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

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Abstract
The ecological transition requires a profound transformation of the global economy, necessitating forward-looking tools for effective policymaking. Currently, macroeconomic analysis predominantly relies on *New Keynesian* Dynamic Stochastic General Equilibrium (DSGE) and Computable General Equilibrium (CGE) models. While widely used, these models face significant challenges, intensified when trying to address the complexities of environmental degradation, climate change, and the transition to sustainability. This work explores whether models from Ecological Macroeconomics (EM), developed within the field of Ecological Economics, can serve as viable complements and alternatives. EM models, built in academic and public institutions and including Stock-Flow Consistent, Agent-Based, and multi-sector disaggregated frameworks, offer critical advantages. They integrate biophysical constraints, capture endogenous economic dynamics, and include a description of endogenous monetary and financial mechanisms, providing insights that align with the demands of the ecological transition. This study highlights the critical shortcomings of mainstream models, including their reliance on equilibrium shock-driven frameworks, unobservable variables, monetary neutrality, and limited treatment of private debt and financial instability. Through a comprehensive review, we show how EM models address these gaps, offering tools better suited to analyse the economic and environmental consequences of transition strategies. While no single model can capture the full complexity of the ecological transition, this paper advocates for a pluralistic approach to economic modelling. We emphasize the importance of integrating a diverse set of complementary models tailored to specific policy challenges, enhancing predictive accuracy and decision-making. By fostering transparency, interdisciplinary collaboration, and institutional adoption of diverse methodologies, this approach can better support the development of effective, feasible and equitable policies for navigating the ecological transition.

Keywords: Ecological Transition Policies, Economic Modelling, Ecological Economics, Integrated Assessment, Policy Analysis, Policy Design
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Highlights:

- Ecological Macroeconomics models can address key gaps in DSGE and CGE models.
- Stock-Flow Consistent models allow linking monetary-financial systems to the environment.
- Agent-Based models enable to capture heterogeneity and endogenous climate-economic dynamics.
- Multi-sector models offer insights into sectoral dependencies and green policies.
- A pluralistic modelling approach is necessary to build relevant ecological policies.

Content

Section 1 - Introduction

Contemporary societies are marked by a major environmental, social, economic, geopolitical polycrisis, which requires a profound transformation of the global economy (Lawrence et al., 2024). Pledges towards such transformation have been taken by the vast majority of governments through the process of the climate and biodiversity COPs. Yet, reaching those goals will require a substantial amount of forward-looking analysis and modelling. For decades, the perspective of the ecological transition has specifically fostered the development of a field known as Ecological Economics. Several macroeconomic models of the field (i.e. Ecological Macroeconomics (EM) models) have now reached a sufficient level of maturity to be used directly for policy making. However, EM models are currently little used by governments and international organisations for macroeconomic analysis in the light of the ecological transition. Such macroeconomic analysis is overwhelmingly conducted using models rooted in general equilibrium theory, especially Dynamic Stochastic General Equilibrium (DSGE) and Computable General Equilibrium (CGE) models. One can therefore ask whether EM models have anything to bring to policy making.

In this article, we argue that EM models have an important role to play. Not only do they avoid common pitfalls faced by general equilibrium models, they are also becoming increasingly relevant as the ecological transition is gathering steam and the economy is being destabilised by climate change impacts. This article offers three contributions to this inquiry. First, it provides an honest update on the usual criticisms of mainstream macroeconomic models. While well-documented limitations persist, recent advances such as Heterogeneous Agent New Keynesian (HANK) models have addressed some of these concerns, albeit as partial solutions not addressing the theoretical core as the potential problem. We integrate these developments into our critique to reflect the evolving state of the literature. Second, we deliver a detailed literature review of alternative EM models suitable for policy making, updating the previous literature review of EE models (Hardt and O'Neill, 2017), and, as a complement to the latter, we highlight how these respond to the challenges faced by mainstream models. This comparative analysis draws attention to the specific value each modelling approach brings to addressing the ecological transition. Third, this article is the first to our knowledge to critically evaluate the extent to which Ecological Macroeconomics models are suitable for concrete policymaking. By assessing the strengths, limitations, and practical applications of these models, we aim to advance the debate on their relevance to Ecological Economics and policy analysis.

Section 2 provides a brief overview of DSGE and CGE models currently dominant in policy making. **Section 3** highlights a list of challenges encountered by these model classes and points out how the ecological transition and environmental degradation are further exacerbating these shortcomings. **Section 4** then presents the field of EM, as well of a list of advanced models which could directly be used in policy making. The robustness of these models to the challenges outlined in **Section 3** is also discussed. **Section 5** concludes.

Section 2 - A brief theoretical description of DSGE and CGE models

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

DSGEs are a more recent category of economic models, used to analyse economic fluctuations and economic policies. They were developed in the wake of the RBC (Real Business Cycle) models and in response to Lucas' critique of the lack of a priori invariance of agents' behaviour in the face of public policy (Lucas, 1976). DSGEs are thus 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 equations, and may have persistent effects on the economy due to the model dynamics. DSGE models are solved numerically and calibrated or estimated using economic data, often in a Bayesian fashion. This is for example the case for the model of Smets and Wouters (2007), published as an ECB working paper and often regarded as canonical.

