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Macroeconomic modeling in the Anthropocene: why the E-DSGE framework is not fit for purpose and what to do about it

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ABSTRACT

Recent years have seen an increasing use of environmental dynamic stochastic general equilibrium (E-DSGE) models for analyzing the macroeconomic effects of the climate crisis. This paper explores to what extent these models are fit for purpose. We identify the limitations of the benchmark E-DSGE framework and explain how these limitations restrict the ability of this framework to meaningfully capture the macroeconomics of the climate crisis. We then explain how the assumptions behind these limitations can be relaxed, but argue that simply relaxing some of these assumptions in isolation is insufficient to address the problem. We therefore call for a broader use of other macroeconomic models, such as ecological stock-flow consistent (E-SFC)

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and ecological agent-based (E-AB) models, that address these limitations simultaneously. We explain how these models do not suffer from the pitfalls of the E-DSGE framework and outline how they need to improve to increase their usefulness as tools that can inform macroeconomic policy making in the Anthropocene.

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1. Introduction

Macroeconomics has entered the Anthropocene. Macroeconomists are increasingly realizing that it is no longer possible to analyze macroeconomic dynamics without considering the implications of the climate crisis (and the environmental crisis more broadly). To better understand these implications, recent macroeconomic modeling has increasingly focused on evaluating the macrofinancial impacts of transitioning to a net zero economy and identifying the necessary policy mixes to achieve climate goals (Dafermos and Nikolaidi, 2019; Battiston et al., 2021).

The climate macroeconomic modeling literature uses a wide range of tools. These include integrated assessment models (IAMs) that focus on growth dynamics (e.g. Nordhaus, 2018), ecological stock-flow consistent (E-SFC) models that concentrate on the role of interconnected balance sheets (e.g. Dafermos et al., 2017; Monasterolo and Raberto, 2018), ecological agent-based (E-AB) models that rely on a bottom-up approach for understanding macroeconomic dynamics (e.g. Lamperti et al., 2018) and environmental computable general equilibrium models (E-CGEs) that explore environment-related sectoral dynamics from an equilibrium perspective (e.g. Babatunde et al., 2017).

More recently, the literature has seen a growing use of environmental dynamic stochastic general equilibrium (E-DSGE) models, which bring climate problems to the New Keynesian macroeconomic tradition. This is not surprising given the widespread use of DSGE models in macroeconomics over the last few decades, which resulted in most macroeconomists around the world being trained based on this modeling approach.

Due to the academic and institutional dominance of DSGE modeling, the increasing use of E-DSGE models is likely to continue. The purpose of this paper is to evaluate the implications of this trend. In particular, we explore to what extent DSGE models constitute a suitable tool for understanding the implications of the climate crisis and for designing climate policies. Our central argument is that E-DSGE models suffer from several limitations that render them of little use as a scientific tool in the Anthropocene. These limitations stem from their approach to money and banking, their assumptions about the interaction between the demand-side and the supply-side of the economy and the adherence to general equilibrium. These characteristics limit the ability of E-DSGE models to meaningfully represent the economy and to provide guidance for the assessment of climate policies. Based on this, we call for a growing use of alternative modeling approaches, such as E-SFC and E-AB models, that do not suffer from these limitations and have the capacity to analyze the interactions between the macroeconomy, the financial system and the ecosystem in a more integrated and realistic way. Our analysis draws on previous studies that have criticized the DSGE approach to macroeconomic modeling (e.g. Fagiolo and Roventini, 2017; Stiglitz, 2018; Rogers, 2018, 2021; Storm, 2021). Our main contribution is that we show how the traditional limitations of DSGE models can lead to misleading results about the macroeconomics of the environment.

The paper is structured as follows. In Section 2, we provide a brief review of the recent E-DSGE literature and explain why the increasing use of E-DSGE models is important from a policy perspective. In Section 3, we analyze in detail the main limitations of E-DSGE models and explain why they are problematic for the analysis of environmental issues. In Section 4, we discuss why alternative models that have already been used in the related literature should be at the core of macro modeling approaches in the environmental crisis era. In Section 5, we summarize and conclude.

2. The rise of E-DSGE modeling and its policy relevance

DSGE models have their origins in Real Business Cycle (RBC) theory[6] and emerged from developments in macroeconomic thought led by Lucas (1976) and Kydland and Prescott (1977). In their current form, DSGE models were established in the late 1990s as the reconciliation of RBC models with New Keynesian theory[7]. Baseline DSGE models, as described for example by Galí (2015), involve households optimizing their saving and consumption decisions through forward-looking utility maximization, while firms in monopolistic competition produce differentiated goods and aim to maximize profits. These models incorporate wage rigidity and nominal price stickiness, which can lead to inflation and deviations from monetary neutrality in the short run. Aggregate demand is driven by household and firm expenditure, with the output gap—defined as the difference between actual and natural output—shaped by real long-term interest rates and the value of capital. The model's dynamics are captured through stochastic difference equations that describe the output gap and inflation.

Published E-DSGE models that analyze the macroeconomic/financial implications of both climate change and the net zero transition can be classified into two groups (see Table 1). The first group of models focuses on the business cycle without considering the role of finance (e.g. Fischer and Springborn, 2011; Heutel, 2012; Angelopoulos et al., 2013). In these models, the standard real business cycle (RBC) structure is extended by incorporating a climate damage function[8] and a carbon price that incentivizes spending on emission-reducing technologies. These E-DSGE models postulate an economy with a representative agent who chooses consumption, investment and spending on emission-reducing technologies to maximize the expected discounted lifetime utility. Output is determined through a production function whereby technology, labor and capital drive economic activity. The government chooses the optimal tax rate given the behavior of the

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[6] RBC theory suggests that the economy tends to a natural state of equilibrium and economic fluctuations are reactions to exogenous shocks such as technological shocks. In this view, cyclical fluctuations in the economy are considered efficient reallocation of resources and fiscal and monetary stabilizing policies are dismissed.

[7] The New Keynesian theory was developed in the early 1980s to reconcile nominal price stickiness, aggregate fluctuations, and non-monetary neutrality with microeconomic foundations. This was mainly done through static modeling.

[8] In a damage function, temperature (or the stock of carbon) is assumed to have a positive impact on damages which captures the proportion of output or productivity that is lost due to climate change.

firm and the consumer. Say's Law[9] holds: more saving leads to more investment and higher economic activity. There is no money in the economy. This group of E-DSGE models has primarily been used for analyzing how carbon prices should be selected so that the economy optimally responds to shocks in the presence of the negative externality associated with global warming.

Table 1: E-DSGE model groups

Model Group	Key features	Application	Examples
E-DSGE models without finance	● Real Business Cycle analysis ● Damage function ● Carbon pricing	Optimal carbon price analysis from a business cycle perspective	Fischer and Springborn, (2011); Heutel (2012); Angelopoulos et al. (2013)
E-DSGE models with finance	● Financial Accelerator ● Climate damages have a limited or zero role ● Carbon pricing and other climate policies	Analysis of the macroeconomic and financial implications of green fiscal, monetary and financial policies	Ferrari and Nispi Landi (2020); Diluiso et al. (2021); Annicchiarico et al. (2023); Carattini et al. (2023)

Source: Constructed by the authors.

The second group of models use as a basis the DSGE framework developed by Gertler and Kiyotaki (2010) and Gertler and Karadi (2011) which takes into account finance by relying on the financial accelerator mechanism of Bernanke et al. (1999). The basic principle behind the financial accelerator mechanism is that there is a moral hazard problem between banks and depositors. Depositors provide funds (the durable goods that they save) to banks, but they might decide to withdraw these funds if they believe that banks might become insolvent. In that case, banks increase interest rates and cut lending.

In the E-DSGE models with finance (e.g. Ferrari and Nispi Landi, 2020; Diluiso et al., 2021; Annicchiarico et al., 2023; Carattini et al., 2023) output is supply-determined and households consume, supply labor and save in the form of deposits and other financial assets, such as government bonds. The government typically has a balanced budget. In some of these models, the central bank does not just set the policy interest rate; it also purchases bonds issued by the non-

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[9] Say's Law posits that supply creates its own demand, asserting that the act of producing goods generates sufficient income to purchase an equivalent amount of goods in the market.

financial corporate sector. Typically, there are two types of firms: firms that produce only low-carbon energy and firms that produce only fossil energy. When climate policies are introduced, they favor green firms and harm fossil firms.

E-DSGE models are constructed, by design, to converge to a (long-run) steady state that is determined by exogenous labor force growth (‘demographics’), capital stock growth and exogenous technological progress (total factor productivity growth). In some DSGE models, this steady state is allowed to be affected by climate damages. However, when this happens, the damage functions that are used are very optimistic about the effects of global warming on the economy and, as a result, the implications of climate damages for long-run growth are negligible. As a result, E-DSGE models are mostly used to study the *transition dynamics* over the medium run. This is done by introducing an unforeseen (policy) shock, such as a (surprise) introduction of a permanent carbon tax in an economy that is initially at the steady state. Scenarios that are considered by E-DSGE modelers, in the case of carbon taxation, vary in the following dimensions: an orderly versus a delayed introduction of the tax; carbon taxation in a model with or without financial frictions; carbon taxation in combination with alternative monetary policy rules; and carbon taxation with or without macroprudential regulation.

We note that, in E-DSGE models, permanent carbon taxation must raise output and welfare in the long run, compared to the no-carbon-taxation policy, if the carbon tax is set at the level such that in the steady state it perfectly internalizes the climate externality. By assumption, the Pigouvian carbon tax induces the first-best level of abatement and the reduction in emissions that the tax brings about will enhance steady-state growth. In the universe of E-DSGE models, the issue is not whether a Pigouvian carbon tax is desirable (because it is), but rather how upsetting its introduction is to the economy in the short and medium run and whether its introduction needs supportive macro policy measures.

Hence, the focus of the E-DSGE models is on the medium-run *transition* and, therefore, the period of analysis is generally between 25 to 40 quarters. Table 2 presents an overview of six recent E-DSGE analyses of the transitory effects of carbon taxation on economic growth, welfare (measured in consumption equivalent units) and CO_2 emissions in the European Union. The following (general) conclusions can be drawn based on Table 2.

