2019) to still obtain an average social cost of carbon is to calculate it as the ratio of the present value of lost GDP from an extreme outcome to the total emission reduction needed to avert that outcome, using plausible probabilities of alternative economic outcomes of climate change. Finally, Ferrari et al. (2022) propose a method based not on the identification of optimal but "robust" scenarios. Noting the deep uncertainties and value-laden preferences, they propose an alternative to single-objective models, positing well-being, temperature and inequality between countries as objectives. By doing so, they obtain four relevant climate policies: three with the least-worst ranking for each objective, and one compromise, with the least-worst ranking for all three objectives. Robustness

[45] Nordhaus for example argues that it should correspond to the observed or expected interest rates, or in estimates of the opportunity cost of capital, to represent the current preferences (see Stern (2007) and Sterner & Persson (2008) for a critique of this approach). Mertens and Rubinchik (2017) argue that it should equal the growth rate of per-capita consumption (about 2% for the USA).

then consists in studying whether the economically optimal climate policies evaluated by standard models are robust to the integration of other objectives and metrics. This robustness approach reduces the range of emissions and temperature trajectories relative to the initial trajectories. It takes into account economic, social and environmental objectives in an explicit and "agnostic" way, and leads in each case to a call for rapid and massive mitigation policies before 2050.