Nowadays, DSGE models are increasingly coming with a New Keynesian (NK) coloration. It consists in the addition of frictions, nominal and real rigidities from sticky wages and prices (à la Calvo, 1983) to habit formation, investment, adjustment costs… Including also monopolistic competition (à la Blanchard and Kiyotaki, 1987), asymmetric access to financial markets, market imperfections, a short-term NK Phillips curve (Galí and Gertler, 1999) based on expectations and “economic slack”, and agent heterogeneity, still applied on a general equilibrium and optimising agent core. Such additions lead to different transitory and long-term results. They can notably imply a short-term non-neutrality of money, restoring room for public policies including expansionary ones (e.g. Taylor rule (1993) for monetary policy). This NK coloration has become widespread since Rotemberg and Woodford (1997) and Christiano et al. (2005). For a retrospective of NK macroeconomics, see e.g. Galí (2018), and for a recent review of DSGEs with numerous references, see Lindé et al. (2016). The latest academic developments, still little used in institutions, are the Heterogeneous Agent New Keynesian (HANK) models, incorporating a distribution of heterogeneous agents (Kaplan et al., 2018).

[1] 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 optimisers who make decisions based on prices, income and technological constraints, again based on the theory of rational behaviour. CGE models are solved by finding the set of prices and quantities that balance supply and demand in all markets, taking into account government policies and external shocks. They are generally calibrated on a "base year", on which everything is assumed to be in equilibrium. A CGE model is first benchmarked with disaggregated data from the Input-Output (IO) tables of the national accounts through Social Accounting Matrices (SAM). Technical and behavioural relationships linked to the general equilibrium theory are then added to the model[2]. Unlike DSGEs, CGE models usually are recursive and do not include forward-looking intertemporal optimisation; if they do, they cannot always be solved intertemporally. CGEs were originally static, but are becoming increasingly dynamic (Babatunde et al., 2017). For an example of a canonical dynamic recursive environmental CGE model, see namely ENV-Linkages of the OECD (Château et al., 2014).

2.1 Uses and purposes of DSGEs and CGEs

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

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

CGE models, on the other hand, are disaggregated, multi-sector models, designed to study the production and trade of each sector and the interde- pendencies 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. Contrary to DSGEs, their aim is not to deduce optimal dynamic policies, but to study the impact of ad hoc policies on the economy. In the context of increased environmental regulation, CGEs have been applied since the 1990s to study the specific impacts of tax-type policies. They were mainly used to compute the social cost of complying with the Kyoto Protocol (externality CGEs, e.g. Böhringer and Rutherford, 2010). The modeled impacts can be on the concerned sector or, through substitution elasticities, on other sectors, as well as on endogenous technological evolution or on the consumption of different resources (e.g. Gao et al., 2024).

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

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

Although useful for the design of economic and environmental policies, CGE and DSGE models face certain theoretical, methodological and practical challenges. Such limitations are non-trivial, especially in the context of the ecological transformation. The aim of this section is therefore to present a constructive summary of these challenges, which have been underlined by regular users and designers of these model classes. **Section 4** subsequently presents diverse solutions in the form of existing modelling tools from the field of Ecological Macroeconomics.

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

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

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

It is important to emphasise that macroeconomic research, like any scientific discipline, is constantly evolving. As presented in **Section 2**, 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; the assumptions of perfect rationality are gradually replaced by bounded rationality (Beqiraj et al., 2018); financial markets and market beliefs are sometimes added (e.g. Annicchiarico et al., 2022); and agent heterogeneity is introduced (HANK models). Although positive, these transformations and additions are only partial and thus insufficient, especially in light of the current economic and environmental situation. In the following pages, we therefore attempt to review the challenges faced by CGEs and DSGEs.

3.1. Output gap, "natural rates" and unobservables

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

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, leading to potentially impactful mistakes[4], and this is a recurring problem with other 'notional' variables such as *r**, defined as the real short-term interest rate compatible with stable inflation, potential output and a balance between savings and investment. Thus, the problem with its use as a binding benchmark for monetary policy is its inherent unobservability and dependence on other unobservable variables, such as the output gap or the natural rate of unemployment, which are themselves subject to substantial statistical uncertainty and estimation bias (Benigno et al., 2024). Furthermore, the assumption that *r** is independent of monetary policy and is the result of the determinants of savings and investment and therefore of the loanable fund market theory is highly questionable (Taylor, 2016; Lunsford and West, 2019; Borio, 2021). Evidence shows that monetary policy actions can significantly influence long-term real interest rates, creating feedback loops that affect perceptions of *r** in a mirror-like fashion, making it potentially endogenous to monetary policy decisions (Hanson and Stein, 2015; Hillenbrand, 2023)[5]. This reliance on *r** as an independent constraint can lead to pro-cyclical policies, such as excessive tightening in the face of perceived inflationary risks or excessive easing in the face of stable inflation, exacerbating financial imbalances, asset bubbles and private debt. Moreover, structural changes in business cycles since the 1980s, driven by financial liberalisation, have shifted the focus of monetary policy from inflation/employment trade-offs to financial stability/employment trade-offs (Borio et al., 2019), highlighting the limits of *r** as a guide to policy[6] - *it's hard to follow the stars*, as central bankers say. This suggests the need for alternative observables-based - like inflation, capacity utilization[7]

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

[4] 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).