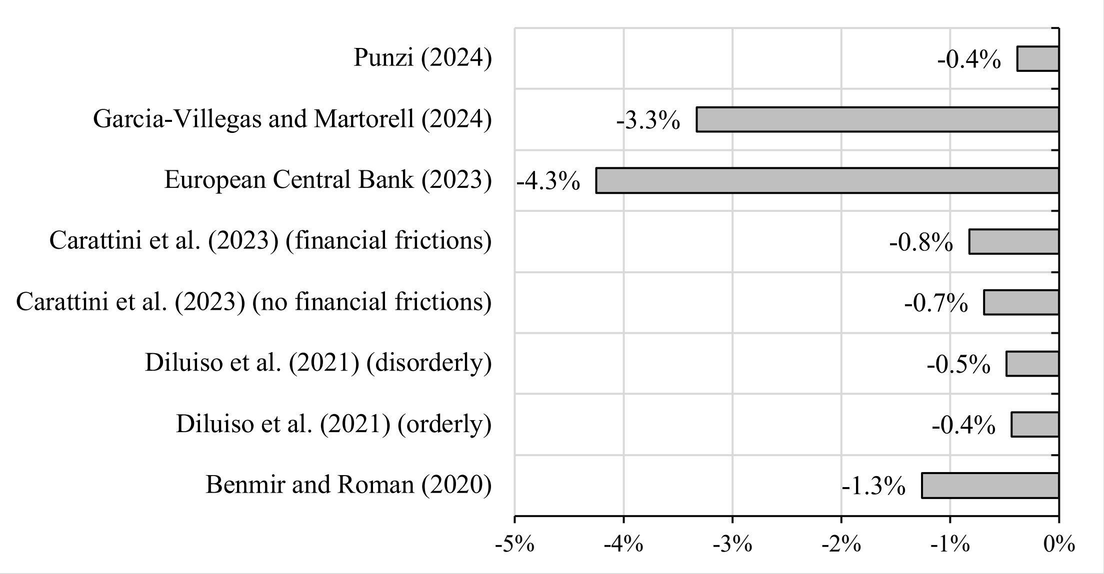
First, all E-DSGE models assume that carbon taxation is very effective in bringing down CO_2 emissions in relatively short periods of time (6-10 years). As will be explained below, one reason for this high environmental effectiveness of carbon prices is the assumption about rational expectations which allows agents to perfectly foresee how carbon prices will evolve in the future. We estimated the carbon tax per kilowatt-hour of electricity (implied by these E-DSGE studies) and find that carbon taxes varying between 1 and 5 eurocents per kWh are held to bring about reductions in CO2 emissions between 11% and 40% (in 2030, compared to emission levels in 1990). The transformative power of rather low levels of carbon taxation is built into these models;

the one exception is European Central Bank (2023), which uses a suite of (E-DSGE) models to assess the effects of carbon taxation.

Second, according to the E-DSGE analyses listed in Table 2, drastic reductions in carbon emissions do hurt economic growth, but only to a relatively limited degree. The average annual growth rate of real GDP is predicted to decline by between 0.02 and 0.22 percentage points over the medium run (of circa 10 years); in the long-run steady state, the average annual rate of economic growth will be higher than in the baseline without a carbon tax.

Medium-run economic growth will be lower, because the carbon tax raises the price of energy which, in turn, depresses investment and the value of assets (especially in the brown sector) – which leads to an increase in the interest rate, as depositors begin to withdraw their funds from their bank accounts. However, the outcomes of the E-DSGE models indicate that the medium-run trade-off between growth and cutting carbon emissions is not very pronounced. This is illustrated by Figure 1, which shows the decline in real GDP in 2030 that is associated with carbon tax rates that, according to the E-DSGE models, are capable of bringing carbon emissions by 55% in 2030 (compared to levels in 1990).

Figure 1: The impact on real GDP (in 2030) of a carbon tax that manages to reduce CO_2 emissions by 55% in 2030



Source: Constructed by the authors.

Third, carbon taxation leads to a loss of social welfare in the medium run, with respect to the (exogenous) steady state, of 0.19% to 2.12%; however, social welfare will bounce back in the long run and be higher than in the steady state without carbon taxation. Hence, the medium-run trade-off between social welfare and climate change mitigation is also found to be remarkably weak.

Finally, while carbon taxation is inflationary in the short run, its medium-run impact on inflation is negligible, because the central bank is assumed to tighten monetary policy in response to the short-run rise in inflation and to be able to bring the inflation rate back to the target inflation rate (of 2%). Simulation outcomes are generally compared in terms of changes in the volatility of inflation, measured by the standard deviation of the annual inflation rate, which will be different depending on how fast and how aggressively the central bank raises the interest rate. In view of the fact that the estimated effects on economic growth and social welfare tend to be small, the variations in inflation volatility will only be of secondary importance to macroeconomic policymaking.

Table 2: E-DSGE models: A summary of findings on carbon tax policy

		Carbon tax per KWh of electricity	Impacts on:			
Benmir and Roman (2020)	Period		Welfare	real GDP	Change in real GDP growth	CO2 emissions
Introduction of carbon tax of \$60-\$80 per ton of CO2	10 years	\$0.03	-0.88%	-0.92%	-0.09%-points	-40%
Diluiso et al. (2021)						
Carbon tax (base-line; orderly transition); level = not specified	10 years		-0.83%	-0.19%	-0.02%-points	-24%
Carbon tax (base-line; disorderly transition, 3-year delay); level = not specified	10 years		-0.91%	-0.21%	-0.02%-points	-24%
Carattini et al. (2023)						
Introduction of carbon tax of \$17.2 per ton of CO2 (no financial frictions)	25 Quarters	\$0.01	0	-0.50%	-0.05%-points	-40%
Introduction of carbon tax of \$17.2 per ton of CO2 (with financial frictions)	25 Quarters	\$0.01	-1.06%	± -0.60%	-0.06%-points	-40%
European Central Bank (2023)						
Increase in carbon tax by 65% from €85 per ton of CO2 to €140 per ton of CO2	9 years	€0.05		-0.5%/-1.2%	-0.05%-points/ -0.12%-points	-11%
Garcia-Villegas and Martorell (2024)						
20% carbon tax; level = not specified	25 Quarters		-2.22%	-2.12%	-0.22%-points	-35%
Punzi (2024)						
20% carbon tax; level = not specified	8 years		-0.30%	-0.35%	-0.04%-points	-50%

Source: Constructed by the authors.

Note: Carbon tax per KWh of electricity has been estimated assuming a carbon intensity of 385 gCO_2 equivalents per kilowatt hour (which is the carbon intensity per kilowatt hour of electricity in Germany in 2022).

The rise of E-DSGE modeling is highly significant from a policy perspective. First, for several decades DSGE modeling has been the main tool for policy analysis for macroeconomists, central banks and international organizations. This suggests that E-DSGE modeling is likely to become the reference point for understanding how climate policies affect the macroeconomy and for guiding fiscal and monetary policy decisions in the future. Second, central banks and financial supervisors are increasingly interested in analyzing how climate change can affect the macroeconomy and the financial system through the so-called transition and physical risks (Campiglio et al., 2018; Battiston et al., 2021). To do so, they need macroeconomic models that capture the macroeconomic and financial implications of climate change and climate policies. Actually, the NiGEM model – a New Keynesian model that relies on the same foundations as the DSGE models – has already been used for developing the scenarios for the Network for Greening the Financial System (NFGS)[10] that are now the basis for climate stress testing around the world (NGFS, 2023). These scenarios are affecting how central banks and financial supervisors are responding to the climate crisis.

Understanding the assumptions, the internal mechanisms and the structure of E-DSGEs is crucial to understanding their role in (fiscal and monetary) policy making for the climate crisis in the medium run. It is critical to ensure the models are used in the right context and do not provide misleading policy directives due to mis-categorized assumptions about the interactions of the macroeconomy and the ecosystem in the medium run.

3. Limitations of E-DSGE models

Table 3 provides an overview of the limitations of E-DSGE models and why these limitations matter for the analysis of climate policies and the interactions between the macroeconomy and the ecosystem. The limitations that we analyze here refer to the benchmark (E-)DSGE models with finance (Gertler and Kiyotaki, 2010; Gertler and Karadi, 2011; Diluiso et al., 2021). The first five limitations are about the unrealistic assumptions that DSGE models make about how the real world works, while the last limitation is about an internal inconsistency related to the internalization of climate damages. In the next section, we discuss (E-)DSGE models that depart from the benchmark approaches and explain to what extent these models can address some of the limitations.

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[10] The NGFS, launched in 2017, is a global network of central banks and financial supervisors that aims to contribute to the development of environment and climate risk management in the financial sector and to the scaling up of green finance.

Table 3: Limitations of the benchmark E-DSGE modeling framework and their implications for the analysis of climate issues

Limitation	**Brief description**	**Relevance for climate issues**
1. Banks are misrepresented as pure financial intermediaries and macrofinancial feedback loops play a limited role	Banks are not money-creating institutions but 'pure intermediaries', which mobilize savings in order to be able to provide loans. As a result, private sector savings drive investment. Banks' borrowers do not default on their debt and, therefore, the capital of banks is not affected by macrofinancial conditions, restricting the role of feedback loops.	Climate policies, such as carbon taxes, green subsidies and environmental regulation, are less likely to cause substantial macrofinancial amplification effects (e.g. green credit booms and dirty credit busts) since banks rely on pre-existing savings. Excluding the possibility of default of carbon-intensive or climate-vulnerable companies does not allow for a decline in the capital of banks due to such defaults to reduce loan provision and generate macrofinancial feedback loops.
2. Demand has a restricted impact on economic activity	Production creates its own demand by generating the income that flows to the factors of production (Say's law). Demand only drives economic activity in the short run as a result of imperfect competition and nominal and real rigidities.	Savings rates need to increase to finance green investment, leading to a decline in other components of aggregate demand to offset the increase in green spending. Green investment cannot, therefore, have expansionary effects making the net zero transition look more costly from an economic output perspective compared to what it might be in reality.
3. Disequilibrium phenomena cannot be adequately analyzed	The rational expectations and representative agent assumptions imply that everyone in the economy perfectly anticipates future economic outcomes, so no disequilibrium phenomena stemming from heterogeneous expectations can arise. Long-run outcomes are independent of short-run developments due to the absence of hysteresis. The steady state of an E-DSGE model cannot be subject to adverse shocks of increasing magnitude on a permanent basis.	Due to rational expectations, carbon pricing policies can have unrealistic expansionary and deflationary effects in the short run. The distributional implications of the net zero transition cannot be modelled. Green structural change driven by higher green spending in the short run cannot be modelled. The economic implications of increasing climate damages cannot be modelled.