[5] For example, markets may interpret rate cuts as signals that *r** will fall, encouraging other policy adjustments based on incorrect premises.

[6] Its use stems from the axiomatic-deductive methodology centred on equilibrium, with the interest rate being the price of money. In non-equilibrium, however, quantity constraints are much more decisive than prices (Lee and Werner, 2018) and policy makers should focus instead on quantity variables (including resource constraints).

[7] Fazzari et al (2014) show that the productive capacity utilisation rate significantly outperforms the output gap as a proxy for the economic slack to identify non-linearities in the effect of public spending, whose multipliers are state-dependent.

and financial imbalances - frameworks that integrate prudential, fiscal and structural considerations, all the more so in the context of a holistic ecological transition requiring a policy mix.

3.2. Equilibrium, optimising shock-driven framework and Say's Law

Standard macroeconomic modelling, including CGEs and DSGEs, is based on an equilibrium framework, not as a result but as an assumption. Blanchard (2018) puts forward as a "widely believed proposition" with "a wide agreement" that "Macroeconomics is about general equilibrium". Through optimising agents solving an intertemporal linear programming problem, the economy moves towards a steady state where history repeats itself indefinitely and no surprises occur. By contrast, most of the specialised literature on General Equilibrium Theory from the 1990s' has shown these postulates to be only exceptionally valid (Ackerman, 2002). Specifically, proven by Boldrin and Montrucchio (1986), the Anti-Turnpike Theorem demonstrates that optimal policy functions in infinite-horizon macroeconomic models can generate any dynamics (including chaotic and unpredictable behaviour), and give *"practically anything"*. (Boldrin and Woodford, 1990). This *negative* result, which can be thought of as a macro equivalent of the Sonnenschein-Mantel-Debreu Theorem in microeconomics[8], challenges the intuition that concavity and discounting (the patience of agents) should lead to stable or regular solutions in dynamic programming problems.

This framework, in addition to eliminating numerous real dynamics, prevents the modelling of a central and fundamental empirical fact: fluctuations that are endogenous to the economic system, in the absence of exogenous shocks. Indeed, macroeconomic variations in those models are not endogenous but caused by exogenous shocks, real or monetary. DSGEs then focus on equilibria that are stationary linear fluctuations from those shocks: a significant portion of macroeconomic analysis relies on the theory of equilibrium cycles, drawing on the foundational concept of the impulse-propagation mechanism - the response of a dynamic system in equilibrium to a shock. Thus, DSGE results depend on poorly or even non-identified shocks which exacerbates the risk of over-adjustment due to the high degrees of freedom inherent in the specification of "exogenous stochastic shocks" (see Romer (2016) and Lindé et al. (2019) for identification and misspecification issues in DSGE). These shocks drive a substantial portion of the model's behavior but limit its out-of-sample robustness and ability to forecast, as regime changes and nonlinearities are often absorbed rather than explicitly modeled. Frequently, innovations—orthogonal residuals of a linear process such as a VAR—are classified as exogenous shocks despite potential endogenous origins[9]. Therefore, macroeconomic fluctuations can be seen as the optimal response of the private sector to those shocks under constraints. This approach, beyond its lack of realism and the *ad hoc, ex-post* nature of the assumed shocks also prevents the modelling of persistent financial crises and economic recessions (e.g. massive and long-term unemployment). Eventually, usually DSGEs

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[8] We thank Félix Ranson for introducing us to this theorem and its equivalence with SMD.

[9] The ambiguity in the definition and ontology of shocks further complicates their interpretation. For instance, Sims (1980), while advocating an atheoretical stance, interprets innovations in macroeconomic models as shocks, whereas Cochrane (2004) views instruments as shocks.

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.

It is therefore not excessive to require a model, especially within an institutional framework, that allows for (i) crises (with persistence and hysteresis), (ii) the possibility of the existence of multiple equilibria, no longer restricting the problem to the convergence of a return to a single equilibrium but rather to the selection and change of equilibria / basins of attraction in the economy (Vines and Wills, 2021)[10], and (iii) nonlinearities to allow endogenous fluctuations and cycles - both at equilibrium and out-of-equilibrium - even without exogenous shocks, e.g. à la Goodwin (1967) with a limit cycle or through the concept of stochastic limit cycles (endogenous dynamics influenced by exogenous shocks, cf. Beaudry et al. (2020))[11]. One resulting challenge is the desire to be able to construct out-of-steady-state Impulse-Response Functions (IRFs) to carry out forecasts, for example following a public policy, without assuming that the economy is in equilibrium at the starting time *t*. As for the disentangling of endogenous fluctuations and exogenous shocks, analysis in the frequency domain (spectral density) seems promising (Ibid. for the empirical analysis of the business cycle, and Sala (2015) for the estimation of parametrics).

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

3.3. Neutrality and exogeneity of money

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[10] See their MEADE (Multiple-Equilibrium And DiversE) paradigm.

[11] Such models would require adapted solution methods as perturbation methods (Taylor approximations) are popular for solving non-linear models but fail to identify solutions involving limit cycles or chaos, as they assume that trajectories must converge to a fixed point and therefore a stationary state (Galizia, 2021). Therefore, it would rule out any limit cycle due to a violation of Blanchard Kahn conditions.

Money is not just a medium of exchange (Keynes, 1936); it also serves as a store of value linked to expectations, beliefs and precaution, a unit of account, and, most importantly, a driver of economic activity through its impact on liquidity, debt, and investment decisions (see Arestis and Sawyer (2006) for a survey). This has led to the idea of non-neutrality of money (Bernanke and Gertler, 1995; Christiano et al., 2005). This hypothesis has been empirically studied following Friedman and Schwartz (1963). While classical RBC and CGE models are models without money or only as a numeraire for relative prices and a proxy for the general price level, more recent CGEs and the current NK DSGEs are monetarist (since a monetary shock is always assumed to be inflationary and to lead to an idiosyncratic short-term increase by agents in the goods they produce, hence to a temporary rise in output). While money is neutral in the short and long term for classical RBC models, it is neutral only in the long run for NK DSGE models, in which money can have real short-term effects on output and employment due to price and wage rigidities, stickiness and adjustment times (see Mankiw and Romer (1991) for a standard illustration), giving room for monetary policy through the Taylor rule. It should nevertheless be noted that Jordà et al (2024) empirically show the non-neutrality of money in the long term using local projections (whereas until now, the 'long term' referred to the period when money was presented as no longer having an impact).

Moreover, considering money as exogenous overlooks the critical role that financial institutions play in money creation, allocation of credit, and thus in influencing economic cycles. A vast literature shows the endogeneity of money, including based on empirical demonstrations (e.g. McLeay et al., 2014; Myatt, 1986; Werner, 2014, 2016). 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 has been integrating money-creating banks where they pre-finance investments (e.g. Jakab and Kumhof, 2015). Such models often integrate short and even long term non-neutrality of money, and can be seen as monetary extensions of Solow's growth model (Van der Ploeg, 1985; Gertler and Kiyotaki, 2011).

3.4. Private debt and financial instability

The economic role of private debt, credit emission and financial markets, both in investment and in financial crises, has been widely documented (cf. work by Fisher, 1933; Minsky, 1977, 1986; Kindleberger and Aliber, 1978), from the Japanese stagnation to the 2008 GFC (Koo, 2009). High levels of private debt in the non-financial sector and rapid credit expansion can lead to financial instability and downsides, and are good predictors for them (cf. *inter alia* Claessens et al., 2012; Drehmann et al., 2012; Gourinchas and Obstfeld, 2012; BIS, 2014; IMF, 2017; Gertler and Gilchrist, 2018; BIS, 2022), but also for the distribution of GDP (Adrian et al., 2019). Those financial cycles (i.e. *"self reinforcing interactions between perceptions of value and risk, attitudes towards risks and financing constraints, which translate into booms followed by bust"*, Borio (2024) reinforce macroeconomic cyclicality, especially from the moment when real income is insufficient to repay the leveraged loan (the so-called *"Minsky moment"*), for example during asset bubbles (Grasselli and Costa-Lima, 2012). Thus, models that integrate private debt can better analyse the implications of debt accumulation and deleveraging processes on economic stability.

However, including private debt is not sufficient when such inclusion is performed in a general equilibrium framework where, by construction and assumption, stabilisers lead to market clearing, capital readjustment and therefore to the drastic reduction in the possibilities of modelling financial crisis results. There is a need to include reinforcing feedbacks in the financial sector and amplification mechanisms which lead to out-of-equilibrium dynamics and therefore to massive financial crises and recessions (e.g. Krugman, 2009). Such additions are necessary if one wishes to simulate the post-2008 recession. Thus, a few NK models were modified to encompass not only private debt, but also further additions like a debt-limit and the deleveraging effect of shocks (Eggertsson and Krugman, 2012). Others were adapted to include monetary transactions and the possibility for default, so that monetary policy could affect the real output even with fully flexible prices (Giraud and Pottier, 2016). By doing so, they show the risk of the impact of rapid deleveraging on the emergence of Fisherian debt deflation (Fisher, 1933), a liquidity trap and a savings paradox. This calls for models to take into account financial assets and their counterparts, not just real assets. These assets must be modelled as stocks, and not only flows. This requires an integration of the financial mechanisms and drivers of these imbalances, notably banks probability of default, non-performing loans, 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*). This is all the more important because recessions that coincide with a financial crisis are more severe and longer-lasting (Jordà et al., 2016), and may even have a *permanent effect* on the *level of* output, not just growth (Drehmann et al., 2017).

The integration of private debt is particularly justified in the context of the environmental crisis and ecological transition, as *"climate change can increase defaults with adverse effects on bank leverage ... can cause an asset price deflation process. Climate-induced financial instability reinforces the growth-reducing effects of climate change."* (Dafermos et al., 2018). On the one hand, the financial risk in the event of non-rapid-enough transition must be taken into account, in relation to the necessary investments for repairing the environmental damage undergone by the economy (Dietz and Stern, 2015; Bovari et al., 2018, 2019). On the other hand, the risk of debt overhang in the event of investments with low returns in the ecological transition need also to be accounted for (cf. Carney (2016) on the dual risk of non-transition and transition). Besides, the management of asset stranding and capital stranding is today a brake on the ecological transition (Giraud et al., 2021) and will tomorrow be a major prudential and financial risk. This further justifies the integration of financial assets in macroeconomic models, also to be able to analyse green prudential policies such as *public bad banks* (Daumas, 2023a).