4. The substitutability assumptions in the production function and portfolio choices are unrealistic	There is a fixed substitutability between fossil and non-fossil energy. There is a high substitutability between human/manufactured capital and natural resources. Perfect substitutability in the portfolio choice implies that any changes in the returns on assets caused by monetary policy are neutral with respect to the level of economic activity.	The fixed substitutability assumption suggests that a phase-out of fossil-fuel-based energy is not feasible for realistic environmental policies. The introduction of a green QE program can have only short-run economic and financial effects. The long-run effects on the environment are very small.
5. The positive effects of expansionary fiscal policy on economic activity are limited.	Governments have two options for funding public spending: (i) issue more debt; or (ii) increase taxes. Option (i) causes an increase in the interest rates, which in turn reduces private spending. Option (ii) leads to a reduction in the private sector's income and, thus, to lower private spending and Thus, expansionary fiscal policy can have significant crowding-out effects. The financial stabilizing effects of government debt as a low-risk asset held by the private sector are ignored. The capacity-enhancing crowding-in effects of public investment are not considered. The use of fiscal policy cannot be justified without resorting to the presence of 'externalities' and 'frictions'	The beneficial effects of green public investment are underestimated, making green investment look more costly from an economic perspective than what it might be in reality. The positive impact of green public investment on the reduction of climate economic damages (and thus steady-state output) are ignored. The complementarity between private and public green investment is not captured.
6. Policies identified by E-DSGE models with frictions and rigidities are not Pareto-optimal	Given the presence of global warming damages (reflecting a negative externality) and given the presence of rigidities and financial frictions, E-DSGE models deal with a 'second-best' world	The social welfare implications of E-DSGE model analyses are unclear. The Theory of the Second-Best states that if all of the distortions in the economy cannot be eliminated, all bets are off. Internalizing climate damage might raise welfare, but can just as easily reduce welfare. The concept of an 'optimal' carbon tax is meaningless.

Source: Constructed by the authors.

Limitation #1: Banks are portrayed as financial intermediaries and macrofinancial feedback loops play a limited role

The theory of money that a macroeconomic model uses has profound implications for the way that the model portrays macrofinancial dynamics: it determines the direction of the causal relationship between saving and investment, the interaction between effective demand and supply, as well as the financial constraints posed to private and public investment. As the ledgers for monetary transactions in modern economies, licensed commercial banks represent a central piece in the money puzzle.[11] Central banks around the world, as well as extensive scholarship on the matter, have unambiguously pointed out that the endogenous money creation approach accurately represents the modern financial system (Moore, 1988; Borio and Disyatat, 2011; McLeay et al., 2014; Borio and Disyatat, 2015; Deutsche Bundesbank, 2017; Doherty et al., 2018). According to this approach, bank loans represent balance sheet expansions of the banking sector that do not require prior savings. 'The essential function of credit […]', wrote Schumpeter (1934, p. 93), 'consists in enabling the entrepreneur to withdraw the producers' goods which he needs from their previous employments, by exercising a demand for them, and thereby to force the economic system into new channels.' The essential function of credit in a capitalist economy is to overcome the constraint of private property, which would 'make development extraordinarily difficult, if not impossible' (Schumpeter, 1934, p. 107).

The determining factors for credit creation are (1) the balance sheet capacity of the banking sector (namely, the ability of the banking sector to take on additional risk by extending more credit given its capital and other factors like the maturity structure of its assets and liabilities that affects liquidity risks), (2) the risk profile of the borrowers and of the projects that they wish to finance and (3) the regulatory environment in which commercial banks operate. Investment (including investment in green capital) is not constrained by the availability of prior savings.

In contrast to this reality, in DSGE models, prior savings are necessary for lending and, therefore, investment is determined by household preferences to deposit their savings in the banking system. Money and banking are modelled based on the 'financial accelerator' approach (Bernanke and Gertler, 1989): banks are primarily concerned with attracting savings that can then be lent out to firms, and market imperfections, such as lack of sufficient information about lenders' projects, can

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[11] In the economic literature three theories of banking have been considered (Werner, 2014): the loanable funds theory, the fractional reserve theory and the credit creation theory. According to the loanable funds approach, banks are only intermediaries between savers and borrowers in the economy. Consequently, they need to attract savings from households in order to grant loans to firms. In a loanable-funds model, aggregate demand in a closed economy without a government cannot exceed current consumption and saving. This justifies the usage of supply-side modeling approaches following Say's law. According to the fractional reserve theory of banking, central bank reserves are a driver of commercial bank lending. In other words, the lack or the presence of reserves determines whether or not a commercial bank can lend**.** Under this theory, the causality runs from central bank reserves to commercial bank lending. Finally, according to the credit creation (or endogenous money) theory, loans are created out of nothing (ex nihilo) and represent commercial bank balance sheet expansions. This theory accounts for the dual role of banks that provide both credit and money, in the form of bank deposits, to the real economy. This theory has been adopted for a long time in the post-Keynesian economics literature.

lead to higher risk premia, making lending more costly, with implications for economic activity. However, since banks cannot create money through balance sheet expansion within this framework, the effects of finance on the real economy are limited. On top of it, benchmark DSGE models do not consider borrowers' defaults which can have important implications for the stability of banks and their ability to provide credit to the economy. As a result, macrofinancial feedback loops are limited in the standard DSGE framework.

The lack of money endogeneity in DSGE modeling approaches has important implications for the macrofinancial dynamic effects of climate policies. Consider, for example, the case whereby stricter environmental regulation, green subsidies or a carbon tax are put in place, affecting the financial position of firms. In a DSGE financial accelerator framework, banks simply amplify the expansionary or contractionary effects caused by the introduction of these policies (e.g. Diluiso et al., 2021). This amplification cannot be large in quantitative terms since banks are constrained by pre-existing savings. In an endogenous money framework, these effects are not only quantitatively larger since banks can expand and shrink their balance sheets much more quickly. The results can also be qualitatively different: banks might initially generate an expansionary effect by providing more loans to firms that need to undertake green investment, but this provision of green loans might gradually lead to higher indebtedness and defaults that can result in a recession.

The non-incorporation of debt defaults in the benchmark E-DSGE model is particularly important from the perspective of climate-related macrofinancial feedback loops. For example, in Diluiso et al. (2021) an increase in carbon taxes has an initial positive impact on the net worth of banks since the increase in the value of low-carbon assets offsets the effect of the devaluation of fossil assets. This initial increase in the net worth of banks leads to an increase in lending due to the financial accelerator mechanism. If the defaults of fossil companies are incorporated into the model, it is possible to have exactly the opposite outcome, i.e. a decline in the capital of banks. Moreover, the existence of defaults is important when the implications of a fossil-penalizing factor are explored. If fossil firms are allowed to default in the model, a fossil-penalizing factor that reduces the provision of credit to fossil firms can lead to an increase in their default rate with feedback effects on the banking system. This is not taken into account in Diluiso et al. (2021). The relevance of defaults becomes higher when we consider that climate change is increasing the default rates of households and firms that are exposed to climate-related events.

Limitation #2: Demand has a restricted impact on economic activity

In DSGE models the behavior of agents relies on utility and profit maximization. In particular, current and future production is chosen such that consumption can be maximized under preferences for consumption smoothing. This is made possible by assuming that Say's law holds, i.e. by assuming that production creates its own demand through the generation of income flowing to the factors of production (capital and labor). In this context, choosing the production of firms is equivalent to choosing the income for households. Intertemporal optimization is then performed by splitting income (production) into saving and consumption depending on the preference of households for consumption smoothing over time (as reflected in the Euler equation). Households anticipate that the accumulation of additional capital stock will lead to additional production in the future, which will automatically create its own demand (Say's law) and thereby future incomes and future consumption.

The loanable funds approach of DSGE models discussed above plays a key role in this setting. Since banks cannot create money endogenously, they cannot create purchasing power and affect the demand of the economy. All the purchasing power comes therefore from the supply forces in the production function. In contrast, when endogenous money is introduced into macroeconomic theory and modeling, investment, and to some degree, consumption spending, are decoupled from the savings decisions of economic agents:[12] banks' money creation can create purchasing power irrespective of the supply side of the economy (as Schumpeter already explained). This implies that we cannot only use current factor returns (wages, returns on capital, etc.) to determine the investment and consumption spending capacity in the economy. The spending generated by credit-driven investment and consumption, as well as fiscal spending, determine supply, rather than supply driving demand through the income generated by the remuneration of the factors of production. At any point in time, it is possible to generate additional demand through endogenous money, which would have to be satisfied by the supply side of the economy. In addition, in reality, firms base their production decision on observed and anticipated demand. Therefore, since supply is governed by demand and demand is only affected and not determined by the remuneration of the factors of production (due to endogenous money creation), the economy becomes demand-led. This also implies that investment in the economy is not determined by savings, but rather by the desired investment of firms and the willingness of commercial banks to create money.

In the context of the climate crisis, the above implies that the investment needed for the net zero transition can be financed out of (new) credit and no belt-tightening by households is needed to generate savings for financing green investment. Since no belt-tightening by households is needed, social welfare is not hurt by green investment, which is in contrast to what E-DSGE models suggest (see Table 3). On the contrary, the use of Say's law and the loanable funds theory in the E-DSGE framework implies that savings rates should increase to finance green private investment, leading to a decline in other components of aggregate demand to offset the increase in green spending. This happens only because output is supply-determined and, hence, an increase in green spending is not allowed to lead to an increase in output. Similarly, if governments would decide to step in to finance some of the necessary green investments in a E-DSGE framework, this would crowd out private investment, as explained in more detail below. Therefore, green investment cannot have expansionary effects in the benchmark DSGE framework, making the net zero transition look

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[12] Consumption can be financed through loans as in the case of investment, but it relies more strongly than investment on factors' remuneration (primarily wages). This is why its decoupling from saving is lower compared to what happens in the case of investment.

considerably more costly from an economic output perspective compared to what it might be in practice.