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

3.5. Representative agent and rational expectations

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

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

Generally, this representative agent has had rational expectations, i.e. perfect foresight in mean (except for stochastic unexpected shocks), ever since the rational expectation "revolution" (Muth, 1961; Lucas, 1977). However, in addition to the vast empirical, psychological and econometric literature contributing to show that agents do not have rational expectations (cf. *inter alia* Lovell, 1986; Pesaran, 1987; Manski, 2004; Guesnerie, 2005; Evans et al., 2018; Kirman, 2021; D'Haultfœuille et al., 2021), the theory illustrates the fundamentally unstable nature of the latter in the presence of non-linear dynamics à la Solow (Cass and Stiglitz (1969)[12] ; Guesnerie (2005) on eductive instability and coordination failures). Moreover, the coupling of rational expectations with the Ricardian hypothesis implies a neutralisation of fiscal policies – agents reduce their consumption by the same amount in intergenerational anticipation of future taxes to pay it back. Such hypothesis is empirically contested (Stanley, 1998; Wroblowsky, 2007) or at least nuanced (Nickel and Vansteenkiste, 2008). This hypothesis holds mainly thanks to (or because of) the *ad hoc* optimisation framework (Ricciuti, 2001), together with the added problem of publication bias (D'Andrea, 2022). Finally, rational expectations may be seen as eliminating the dynamic character of even a multi-period model in discrete time, since backward induction may just double the number of equations in a single period.

Some models now integrate bounded rationality, as well as suboptimal and heterogenous forecasting power of agents, with heuristics (e.g. Deak et al., 2017). Nevertheless, the intertemporal optimisation goal of agents, even in a framework of bounded rationality, leads to a smoothing of the impact of economic shocks, through a modification of the capital stock seen as extremely flexible and able to be reallocated intertemporally to achieve the desired return, which can underestimate the impact of negative economic shocks (for example, underestimating the impact of capital stranding in the case of ecological transition). To overcome this problem, Heterogeneous Agents New Keynesian (HANK) models aim to replace the aggregate Euler's Equation (IS curve) with more modern theories of consumption and saving (e.g. *"buffer stock"* model), with a diversity of households (and sometimes firms), which are heterogeneous ex-ante and ex-post, with incomplete financial markets and imperfect risk sharing among them. Drawing on seminal models with heterogeneous agents (à la Bewley-Huggett-Aiyagari), this approach is based on a vision of macroeconomics as joint distributions of variables (productivity, income, wealth of agents, etc.), reminiscent in a way of reaction-diffusion models in biology. It makes it possible to relax the Ricardian hypothesis and the hypothesis of intertemporal optimisation behaviour through word-of-mouth agents, because empirical work tends to show that consumption is not very sensitive to variations in real rates and that it reacts strongly and very heterogeneously to transitory variations in income. In particular, HANKs provide a much better understanding of the transmission mechanisms of monetary policies and their distributional effects, not only through the optimal reallocation of savings and consumption à la Ramsey (DSGE) but above all through the indirect effects on wages and employment, and on the valuation of financial assets. 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.

The heterogeneity of agents and their behaviour, beyond realism, is an important element as it can undermine policy model analyses, for example of standard NK DSGE results, as optimal monetary policies and distributional effects are affected by this heterogeneity and differences in expectations (e.g. Gasteiger, 2014; Di Bartolomeo et al., 2016). However, the complexity of HANKs added onto the NK DSGE structure leads to important computational issues, as *"solving*

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[12] 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.

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

3.6. Substitutability of inputs in production functions

Economic models generally build on production functions, which take production factors as inputs (mostly capital and labour) and give production level as output. If standard models generally do not include energy into production factors, energy plays a fundamental role in the economy, which can also be conceptualised as a dissipative structure requiring energy and material flows to sustain itself (Herbert et al., 2023). If energy is rarely mentioned as a factor of production, often hidden as a residue of capital, it is included in current economic-energy-environment models, usually through a nested KLEM (Capital, Labour, Energy and Materials) production function. Yet, a problem emerges regarding the degree of substitutability between inputs in the production functions (i.e. the ability to compensate for one factor of production with another while maintaining the same level of production). Those functions are generally of the Cobb-Douglas type or CES (Constant Elasticity of Substitution) type, with different elasticities of substitution (eos) between production factors. The value of substitutability between energy and other inputs in nested CES production functions has a critical impact on the transition trajectories obtained from the models. Trivially, the higher the eos, the easier it is to transition and the less costly it is. Indeed, high eos indicates an ease to replace the productive apparatus with a "clean" one, thus implying a low degree of path dependency for the system. This is in line with one of the common criticisms against large scale CGEs: the fact that, from a certain scale, we no longer know what determines the trajectory, whether public policy or the choice of certain parameters' values. It also ties in with Pindyck (2017)'s criticism of the arbitrary calibration within Integrated Assessment models (IAMs) of parameters that are nonetheless crucial to the model dynamics and results. Besides, the possibility itself to estimate production functions and the values of the substitution elasticities is questioned, and may not be robust (Shaikh, 1974; Felipe and McCombie, 2005, 2010; Csereklyei et al., 2016). This estimation is derived more from tautological accounting identities and statistical artefacts than from technological relationships (Felipe and McCombie, 2010).