It is important to note that demand is allowed to play a role in the short run in the DSGE framework. What is meant, however, by demand-side effects in the DSGE framework is the divergence of real production from the real aggregate income generated by production. This divergence is attributed to imperfect competition, nominal rigidities (e.g. menu costs) and real rigidities that make it optimal for firms to temporarily produce whatever is demanded. For example, faced with higher nominal demand, firms would in principle want to increase prices, which would then reduce demand making it equal to supply-determined output. However, rigidities make it costly for firms to adjust prices quickly. Thus, it is optimal for them to increase production in line with the increase in demand. This has nothing to do with the original idea of Keynes that the economy is fundamentally demand-driven both in the short run and the long run through commercial bank credit creation and fiscal spending. In particular, the agents in a DSGE model still maximize consumption over time by maximizing supply and assuming that incomes will reflect production, albeit taking into account the possibility of shocks that can temporarily result in actual production differing from the expected one.

Therefore, to appropriately capture the role of demand in macroeconomic modeling, it is not only necessary to abandon Say’s law and the loanable funds theory. It is also essential to get rid of intertemporal optimization which is at the core of the DSGE framework. Intertemporal optimization at the macroeconomic level is possible only if aggregate and individual economic behavior are similar. By assuming that this is the case, DSGE models conveniently define away the intractable aggregation problem. We say ‘conveniently’, because it is known that, for example, the conditions under which an aggregate production function can be derived from micro production functions are so stringent that it is difficult to believe that actual economies satisfy them (Felipe and Fisher, 2003).

The assumption that aggregate and individual economic behavior are similar has one more drawback: the ‘paradox of thrift’ cannot occur, by design, in (E-)DSGE models. In contrast, in models of demand-led economies with endogenous money, decreased spending (increased saving) signals to the firms in the economy that less production and investment are needed in the future, leading to a slower growth and a slower overall wealth accumulation in the economy. Within a supply-led optimization setting of E-DSGE models, this phenomenon does not occur as an increase in savings drives intertemporal investment which creates demand. Since DSGE models have intertemporal optimization at their core they have to stick to a supply-led approach and define away the aggregation problem in order to avoid having to deal with this and other fallacies of composition. It is not, therefore, unreasonable to conclude that E-DSGE models are unable to deal with the central problem of macroeconomic analysis: the coordination of decision-making concerning investment and consumption by different (groups of) agents in the economy at a particular moment in time and over time.

Limitation #3: Disequilibrium phenomena cannot be adequately analyzed

Broadly speaking, models employing the concept of a dynamic general equilibrium do not use time as a dimension in which agents coordinate and in which adjustments towards a potential equilibrium take place. Instead, time is treated just as any other commodity in the economy, in the sense that resources are optimally allocated at each point in time, without much thought on how, or if, these optimal allocations can actually arise from the interactions of agents over time.

Four aspects of the dynamic general equilibrium framework are particularly important. The first is the concept of rational expectations (REs). The second is the representative agent framework. The third is the lack of hysteresis, i.e. the fact that long run outcomes are independent of short-run developments. The fourth is the inconsistency of the equilibrium framework with the idea that the steady state might be constantly subject to shocks, the adversity of which can increase as time passes.

Let us first analyze the rational expectations concept. Under rational expectations, the economy is not only always in equilibrium, but the actual economic outcomes in a particular period are, on average, equal to the expected ones. In essence, agents are, on average, able to (correctly) forecast future production, incomes and consumption in terms of a certainty equivalent and Say's law provides a device for making this possible. REs are inherently an 'equilibrium' concept, as they require that the coordination of all the agents in the economy has already occurred and the future is known (on average). Because the coordination of the agents on the rational expectation is assumed ex ante, dynamic general equilibrium models do not have a meaningful representation of time and out of equilibrium dynamics. Crucially, REs allow agents to anticipate the impact of future policies. For instance, in the context of deficit spending, agents are assumed to anticipate future tax increases, as they incorrectly assume that public debt needs to be repaid in time.

REs are a source of two limitations for DSGE models: First, REs misrepresent the role of uncertainty in the decision-making process of agents. In deterministic models, decisions are made based on knowing future economic outcomes exactly, while in stochastic models, agents build certainty equivalents of the future based on the objective knowledge of the distribution of future events, which, still implies that agents employing REs know the behavior of all other agents in the economy in all possible future states of the economy and coordination has taken place across all agents. Hence, the economy-wide consequences of government or central banking policies are immediately understood and accounted for by the agents – this is not close to what happens in the real world. Second, REs do not really allow for heterogeneous expectations among agents, as there is only one rational (model-consistent) expectation that is on average correct.

The use of REs in E-DSGE models raises a paradox related to the role of climate damages. If the forward-looking agents in the E-DSGE universe can (on average) correctly predict the future, then they must be cognizant of the non-negligible future climate damages and of the non-zero probabilities associated with potentially catastrophic, irreversible climate change. Weitzman

(2010) demonstrated that even small risks of climate catastrophes could be so destabilizing as to completely dominate any other aspect of the analysis. For example, if climate sensitivity studies show a 1% probability of global mean temperature increases over the next 100 years of (say) 4 degrees Celsius, the negative consequences for social welfare are unbounded, as Earth's ecosystems may be careering toward collapse if climate tipping points are breached. In this case, it would be rational for these agents to step up investments in climate mitigation and adaptation today to reduce the probability of potentially catastrophic increases in global mean temperatures from 1% toward zero.

In a model populated by rational forward-looking agents, this would mean that (precautionary) savings must rise, financing the necessary step-up in green investment – it would be in the narrow self-interest of the infinitely-lived rational agent (or the infinitely lived dynasty of rational agents) to internalize the climate damages in costs and prices so as to avert the potentially catastrophic future climate damages. Since this is not what these agents do in E-DSGE models, their self-centered rationality must be taken with a few pinches of salt. On the contrary, when climate damages are introduced in E-DSGE models, they are typically calibrated using the damage function in the DICE model in which the economic damages caused by global warming are significantly under-estimated and irreversibility is not considered (see Keen, 2021). Therefore, from a forward-looking perspective, agents are not induced to take action to protect their future welfare.

However, the REs assumption can also generate unrealistic results in the short run, right when climate policies are introduced. For example, in Diluiso et al. (2021) an increasing carbon tax pathway leads to an increase in output and a decline in inflation in the short run. This is so because agents anticipate the continuous increase in the carbon tax and respond to this by increasing production in the short run when the carbon tax is still relatively low. At the same time, workers, who also have rational expectations, supply more labor and save more, given that they expect a reduction in their wages in the future. The overall expansion of supply creates deflationary forces in the short run. This modeling artefact squarely contradicts the fact that in reality, an increase in carbon tax is more likely to lead to higher inflation and create recessionary pressures.

We now focus on the second aspect of the dynamic general equilibrium framework: the concept of the representative agent. The concept goes hand-in-hand with REs. Meaningful agent heterogeneity has to involve differences in information sets and the instruments used to process the information (interpretation of the information). These differences invariably give rise to heterogeneous expectations that are not compatible with the REs approach. The REs approach can only deal with heterogeneity on the level of the production technology and/or endowments of economic agents (see, for example, Aiyagari, 1994). This means that most of the heterogeneity that exists in the real economy cannot be represented when using the REs approach, which keeps even heterogeneous-agents REs models close to representative agent models in terms of their understanding of the dynamics of an economy. By assuming away important dynamic interactions across heterogeneous agents, the REs approach runs the risk of ignoring important distributional effects (on income and wealth) of macroeconomic policies, including net zero policies.

Let us now turn to the third important aspect of the dynamic equilibrium framework: the lack of hysteresis – a key feature of disequilibrium processes. The absence of hysteresis in the DSGE framework is due to (i) the assumption that demand (which is strongly path-dependent since it relies on the dynamic evolution of wealth and debt) has no long-run impact on economic activity and (ii) the assumption that supply is not affected by demand. In the context of the next zero transition, these assumptions imply that more green spending in the short run cannot lead to higher supply and higher economic activity in the long run due to the creation of additional capital stock. In other words, green spending cannot move the economy away from the equilibrium reflected in the steady state of DSGE models.

The fourth aspect of the dynamic equilibrium framework that is important for our analysis is that it is inconsistent with the idea that the steady state of a model might be subject to adverse shocks of increasing magnitude on a permanent basis, making this steady state time-varying. This is the case with the climate crisis: the increasing temperature leads to higher economic damages as time passes which have a direct impact on the supply-side of the economy and, thus, on the steady state in the DSGE framework. A time-varying steady state is not compatible with the way that dynamic analysis is conducted in DSGE models.

A direct implication of this incompatibility is that when climate damages are introduced in the DSGE framework, it is necessary to make unrealistic assumptions from a climate perspective to avoid having a time-varying steady state. For example, Ferrari and Nispi Landi (2023) assume in their E-DSGE model that in the steady state the carbon concentration is constant so as for climate damages to be constant and the steady state to remain unchanged (when no economic shock is imposed). The reality, however, is that carbon concentration has been continuously increasing over the last decades and assuming that this is not the case does not permit a meaningful dynamic analysis of the economic implications of the climate crisis.

Limitation #4: The substitutability assumptions in the production function and portfolio choices are unrealistic

From a climate perspective, three types of substitutability in E-DSGE models are of particular importance: (i) the substitutability between fossil and non-fossil energy sources; (ii) the substitutability between human/manufactured capital and natural sources in the production function; and (iii) the substitutability between different assets in financial portfolios.

In terms of the first type of substitutability, E-DSGE models assume a fixed elasticity of substitution between fossil and non-fossil energy (see e.g. Diluiso et al., 2021). This allows these models to remain tractable in the context of the perfect foresight optimization procedures used to solve them. However, an implication of the fixed elasticity assumption is that a phase-out of fossil energy is not feasible without extremely strict environmental policies. In reality, the development of substitutability-enhancing infrastructure, such as energy storage technologies, can make it possible for non-fossil energy sources to replace fossil energy sources (Fenichel and Zhao, 2015; Mattauch et al., 2015; Yanovski and Lessmann, 2021). This is necessary for a quick decarbonization process: energy efficiency and renewable energy productivity have an upper bound due to limits related to the second law of thermodynamics (see Meran, 2019), so the net zero transition cannot happen without an almost complete substitution of non-fossil energy for fossil energy. Due to the constraints imposed by numerical solution methods in the context of perfect foresight optimization, it is hard to include endogenous substitutability across energy types in E-DSGE models and therefore capture properly the real-world properties of green structural change.

Turning to the second substitutability issue, E-DSGE models use a production function whereby there is a high substitutability between energy, capital and labor (matter is not typically considered). This comes in contrast to the ecological economics tradition that emphasizes that there is limited substitutability between human/manufactured capital and natural sources, which is also supported by empirical evidence (e.g. Cohen et al., 2019). The assumption of high substitutability is important since it softens the impact on growth of a switch away from specific finite natural sources. Although E-DSGE models do not focus on the issue of growth per se, this assumption still plays an important role since it drives the dynamics of potential output.

As far as the third substitutability issue is concerned (the substitutability in financial portfolios), benchmark DSGE models assume perfect substitutability in the portfolio choice of households and banks. As a result of this, monetary policy interventions in the form of asset purchases have neutral effects. To understand why this is the case, suppose, for example, that a central bank buys corporate bonds as part of a corporate quantitative easing (QE) program. These can be bought either on the primary market (i.e. the central bank directly buys the bonds when companies issue them) or on the secondary market (i.e. the central bank buys the bonds from households and banks that already hold them, increasing households' and banks' money holdings). This overall creates a higher demand for these bonds that tends to increase their price and, thus, reduce their yields. However, the lower yield of corporate bonds makes them less attractive for households and banks from a rate of return perspective. Due to the assumption of perfect substitutability in benchmark DSGE models, households and banks take full advantage of the arbitrage opportunity: they replace these bonds with other assets that have a higher rate of return in a way that completely offsets the increase in the demand that comes from the central bank. The overall outcome is that the yields of these bonds increase until their rates of return become equal to the rates of return of other assets. This means that, under the assumption of perfect substitutability, the central bank asset purchases do not have an impact on the cost of borrowing facing the issuers of these bonds. However, this is not in line with empirical evidence that shows that quantitative easing has non-neutral effects on bond yields (see e.g. Zaghini, 2019; Todorov, 2020).

Perfect substitutability has implications for the analysis of the effects of green monetary policy. By adopting a perfect substitutability assumption, any monetary policy intervention (such as asset purchases or collateral frameworks) that increases the demand for green bonds and reduces the demand for dirty bonds has no impact on the relative cost of undertaking green or conventional investment.

In an E-DSGE model, monetary policy can become non-neutral in the short run by assuming some portfolio adjustment costs. For instance, Ferrari and Nispi Landi (2023) introduce adjustment costs in the portfolio choice of banks between green and dirty bonds. As a result of this, banks do not instantaneously adjust their portfolio when central bank asset purchases change the relative returns of bonds. For example, the implementation of a green QE leads to a decline in the yield of green bonds compared to the yield of dirty bonds, incentivizing banks to reallocate their wealth towards dirty bonds since the latter provide a higher return. Due to adjustment costs, this reallocation of wealth does not fully offset the relative decline in the yield of green bonds caused by the green QE. The overall result is a boost in green investment due to the lower cost of borrowing associated with green bonds, implying that monetary policy (in this case QE) is not neutral in the short run. However, in the long run, no adjustment costs exist and, therefore, monetary policy is neutral.

Limitation #5: The positive effects of expansionary fiscal policy on economic activity are limited

Standard neoclassical theory employed in the benchmark (E-)DSGE models has implications for the role of fiscal policy and government debt. Four issues are particularly important. The first one is the crowding-out effect of public investment on private investment. In E-DSGE models there are two options for funding green public spending: the government can (i) increase taxes or (ii) issue more debt. Option (i) leads to a reduction in the private sector's income and, thus, to lower private spending. Option (ii) causes an increase in interest rates, which in turn reduces private spending and consumption. The underlying assumption is that interest rates have to rise to allow for deficit spending to take place, as households need to be persuaded to save more in order to buy government bonds (see, for example, Mian et al., 2021).[13] This crowding-out effect is, however, inconsistent with how real-world economies work where money and bonds are both introduced into the economy during deficit spending and where the savings are generated (in an ex-post sense) by additional spending. One important implication for the climate crisis is that E-DSGE models underestimate the beneficial effects of green public investment, making green investment look more costly from an economic perspective than what it might be in reality.

The second issue is the interpretation of government debt as a burden to future generations, and not as a low-risk private sector asset. In the neoclassical treatment of the issue of public debt, the government needs to increase taxes in the future in order to get additional 'money' to pay back the

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[13] Another reason is that an increase in public investment is assumed to be inflationary, inducing the central bank to increase interest rates due to the Taylor rule.

accumulated debt. This is then interpreted as government debt representing a burden to future generations. However, in reality government liabilities represent low-risk interest bearing assets that are useful to the private sector, particularly in their role as pristine collateral. Government debt can therefore be rolled over, does not need to be paid back and cannot be interpreted as a burden to future generations (see also Mitchell et al., 2019, ch. 21 and 22). Furthermore, in many cases government debt does not even need to be held by the private sector, as central banks are often allowed to buy it on the secondary market (and sometimes even on the primary market) and hold it on their balance sheets.

The third issue is that benchmark E-DSGE models do not allow public spending (financed by government debt) to be productive by crowding in private investment and raising productive capacity, leading thereby to higher output levels in the steady state. This assumption that public spending is not productive is even more unrealistic in the face of the substantial future damages associated with global warming. It is now widely accepted that in a business-as-usual scenario in which the net zero transition does not materialize, global GDP is likely to decline substantially.[14] Given that the cost of climate inaction is excessively high, the macroeconomic payoffs to public investment in climate mitigation and adaptation are substantial. Even if public climate spending does not raise steady-state growth, it is of vital importance in containing a drastic decline in the steady-state growth rate.

The fourth issue is that the supply-side optimization at the heart of DSGE models implies that resources in the economy are generally employed efficiently without any government involvement. Therefore, DSGE modelers always have to resort to justifications for the use of fiscal policy rooted in 'externalities' and 'frictions' which prevent the supply-side optimization from working in a welfare maximizing fashion. On the contrary, in real-world economies, where endogenous money and demand are significant drivers of economic dynamics, the role of fiscal policy revolves around fixing coordination failures resulting from fallacies of composition, as well as remedying short-termist behavior inherent to competitive environments in which short-term fitness is essential for survival (Mazzucato, 2017). This is particularly important in the context of the climate crisis. To address this crisis, we need investments that can decarbonize production processes as well as green technological innovation that requires a long-term investment horizon and can be very risky in nature (Mazzucato, 2017; Mazzucato and Semieniuk, 2018). Private investment alone is unlikely to be able to live up to the task and coordination between the public and private sectors is needed for the necessary infrastructure investments to take place. Benchmark E-DSGE models cannot appropriately capture this complementarity between private and public green investment.

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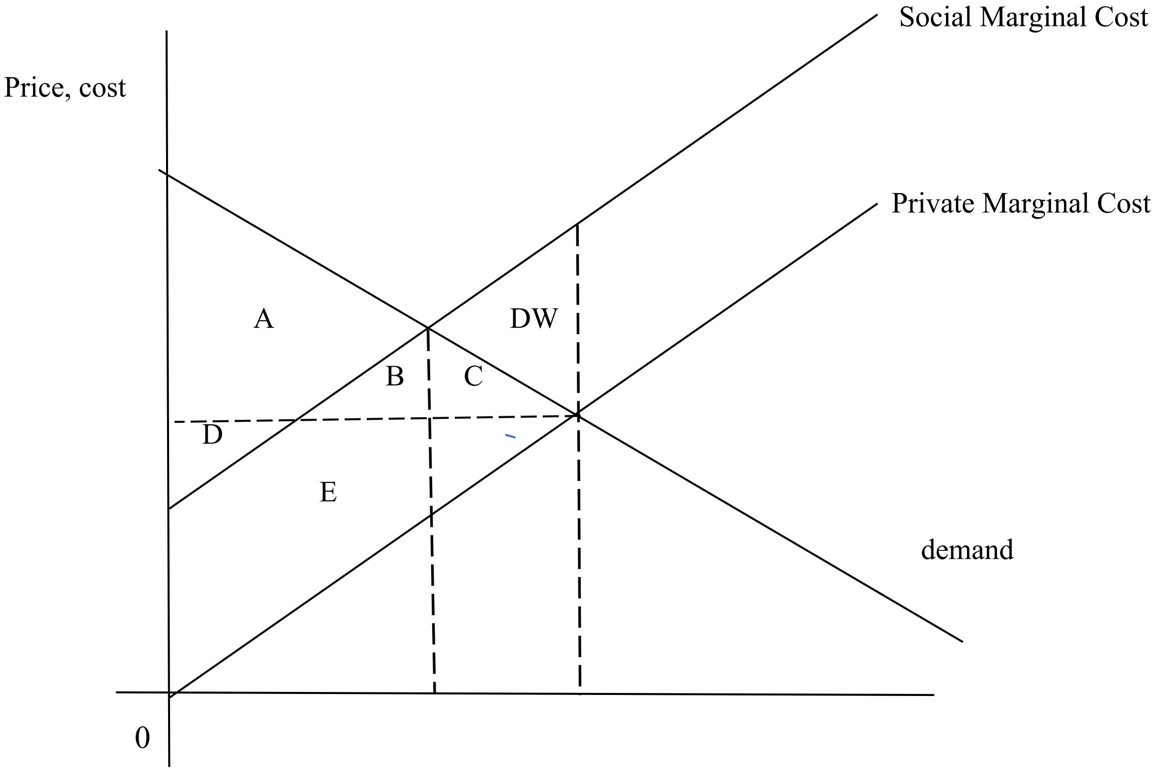
[14] For example, using projections from 33 global climate models, Waidelich et al. (2024) estimate that global GDP could decline by up to 10% if the planet warms by +3ºC; Since the study does not include non-economic impacts, droughts, sea-level rise, and climate tipping points, the authors argue that the total cost of climate change is likely considerably higher.

Limitation #6: E-DSGE models cannot identify Pareto-optimal (carbon) policies

According to the E-DSGE analyses listed in Table 2, carbon pricing leads to a decline in social welfare, relative to the business-as-usual (BAU) scenario. This is remarkable, because a central tenet of neoclassical welfare economics holds that the internalization of a negative external cost (in costs and prices) must lead to an increase, not a decrease, in social welfare (Kochen, 2022). The point is explained in Figure 2. E-DSGE models thus suffer from a logical inconsistency (Rezai et al., 2012, 2018): the presence of the negative climate externality implies that market prices are too low (because these do not account for the social cost of carbon emissions) and hence, BAU social welfare is overestimated. Hence, correcting this negative externality has no real opportunity cost — contrary to what the E-DSGE models suggest. It follows from the neoclassical logic on which the E-DSGE models are based, that internalizing the GHG externality by means of a carbon price confers a *net benefit* to humanity rather than imposing a cost.