3.7. International trade, finance and flows

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

Conclusion

In conclusion, we attempted to draw up a list of challenges faced by economic modellers working on the ecological transition. **Table 1** presents a complementary list of modelling priorities and challenges. Recent new features and improvements of DSGE and CGE models bring some innovations, adaptations, and partial answers to those challenges. We argue that diversifying the classes of models used can lead to more comprehensive and systematic responses to the challenges presented in this section. This is also due to the fact that, as Dow (2021); Storm (2021); Blanchard (2016) show, New Keynesian extensions and additions to DSGEs and CGEs are applied on an already existing structure, leading to limits in the scope of additions, complexity and tractability. Models with a different core structure therefore seem to have all their place to complement the macroeconomic models currently used for policy making. The following section aims to present such complementary modelling tools and their added-value.

I. Other Modelling Priorities

- **Climatic and Economic Uncertainty**

High uncertainty in key parameters such as climate sensitivity to GHGs, carbon system inertia, technological innovation, and fiscal/monetary policy impacts.

Use of probability distributions (e.g. Bovari et al., 2019).

Behavioral models like EIRIN explore green investment and financial risks.

- **Putty-Clay Capital and Path Dependency**

Investment constraints leading to irreversibility in technical combinations after investment (*Putty-Clay* capital e.g. Johansen, 1959; Cass & Stiglitz, 1969) and delay-to-build as capital drives GHG emissions and determines stranding issues.

- **Capital Accumulation and Endogenous Growth**

Shift from exogenous growth models to endogenous growth frameworks with Schumpeterian innovation dynamics.

EIRIN incorporates green technology investment effects and E3ME microfounds technological change through a bottom-up process.

- **Regionalization and Geographic Disaggregation**

Tailoring behavioral equations to country-specific parameters for multi-region and multi-sector integration.

- **Structural and Regime Changes in the Phillips Curve**

Integration of wage bargaining decline, competition effects, and non-linearities in inflation dynamics.

- **Inclusion of Services**:

Accounting for the dominance of services in GDP and their hidden energy consumption impacts.

II. Further Modelling Challenges

- **Estimation, Calibration, and Backtesting**

Addressing challenges in parameterization, *ad hoc* calibration and Bayesian estimation criticized for arbitrariness (e.g. Blanchard, 2016; Romer, 2016).

Rolling backtesting methods to enhance empirical robustness of models.

- **Financing Constraints and Endogenous Cycles**

Incorporating credit and liquidity constraints to model ecological transition financing, and allowing for amplification and persistence.

- **Capital-Labor Substitution**

Revisiting elasticity assumptions (e.g. Knoblach et al., 2020) and considering socio-political determinants of factor distribution (e.g. Goodwin, 1967).

- **Environmental Feedback Loops and Extended Damage Functions**

Expanding beyond temperature anomalies to include biodiversity, resource extraction, and agricultural impacts (e.g. Vidal et al., 2018).

- **Intergenerational Inequalities and Discount Rates**

Reassessing discount rates and social cost of carbon calculations to account for uncertainty, ethical choices, and intergenerational equity (e.g. Stern, 2007; Fleurbaey & Zuber, 2013).

Alternative agnostic approaches to social discounting like robust scenario planning (Ferrari et al., 2022).

Table 1. List of other modelling priorities and modelling challenges, not addressed in **Section 3.**
See Giraud and Valcke (2023) for a reformulation of the current scientific challenges of the interaction between the environment and macroeconomics.

Section 4 - Insights and solutions brought by models from Ecological Macroeconomics

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

1. Output gap, “natural rates” and unobservables;
2. Equilibrium, optimising shock-driven 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 of inputs in production functions;
7. International trade, finance and flows.

Table 2 presents a list of advanced models from Ecological Macroeconomics (EM), assessing for each model its robustness to the critiques from **Section 3**. Those models present an important variety of sizes and scopes. In the following paragraphs, the models from **Table 2** are further detailed in terms of features, aim and scope. **Table 3** then lists the scientific literature related to these models

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

Table 2. List of advanced EM 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.

Model	Scientific literature
DEFINE	Dafermos et al. (2017, 2018) Dafermos & Nikolaidi (2019, 2021, 2022) George & Dafermos (2023)
DSK	Lamperti et al. (2018, 2019, 2020, 2021) Lamperti & Roventini (2022)
E3ME	Dwesar et al. (2022a,b)
EIRIN	Monasterolo & Raberto (2018, 2019) Gourdel et al. (2022, 2024) Ranger et al. (2022) Gourdel & Monasterolo (2022) Dunz et al. (2023)
EUROGREEN	D'Alessandro et al. (2020) Cieplinski et al. (2021)
GEMMES	Yilmaz & Godin (2020) Woillez & Espagne (2022) Truong et al. (2023) Yilmaz et al. (2023) Godin et al. (2024) Moreno et al. (2024)
MEDEAS	Nieto et al. (2020a) Nieto et al. (2020b) Capellán-Pérez et al. (2020) Blas et al. (2018) Álvarez-Antelo et al. (2018)
WILIAM	LOCOMOTION project reports Lifi et al. (2023) Samsó et al. (2023)
ESTEEM	Magacho et al. (2023a) Magacho et al. (2023b)

Table 3. List of advanced alternative models. For each model, the related scientific literature is given.

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[13]: 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)[14].