Figure 2: Internalizing climate damage by means of a Pigouvian carbon tax



Source: Constructed by the authors.

Notes: Absent a (Pigouvian) carbon tax, private welfare = producer surplus + consumer surplus = (A + B + C) + (D + E); social welfare = A + D – deadweight loss (DW). With a Pigouvian carbon tax, social welfare = A + D.

The E-DSGE models listed in Table 2 include more distortions (e.g., rigidities and financial frictions) than just the negative climate externality (see Table 4). For instance, shocks to the economy get amplified through fluctuations in the banking sector's equity capital, which is assumed to restrict the lending capacity of banks. Importantly, "bankers do not internalize this effect that their net worth has on the economy – this is analogous to a second externality – and thus the equilibrium is inefficient" (Caratinni et al., 2023, p. 783). In the presence of multiple distortions, social welfare may decline in response to the introduction of a carbon tax. E-DSGE models are, therefore, describing a second-best economy — and this, in turn, implies that the results of these model analyses are intrinsically ad hoc and cannot be generalized (Lipsey, 2007). The Theory of the Second-Best states that if all of the distortions in the economy cannot be eliminated, all bets are off. "[I]f there is introduced into a general equilibrium system a constraint which prevents the attainment of one of the Paretian conditions, the other Paretian conditions, although still attainable, are, in general, no longer desirable" (Lipsey and Lancaster, 1956, p. 12). Hence, internalizing climate damage by means of a carbon price might raise welfare, but can just as easily reduce welfare. The concept of an 'efficient' or 'Ramsey-optimal' carbon price is meaningless in a second-best world.

The ad-hoc nature of the second-best analyses is illustrated by the fact that E-DSGE modelers introduce a variety of market failures in their model analyses (see Table 4). Due to the variety of sources of inefficiency, the results and policy implications of E-DSGE analyses are difficult to compare, while generalization (in terms of Pareto optimality) is not possible. And as Lipsey (2007) and Storm (2021) point out, there exist many additional sources of market failures, many of which are not (yet) included in E-DSGE models, including missing futures (insurance) markets and Knightian uncertainty (which means that firms are better seen as groping into an uncertain future in a profit-seeking manner, rather than maximizing the present value of expected future profits).[15]

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[15] As Lipsey (2007, p. 355) points out, 'An important implication is that the conditions for an efficient allocation of resources cannot even be defined when technology is changing endogenously under conditions of uncertainty—we do not know what allocation will produce the best results, however defined, until after the results are in.' Intertemporal optimization, as assumed in E-DSGE models, is impossible.

Table 4: A smorgasbord of E-DSGE market failures

Market failure	1	2	3	4	5
1. The global warming externality	X	X	X	X	X
2. Financial frictions between banks and depositors due to the agency problem in the banking sector that gives rise to positive interest rate spread limiting the amount of credit and, therefore, of installed capital	X	X	X		X
3. The existence of monopolistically competitive firms in the final goods sector		X			X
4. Costly price adjustment and investment adjustment cost		X			
5. Financial frictions between banks and firms due to a higher probability of default of fossil-fuel firms					X
6. Asymmetric information: depositors charge a common deposit risk premium – on the fraction of uninsured deposits – that is a function of the average risk of bank failure, which encourages excessively risky behavior by banks				X	
7. Banks' limited liability and deposit insurance, which encourages banks to increase leverage				X	

Source: Constructed by the authors.

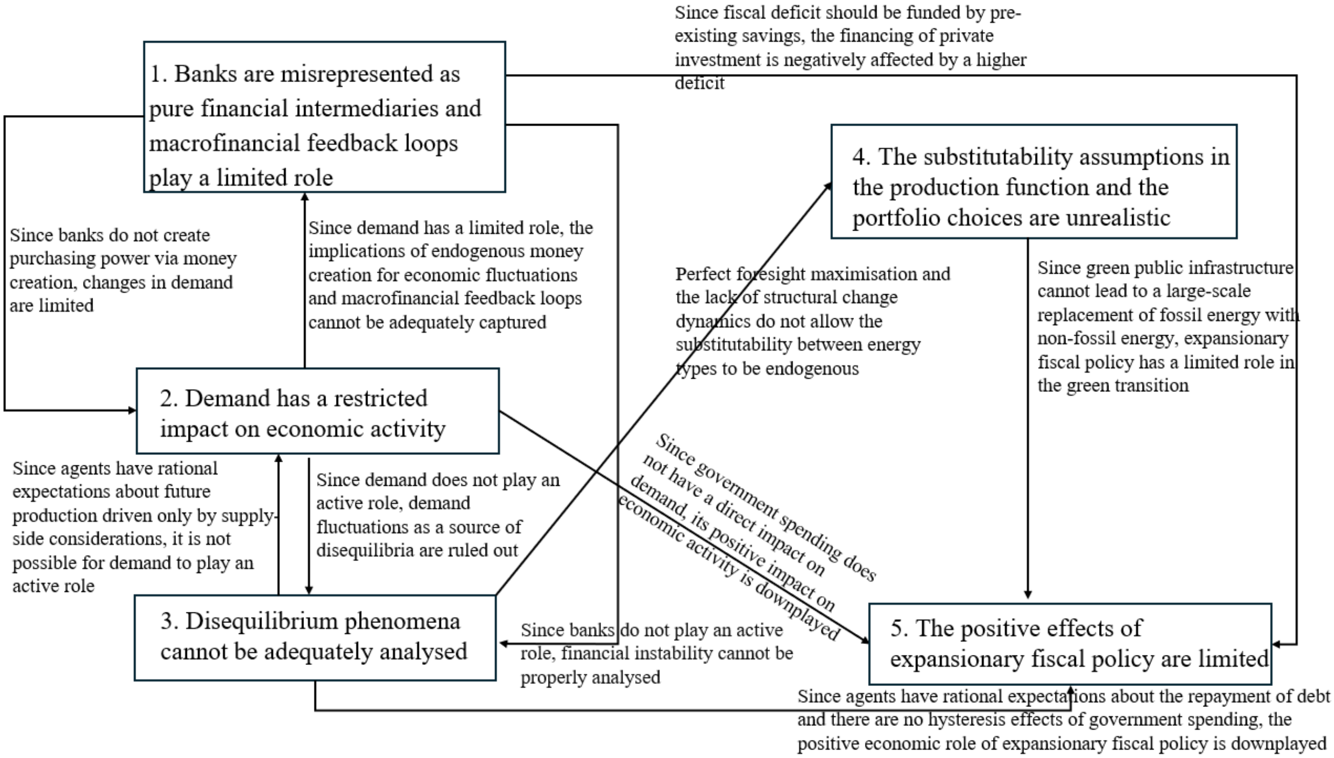
Notes: 1 = Benmir and Roman (2020); 2 = Diluiso et al. (2021); 3 = Carattini et al. (2023); 4 = Garcia-Villegas and Martorell (2024); 5 = Punzi (2024).

4. Addressing the limitations of E-DSGE models

4.1 Can the limitations be addressed within the E-DSGE framework?

Many users of DSGE models have become aware of one or more of the weaknesses of these models. In response, they have ‘broadened’ or ‘extended’ the model, typically in an ad-hoc manner (Stiglitz, 2018; Storm, 2021). Can the limitations and inconsistencies of benchmark E-DSGE models be addressed through the extensions of the DSGE framework? To answer this question, we primarily refer to existing DSGE or E-DSGE models that have relaxed some of the problematic assumptions of the DSGE benchmark framework. Our main conclusion is two-fold. First, when DSGE models try to address a specific limitation in isolation they can only be partially successful in doing so. Because of the interconnected nature of the limitations that were discussed in the previous section and summarized in Figure 3, a specific limitation cannot be addressed by simply relaxing a specific assumption and keeping the rest of the structural assumptions of E-DSGE models the same. Second, it does not look possible to develop an E-DSGE model that addresses all the limitations and inconsistencies at the same time.

Figure 3: Limitations of E-DSGE models and their interconnections



1. Banks are misrepresented as pure financial intermediaries and macrofinancial feedback loops play a limited role

2. Demand has a restricted impact on economic activity

3. Disequilibrium phenomena cannot be adequately analysed

4. The substitutability assumptions in the production function and the portfolio choices are unrealistic

5. The positive effects of expansionary fiscal policy are limited

Since fiscal deficit should be funded by pre-existing savings, the financing of private investment is negatively affected by a higher deficit

Since banks do not create purchasing power via money creation, changes in demand are limited

Since demand has a limited role, the implications of endogenous money creation for economic fluctuations and macrofinancial feedback loops cannot be adequately captured

Perfect foresight maximisation and the lack of structural change dynamics do not allow the substitutability between energy types to be endogenous

Since green public infrastructure cannot lead to a large-scale replacement of fossil energy with non-fossil energy, expansionary fiscal policy has a limited role in the green transition

Since government spending does not have a direct impact on demand, its positive impact on economic activity is downplayed

Since agents have rational expectations about future production driven only by supply-side considerations, it is not possible for demand to play an active role

Since demand does not play an active role, demand fluctuations as a source of disequilibria are ruled out

Since banks do not play an active role, financial instability cannot be properly analysed

Since agents have rational expectations about the repayment of debt and there are no hysteresis effects of government spending, the positive economic role of expansionary fiscal policy is downplayed

Source: Constructed by the authors.

Limitation #1: *Banks are misrepresented as pure financial intermediaries and macrofinancial feedback loops play a limited role*

Some E-DSGE models incorporate an endogenous loan default rate, generating some macrofinancial feedback loops. For example, Huang et al. (2021, 2022) and Annicchiarico et al. (2023) assume that when firms default, banks collect their assets and pay a monitoring cost to verify what the borrowers report. This in turn can lead to an increase in the interest rate that has a negative effect on economic activity. In this formulation, banks' balance sheet is not affected and, therefore, there is no credit tightening effect. Hristov and Hulsewig (2017) go one step further. In their model, when firms default as a result of having insufficient revenues to cover the borrowing costs, the capital of banks goes down and this in turn leads to lower credit availability. Moreover, the decline in the capital of banks increases the interest rate on loans (risk premium) which further increases the rate of default.

These formulations have three limitations, however. First, the default mechanisms take place within a financial intermediary framework: (non-money-creating) banks strictly rely on depositors to provide loans. Investment continues to be restricted by available savings and public deficits continue to crowd out private investment, which is not in line with economic reality. Second, it is not clear if this modeling framework can capture credit booms and busts as in Minsky's framework. In E-DSGE models, financial instability cannot endogenously arise as a result of the creation of credit and the accumulation of debt that can lead to debt defaults. In the impulse response functions analysis, it is basically shown that the existence of default magnifies the quantitative effects of shocks. However, after some time the economy gets back to equilibrium. This means that defaults are not a source of financial instability and crises. Third, the default rate seems to be independent of the credit provided by banks. In reality, debt defaults increase when banks are not willing to provide more liquidity to the real economy.

There are no E-DSGE models with endogenous money. However, aspects of endogenous money creation can be introduced in an E-DSGE framework. Jakab and Kumhof (2019) have developed a DSGE model in which banks are allowed to expand their balance sheet. However, in relation to the limitations discussed in the previous section, the model remains supply-led in the sense that the production decisions are made based on the premise that the production creates its own demand, allowing for a feasible solution in the context of intertemporally optimizing economic agents. As shown in Figure 3, a DSGE model that incorporates endogenous money, but keeps Say's Law according to which supply creates its own demand, cannot meaningfully address the misrepresentation of banks as financial intermediaries in E-DSGE models. An implication of endogenous money is that consumption, investment and government spending can always increase as long as finance is available – this spending determines the level of output in the economy irrespective of pre-existing savings (supply constraints can lead to inflationary pressures, but this does not change the fact that newly-created money can lead to higher levels of economic activity).

If a DSGE model assumes that output is supply-determined either in the short run or in the long run, it does not properly capture the implications of endogenous money for economic activity.

An additional limitation of the model of Jakab and Kumhof (2019) is that it effectively assumes a barter rather than a money-using economy (see Rogers, 2018). This has two implications. First, the act of borrowing and lending is actually an exchange of commodities for commodities and there is no need for money as a means of final settlement. As in the benchmark DSGE model with finance, money continues to be conceptualized in a vague way and is not considered to be essential for reducing the inefficiencies of a barter economy (see Borio and Disyatat, 2011). Second, when banks are portrayed to create money, they actually create commodities, which is counterintuitive: banks cannot produce commodities like firms.

Limitation #2: Demand has a restricted impact on economic activity

Some DSGE models have made some ad-hoc assumptions to allow demand to play a role in the long run by affecting the supply side of the economy through hysteresis. For example, Engler and Tervala (2018) incorporate some form of hysteresis into a DSGE framework by assuming that actual employment, which is affected in the short run by demand, can have an impact on productivity and therefore on long-run output through the production function. The rationale is that higher unemployment has an adverse effect on skill accumulation which is a key driver of productivity. As a result of this mechanism, any policy that affects actual employment can also have an impact on the supply side of the economy.

However, this mechanism does not allow demand to have a direct impact on output in the long run due to the inherent assumption that Say's Law holds in the long run (as rigidities and/or frictions are overcome). In addition, even in the short run, the role of demand is downplayed since this approach does not address the issue of the misrepresentation of banks in the DSGE framework (see Figure 3). The fact that this other limitation is not addressed at the same time implies that demand is not driven by money creation. A proper consideration of demand also requires that DSGE models abandon the assumption that agents have rational expectations about future production driven only by supply-side considerations (see Figure 3).

Limitation #3: Disequilibrium phenomena cannot be adequately analyzed

The fact that E-DSGE models only study equilibria and that adjustments towards a new equilibrium are not considered cannot be changed, as the equilibrium paradigm is required for the intertemporal optimization that underlies neoclassical dynamic models. However, DSGE models can incorporate non-rational expectations and heterogeneous agents. They can also analyze certain forms of hysteresis as explained above.

Rational expectations can be replaced with adaptive expectations, where agents try to minimize their forecasting errors over time (see e.g. Gelain et al., 2019 and the references therein). Ferrari and Nispi Landi (2022) have shown that when rational expectations about carbon pricing are replaced with adaptive expectations, carbon price increases can create inflationary instead of deflationary pressures and can be recessionary instead of expansionary in the short run. Annicchiarico et al. (2024) have also investigated the implications of carbon pricing with different forms of expectations. They have shown that under the presence of bounded rationality, carbon prices are less effective in reducing emissions compared to the case in which rational expectations are assumed. Overall, both cases illustrate the central role that rational expectations play in the dynamics generated by E-DSGE models that analyze climate policies.

In DSGE models with heterogeneous agents it is common to assume that there are two types of households: the Ricardian households and the non-Ricardian households (e.g. Coenen and Straub, 2005; Bhatnagar, 2023). Ricardian households are the same as the standard households in DSGE models, while non-Ricardian households consume part of their income and do not rely on utility maximization and rational expectations to decide about their consumption expenditures. The higher the proportion of non-Ricardian households, the more likely it is that fiscal and monetary policies affect economic activity through the increase that they generate in the income of households.

However, E-DSGE with some form of non-rational expectations, heterogeneous agents and hysteresis cannot still meaningfully analyze disequilibrium phenomena. For these phenomena to be analyzed sufficiently, E-DSGE models need to allow banks to create money (so as to contribute to financial cycles) and permit demand to be a driver of economic activity (see Figure 3).

Limitation #4: The substitutability assumptions in the production function and the portfolio choices are unrealistic

The issue of limited substitutability across energy types in E-DSGE models cannot be addressed without getting rid of perfect foresight maximization and without introducing some form of disequilibrium that captures structural change. Doing so would allow the elasticity of substitution between fossil and non-fossil energy to become endogenous (see Figure 3). DSGE models can only very partially address the issue of limited substitutability between energy sources by assuming that the elasticity of substitution between fossil and non-fossil energy is higher than 1 (see e.g. Diluiso et al., 2021) contrary to what is typically the case (most E-DSGE models assume an elasticity lower than 1).

In a DSGE framework, the assumption of long-run neutrality of monetary policy can be relaxed by allowing investors (households or banks) to get utility/disutility from holding specific assets. For example, Ferrari and Nispi Landi (2023) assume that households enjoy utility from holding green bonds and get disutility when they hold dirty bonds. This means that they do not perfectly replace green bonds with dirty bonds when the relative rate of return of the latter increases. In their setting, this allows green quantitative easing to have non-neutral effects on the cost of borrowing of firms in the long run. However, it looks strange that imperfect substitutability has to be justified via arguments about the utility that households receive from holding specific assets, without reference to social norms and institutional factors. Moreover, it is unclear whether DSGE models can include signaling effects of central banks asset purchases in the portfolio choice of households and banks. These signaling effects can be particularly important in the case of green QE programs (e.g. if central banks start selling dirty bonds, it is more likely that banks might do the same for signaling reasons).

Limitation #5: Expansionary fiscal policy has unrealistic adverse economic effects

Within a DSGE framework, the crowding-out effect of expansionary fiscal policy can become less strong by relaxing specific assumptions about monetary policy and wages (see Dupor et al., 2019). For example, if active monetary policy is replaced with passive monetary policy, the inflationary effects of expansionary fiscal policy (which are associated with the fact that a higher output leads to higher marginal costs) result in a lower real interest rate that stimulates consumption. However, a problem with this mechanism is that it requires a high responsiveness of economic activity to the real interest rate for the crowding out effects of expansionary fiscal policy to be counteracted. Another example is to assume that the economy faces high nominal wages that prevent firms from hiring workers. In that case, the increase in inflation that is caused by government spending reduces real wages leading to higher employment. A problem with this mechanism is that it relies on the standard DSGE assumption that firms always hire more workers when real wages go down.

Another way through which DSGE models can allow for a more positive role for expansionary fiscal policy is to include government capital in the production function (e.g. Alloza et al., 2020). This permits public investment to have a direct impact on the steady-state output via the supply side of the economy.

A DSGE model that only relaxes such assumptions continues to downplay the positive impact of (green) expansionary fiscal policy on GDP since four other significant assumptions remain unchanged: (i) private investment competes with public investment for pre-existing financial resources. (ii) demand is not a driver of economic activity in the long run and thus fiscal spending does not have a direct impact on output as a source of demand; (iii) agents have rational expectations about the repayment of debt and there are no hysteresis effects of government spending, and (iv) green public infrastructure cannot lead to a large-scale replacement of fossil energy with non-fossil energy. Without relaxing these assumptions, it is not possible to fully address the misleading approach of DSGE models to fiscal policy (see Figure 3).

4.2 Addressing the limitations using alternative modeling approaches

An increasing body of literature employs environment-economy models that overcome the limitations inherent in E-DSGE models. These are primarily the E-SFC and E-AB models. The key feature of E-SFC models is that they pay explicit attention to the accounting structure of the macroeconomy, analyzing coherently monetary transactions (flows), assets/liabilities (stocks) and their interactions (Nikiforos and Zezza, 2017). Due to the accounting foundations of these models, money is by construction an inherent feature of the analysis: it is not introduced as an afterthought, as is the case in DSGE models. The key feature of agent-based models is that they rely on a bottom-up approach whereby aggregate outcomes are the result of the interactions between heterogeneous agents.

We explain below how E-SFC models and E-AB models can address the limitations of E-DSGE models. It is important to note that not all SFC and agent-based models deal with the limitations of the DSGE models described above. For example, some simple E-SFC models incorporate endogenous money but do not have an active banking sector that is a source of macrofinancial feedback loops. However, we need to make a distinction between (i) unrealistic assumptions adopted for simplicity and (ii) unrealistic assumptions that cannot be relaxed due to the inherent features of a modeling approach.

Addressing Limitation #1: Banks provide loans in line with the endogenous money approach and macrofinancial feedback loops play a key role.

In SFC models, money is endogenously created when banks decide to provide loans to borrowers and banks' balance sheets are not constrained by the pre-existence of real goods. This means that the endogenous creation of money by banks can support/restrict investment and consumption, and affect economic activity and financial fragility. Banks might be constrained in providing loans when they face insolvency and illiquidity issues or when there is not sufficient demand for them (see McLeay et al., 2014). Despite these constraints, banks' financial decisions can still be a significant driver of economic fluctuations and financial stability. Macrofinancial feedback loops also play a key role in E-SFC and E-AB models (see e.g. Dafermos and Nikolaidi, 2019, 2022; Dunz et al., 2021; Lamperti et al., 2021; Gourdel et al., 2024). This means that the effects of lending can have second-round effects that can propagate through the financial system and the macroeconomy. For example, the financial problems of a bank that can arise due to defaults do not only affect its own financial position but can also affect its lending capacity. Overall, macrofinancial feedback loops can further destabilize the financial system and the macroeconomy.