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

An advanced, empirical SFC model is the EIRIN model (Monasterolo and Raberto, 2018, 2019). It was specifically developed to analyse the direct and indirect impacts of climate risks, green fiscal and finance policies on the real economy and on finance. EIRIN is an open economy model composed of a limited number of heterogeneous agents and sectors of the real economy, public and private finance. Agents are heterogeneous in terms of sources of income and wealth, access to financial markets, access to capital, skills and GHG emission intensity. Thanks to this, the distributive effects of green policies are assessed in terms of income inequality and wealth concentration (Monasterolo and Raberto, 2018). Agents are endowed with behavioural decisions based on empirical information and heuristics. They formulate decisions based on adaptive expectations. Agents and sectors interact through a set of real and financial markets,

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

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

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

Another prominent SFC model is EUROGREEN (D'Alessandro et al., 2020; Cieplinski et al., 2021). This model is especially focused on inequalities and was designed to assess the impacts of alternative packages of climate policies in terms of employment and wealth distribution between various population groups. The model was developed in the wake of the *"Gilets jaunes"* (*Yellow Vests*) movement and was focused on the case of France, partly due to the availability of extensive national data on welfare accounting, which allowed a thorough country-specific calibration of the model. The EUROGREEN model comprises 13 heterogeneous population groups, defined in terms of skills and working status. It gives a detailed description of the French welfare system and of the various income sources of each population group. The policy packages studied in the model include incentives for different types of technological innovation, carbon border adjustment mechanism, working time reduction, job guarantee program and a wealth tax. Next to income distribution and unemployment, the model also studies the impacts of different policy mixes on economic growth, energy demand, GHG emissions and government budget. The respect of the Maastricht criteria are discussed in each scenario and the simulation results are compared with the forecasts from the EU's official reports. Besides, a distinctive feature of the EUROGREEN model is its endogenous determination of technological progress. Production in the model is defined by an input-output matrix including multiple industries. Endogenous investment decisions determine innovation and the emergence of various new industry-specific technologies, which are then adopted or not by the agents based on a cost-minimisation (D'Alessandro et al., 2020). This confirms the previous literature review of EM models (Hardt and O'Neill, 2017) which found that combining input-output and stock-flow consistency analysis was a promising approach.

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

Moreover, the French Agency for Development (AFD) developed an advanced and highly detailed SFC model: the GEMMES model. GEMMES (General Monetary and Multisectoral Macrodynamics for the Ecological Shift) is an SFC macromodel in continuous time. It represents a small developing economy with an open financial account, explicitly accounting for all gross financial flows (and not just net flows). This model exhibits disequilibrium dynamics with both prices and quantities adjustment. Such dynamics apply namely to the supply-demand relationship for consump- tion goods and to the determination of the exchange rate. The accumulation of foreign exchange reserves are included in a robust way in the model, with clearly identified causal mechanisms, encompassing the role of agents' expectations. Real and financial flows are distinguished from each other and the interdependence between both is modelled. The GEMMES model therefore adequately answers the international trade, finance and flows critique from Section 2.2. The canonical GEMMES model (Godin and Yilmaz, 2020)[15] was developed to study how fluctuations in major financial centres could induce boom and bust episodes in such an open economy, via portfolio flows and cross-border lending (as shown by

[15] Building on the seminal paper of Bovary et al. (2018) that uses the Goodwin-Keen model in a SFC-ecological framework.

Rey (2015)). It then led to the development of various country-specific versions, for example for the case of Vietnam (Woillez and Espagne, 2022; Truong et al., 2023), Tunisia (Yilmaz et al., 2023) or Colombia (Godin et al., 2024; Moreno et al., 2024). GEMMES was also coupled with several biophysical models, namely crop production models under different climate scenarios (Yilmaz et al., 2023) and energy models (LEAP for Morocco & Vietnam – ongoing work). Moreover, (Woillez and Espagne, 2022) added to GEMMES, under different climate scenarios, various sectoral climate damages which were interconnected and could lead to an aggregate damage which was higher than the sum of its parts. Thus, GEMMES has been extensively used to study how climate change and/or decarbonisation policies 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 asym- metric information. The model also includes explicit aspects of tensions between economic actors, leading to temporary or permanent imbalances. Furthermore, GEMMES incorporates investment functions à la Bhaduri and Marglin (1990), which allow to model economies that can be driven by both supply and demand (profit rate and productive capacity utilisation rate, cf. Blecker and Setterfield, 2019).

4.2 Agent-based modelling

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

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

4.3 Multi-sector disaggregated models

The six alternative models presented so far are all suitable complements to DSGEs, since their level of detail, scope and applications are similar in nature. However, none of these models focuses on representing a multi-sector, disaggregated economy with its interdependencies, in the way that CGEs do[16]. The goal of the MEDEAS, then LOCOMOTION projects was to fill this gap[17]. Those two research projects were funded by the European Union's Horizon 2020 research and innovation program and led to the development of the MEDEAS IAM, followed by WILIAM. MEDEAS is a system dynamics model, in the fashion of the pioneering WORLD3 model of Meadows et al. (1972). The main goal of MEDEAS is to provide a detailed, multi-sectoral model which endogenously accounts for biophysical constraints (energy and resources, namely). The economic module (one of the 9 main modules composing the model) is based on a dynamic Input-Output (IO) framework, with a sectoral disaggregation into 35 industries. MEDEAS has been developed at three different scales: global (Nieto et al., 2020b; Capellán-Pérez et al., 2020), EU (de Blas Sanz et al., 2018; Nieto et al., 2020a) and country-level (Álvarez Antelo et al., 2018). Those three models are nested into each other, with a one-way integration: the parent models (World, EU) provide the child models (EU, country) with the constraints in terms of energy and materials availability deriving from regional or global dynamics. In the same way, CO2 concentration and global temperature increase are determined

[16] Except maybe GEMMES, when coupled with physical multi-sectoral models.
[17] More information on these two projects can be found on their respective websites: https://medeas.eu/ and https://www.locomotion-h2020.eu/

by running MEDEAS-World. They are then taken as inputs by the EU and country models, based on which these models compute heterogeneous climate damages (Nieto et al., 2020b; Capellán-Pérez et al., 2020).

The LOCOMOTION project departed from the legacy of MEDEAS to develop WILIAM (Within Limits Integrated Assessment Model). In WILIAM, the economic model of MEDEAS was replaced by a dynamic econometric multi-regional Input-Output (IO) model[18]. 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 production and income generation and distribution on the other. The different regions are linked through trade flows, with trade shares defined through Armington elasticities, which enables the analysis of different configurations of supply chains (e.g. globalisation, near-shoring, or back-shoring) (Lifi et al., 2023; Samsó et al., 2023).

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

Finally, the ESTEEM model developed by the AFD is complementary to the other models listed above. This model relies on a multi-regional IO framework to analyse the exposure of multiple countries to sunset industries according to three dimensions: external (sunset industries being a source of foreign exchange), fiscal (government revenues) and socioeconomic (job losses). The

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

carbon-intensive industries are identified and each country's dependence on these industries, both direct and indirect, is analysed. Such dependency is unique for each country and depends on the structure of its economy and on its trade relations with other countries. Magacho et al. (2023a) performed such analysis for 189 countries, assessing their level of exposure and how transition risks could be addressed in each case to ensure an adequate transition path. The impacts of CBAM (Carbon Border Adjustment Mechanism) on EU trade partners was also analysed with ESTEEM (Magacho et al., 2023b). Thus, this model provides an insightful tool to study the intertwine between cross-sectoral dependencies and international flows' interdependence.

Section 5 - Conclusion

Currently, macroeconomic policy analysis overwhelmingly relies on the use of CGE and DSGE models. A series of weaknesses of those models were highlighted in **Section 3**, which become exacerbated in the context of the ecological transition. We argue that the extensions and additions to CGE and DSGE models do not fundamentally remedy them, while facing their own limits regarding complexity and tractability. On the contrary, most of the Ecological Macroeconomics (EM) models presented in **Section 4** were developed with the specific aim of overcoming one or several of these challenges. These models are not merely of academic interest. They are capable of responding to the practical needs of policy makers. Using them in complement to CGEs and DSGEs would allow public institutions to significantly enhance their modelling capabilities. Yet, as can be seen from **Table 2**, 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 fact that the diversity of models adds to predictive accuracy is widely documented (Hong and Page, 2004; Guerrien and Jallais, 2009; Garnett et al., 2009; Page, 2007). As Page (2010) puts it in a very simple way:

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

A counter-argument to the diversification of modelling tools is the risk of "anything goes," as Gräbner and Strunk (2020) caution. While diversification enhances the ability to address complex realities, it must not compromise scientific rigor. Constructive communication and collaboration within the scientific community are essential, as illustrated by climate science: since 1997 with the Coupled Model Intercomparison Project of the World Meteorological Organisation, climate scientists have developed best practices, including standardized databases and systematic comparisons for General Circulation Models (GCMs) used to simulate the Earth's climate. These efforts ensure transparency, robustness, and continuous improvement, offering a model for other disciplines in managing the complexity of diverse modelling approaches. This need for transparency in the choice of hypotheses 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).

Having a co-existence of DSGEs and CGEs with alternative models is therefore key for policy discussion[19]. Existing examples of models diversification include the World bank, which jointly used E3ME and MANAGE (a CGE model) for producing the Country Climate and Development Report for China (World Bank Group, 2022a) or the Task Force on Climate-Related Financial Disclosures (TCFD), IMF and European Central Bank which released a series of technical papers using the EIRIN model (*see supra*). Thus , this growing institutional recognition of the value of model diversity underscores the beginning of a fundamental shift: indeed, to navigate the complex, interconnected challenges of the ecological transition, the future of policymaking must embrace a pluralistic approach to economic modelling to build solutions that will be transformative.

Statements and Declarations

Authors' Contribution

All authors contributed equally to the conception of the research question, the literature review and the draft. More specifically, P.J. suggested the original project, analysed and presented the alternative models and their contributions (Section 4) and managed contact with their respective research teams. C.S. analysed the canonical models and established the modelling challenges (Sections 1, 2 and 3). Both authors contributed to the writing of all sections.

Competing Interest

The idea of writing this article emerged from discussions with the team of Philippe Lamberts, who is president of the Greens/EFA European Parliamentary group.
Pierre Jacques is conducting his PhD under co-supervision of Antoine Godin, who is senior economist at the French Agency for Development (AFD).

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[19] 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).

presentation of their respective Ecological Economics models presented in the article, as members of their research teams.

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