To illustrate the importance of modeling macrofinancial feedback loops in the analysis of environmental policies, Dafermos and Nikolaidi (in progress) compare the results of environmental regulation when they use two different versions of their E-SFC model: one with endogenous credit rationing (whereby credit availability is affected by firms' and banks' performance), and one with exogenous credit rationing. They show that in a version with endogenous credit rationing, the recessionary effects of environmental regulation are much more significant compared to what is the case in the version with exogenous credit rationing (see also Gourdel et al., 2024 for the importance of macrofinancial feedback loops).

Debt defaults have also been incorporated in E-SFC and E-AB models (see e.g. Dafermos and Nikolaidi, 2019, 2022; Lamperti et al. 2021; Gourdel et al., 2024). For example, in the model of Dafermos and Nikolaidi (2019, 2022), the introduction of carbon prices negatively affects the profitability of dirty sectors and the ability of these sectors to repay their loans. This can in turn affect the financial fragility of the dirty sectors and, therefore, their rate of default. This increase in the default rate of loans can negatively affect the financial position of banks and their ability to increase lending due to solvency constraints. This lower lending capacity can significantly amplify the macrofinancial implications of carbon pricing.

Addressing Limitation #2: Demand plays a key role both in the short run and the long run.

Drawing on post-Keynesian macroeconomics, E-SFC and E-AB models place special emphasis on the role of demand (see e.g. Dunz et al., 2021; Lamperti et al., 2021; Gourdel et al., 2024). There are also SFC models that at the same time consider supply constraints due to capital/labor shortages or due to environmental restrictions (see Dafermos et al., 2017). In these models, consumption and investment are determined through behavioral equations and, as long as the economy operates below full capacity and there is excess labor force, expansionary fiscal policy can increase economic activity. Supply constraints can be avoided via investment that increases labor and capital productivity or increases in material/energy efficiency and the use of renewables through green investment. Importantly, demand can have a positive effect on the supply side of the economy. For example, higher demand can induce firms to increase their capital stock and their productivity (through the Kaldor-Verdoorn law). Hysteresis is built into these models.

Addressing Limitation #3: Disequilibrium phenomena can be easily analyzed.

In E-SFC models, the economy does not need to be in equilibrium and financial instability can endogenously arise as a result of the creation of credit and the accumulation of debt that can lead to debt defaults. In addition, cyclical behaviors can arise as a result of the interactions between macrofinancial and environmental factors. For example, in Dafermos and Nikolaidi (2022), an increase in carbon prices reduces firms' profitability and initially reduces investment. However, after some point, emissions might go down and the carbon taxes that firms pay might become lower. Therefore, the profitability of the firms might improve, contributing to an increase in economic activity.

In E-AB models, disequilibrium phenomena emerge from the interactions between agents: heterogeneity and its dynamic implications are an inherent feature of these models. In E-SFC models heterogeneity can be introduced by assuming different types of households, firms and banks. For example, in the E-SFC model of Gourdel et al. (2024) there is a distinction between workers and capitalists, while Cieplinski et al. (2021) develop an E-SFC model that differentiates between agents based on their age and gender and between different corporate sectors using an input-output structure.

E-SFC and E-AB models typically assume some form of adaptive expectations. It is not possible for the agents to 'solve the model' and all expectations to be model-consistent, as is assumed in DSGE models with rational expectations. However, forward-looking expectations can be introduced in such models. For example, Dafermos and Nikolaidi (in progress) consider the case in which firms act based on their expectation and the announcement of the implementation of environmental regulation after a few years is credible and they compare this case with the case in which this announcement is not credible. Dunz et al. (2021) assume that banks have climate sentiments. These sentiments capture their expectations about how climate policies, such as carbon prices, can affect the profitability of their borrowers in the next years. Banks adjust their lending behavior based on these sentiments. Campiglio et al. (2024) incorporate heterogeneous expectations of firms about future carbon prices. Depending on how credible the firms consider the announcements of the government about future carbon prices, they adjust their green/dirty investment with implications for the green transition. Gourdel et al. (2024) introduce the expectation formation mechanism of Dunz et al. (2021) into the firm sector and show the importance of the credibility of carbon taxes for firms.

Addressing Limitation #4: The substitutability assumptions in the production function and financial markets are more realistic.

In E-SFC models, firms can switch from fossil energy to non-fossil energy as long as there are certain policies and financial incentives in place that lead them to do so. However, this switching takes time since it requires the accumulation of a specific form of capital which cannot happen overnight (also due to financial constraints).

E-SFC models assume imperfect substitutability between capital, labor and natural resources in the production function in line with the strong sustainability assumption in the ecological economics tradition. Dafermos et al. (2017) and Dafermos and Nikolaidi (2019, 2022) use a Leontief-type production function with capital and labor as well as matter and energy whereby green and more technological progress can reduce the reliance on energy and matter but only within certain biophysical limits. Monasterolo and Raberto (2018, 2019) use a similar Leontief-type production function with capital, labor and raw materials.

SFC models also assume imperfect substitutability in the portfolio choice of the private sector. This imperfect substitutability, which renders monetary and financial policies non-neutral in both the short run and the long run, is justified based on institutional constraints, behavioral norms and the liquidity preference of agents. As a result of imperfect substitutability, green quantitative easing and other monetary policy interventions have non-neutral effects on green investment and emissions, even in the long run (Dafermos et al., 2018).

Addressing Limitation #5: Expansionary fiscal policy does not have unrealistic crowding out effects.

Since in SFC and AB models, output is demand determined and money is endogenous, expansionary fiscal policy does not lead to the crowding out of private spending. Actually, higher government spending and lower taxes can have crowding-in effects since they stimulate the income of the private sector and can increase private investment and private consumption (as long as there are no supply-side constraints). For the crowding-in effects of government spending on green private investment see Ang et al. (2017) and Azhgaliyeva et al. (2023). The economic literature suggests that targeted public investments can play an important role in coordinating complementary private investments in industry and (energy) infrastructure (see e.g. Castrejon-Campos et al., 2022, for the positive impact of public investment in research, development & demonstration for clean energy technologies on capital cost reductions and technology diffusion). In addition, public investments can provide additional certainty for the private sector and help overcome market failures like financial frictions that may impede the development of infant green industries (see e.g. Badertscher et al., 2013 for the positive impact that the public sector presence has on the responsiveness of private firms to investment opportunities). This crowding in of private investments is more likely to occur when the economy is not at full capacity.

Moreover, in E-SFC models expansionary fiscal policy can increase fiscal deficits but it can also increase economic activity. So, the public debt-to-GDP ratio does not necessarily increase when expansionary fiscal policy is introduced. This is important for the analysis of the implications of green public investment and green subsidies. In E-SFC models, an increase in green public spending increases economic activity and supports firms' profits and the income of households (see Dafermos and Nikolaidi, 2019, 2022; Monasterolo and Raberto, 2019). This makes a public-led green transition look less costly than what is the case in E-DSGE models. E-SFC models also allow the formulation of some adverse environmental effects of expansionary green fiscal policy, since higher economic activity has rebound effects on emissions and other types of pollution.

4.3 How can alternative modeling approaches improve?

The fact that E-SFC and E-AB models address the limitations of the E-DSGE models does not mean that these models do not have their own drawbacks. However, in contrast to E-DSGE models, these drawbacks are not fundamental and the vast majority of them can be addressed through additional research. We focus below on the most important issues.

First, the techniques for calibrating parameter values in these models are not sufficiently developed yet. SFC and AB models typically calibrate parameters using either econometric estimates or techniques that allow the model results to replicate some stylized facts. The out-of-steady-state analysis and the complexity of the models makes it more difficult to use Bayesian techniques, as is the case in many DSGE models. To address this issue, an increasing number of E-SFC and E-AB models use validation techniques that compare the simulated data with real data and check if the data structures generated by the models are sufficiently close to the data structures of real data (see e.g. Dafermos and Nikolaidi, 2021; Lamperti and Roventini, 2022). However, these techniques need to be further developed. More work is also necessary on the sensitivity analysis of the parameters used in these models.

Second, the behavioral assumptions of the SFC and AB models are often perceived to be relatively arbitrary and without forward-looking elements. This is so because these models do not formulate the decision-making process of economic units as an intertemporal profit or utility maximization problem. As highlighted in the previous section, there is a growing number of SFC and AB models that incorporate forward-looking perspectives (without rational expectations). More work needs to be done in this direction. In addition, it is necessary for E-SFC and E-AB modelers to provide better justifications of the behavioral assumptions that they adopt and to be more transparent on how the results of models might differ depending on these assumptions.

Third, country-specific SFC and AB models are in short supply. To some extent, this is explained by the higher data requirements that characterize these models. Developing country-specific models that take into account the distinct features of different economies is important for informing policy making (Zezza and Zezza, 2019).

Fourth, as is the case with the vast majority of macroeconomic models, E-SFC and E-AB models do not analyze the role of power. Power dynamics are particularly important for understanding the political economy of the green transition. Although it is difficult to endogenize power dynamics in these models, there are ways to analyze how specific groups or social classes can become more or less powerful depending on the macroeconomic, financial and social implications of climate change and certain climate policies.

5. Conclusion

The hegemonic DSGE program is now being extended to incorporate climate issues. As it has happened with the analysis of traditional macroeconomic issues, this is very likely to crowd out alternative climate macroeconomic modeling approaches. In this paper, we explained why this is problematic. We identified several limitations of E-DSGE models that can generate misleading results in terms of the macrofinancial implications of climate change and the effectiveness of climate macroeconomic policies. Although several (E-)DSGE modelers have tried to address some of these limitations, the interconnected nature of these limitations makes it impossible for these to be tackled within the DSGE framework.

It is therefore necessary to create space for the development and improvement of alternative macroeconomic models that rely on very different foundations that do not suffer from the weaknesses of DSGE models. Failure to do so would risk developing deceptive narratives about the macroeconomic policies that we need to implement to tackle the climate crisis and would lead to an underestimation of climate-induced macrofinancial instabilities. As the time to act on the climate crisis is shrinking, we cannot afford to spend resources on models that fail to capture how real-world macroeconomic, financial and climate systems work and interact.

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