Assessing climate policies: an ecological stock–flow consistent perspective

Yannis Dafermos
Department of Economics, SOAS University of London, UK

Maria Nikolaidi
School of Accounting, Finance and Economics, University of Greenwich, London, UK

Addressing the climate crisis requires a deep socio-ecological transformation of our economies. This transformation involves the implementation of climate policies that not only transform standard macroeconomic and financial tools but also lead to sufficiency-based consumption patterns. The assessment and design of such policies require a systems-based approach that is not restricted by the straightjacket of cost–benefit analysis. In this paper, the authors employ an ecological stock–flow consistent model to provide a systems-based evaluation of certain macroeconomic, financial and sufficiency policies for climate mitigation. They show how the use of such an approach allows them to identify policy mixes that have the potential to address the climate crisis without undermining macrofinancial and social stability.

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1 INTRODUCTION

For a long time, carbon pricing has been viewed as the key policy for addressing the climate crisis (Nordhaus 2013; Rosenblum et al. 2020). This has changed over the last few years. Researchers and policymakers are now paying more attention to other climate fiscal policy tools as well (such as green public investment), but also to the role that central banking and financial regulation can play in the fight against climate change (for example, Campiglio et al. 2018; Dafermos et al. 2021; NGFS 2021). On top of this, the need to change consumption patterns for achieving socio-ecological transformation is receiving growing support (for example, OECD 2020; Wiedmann et al. 2020; Mastini et al. 2021).

Implementing this wider range of climate policies is essential for achieving the targets of the Paris Agreement. However, assessing these policies and designing a policy mix that is conducive to a successful socio-ecological transformation requires us to move beyond the standard 'cost–benefit analysis' that has dominated the climate–economy literature and climate policymaking for decades. Cost–benefit analysis provides a reductionist perspective to the evaluation of policies. It relies on a narrow definition of welfare which requires the monetisation of costs and benefits. Cost–benefit analysis also ignores the complex interactions between economic, financial, social and ecological systems that have been highlighted in ecological and post-Keynesian economics (Dafermos/Nikolaidi 2019; Mercure et al. 2021).

The recent literature on ecological macroeconomic modelling has assessed climate policies without being restricted by the straightjacket of cost–benefit analysis. Ecological macroeconomic models − which typically rely on agent-based or stock–flow consistent (SFC) approaches – have been used to evaluate climate policies based, implicitly or explicitly, on what can be called a 'systems-based analysis' (for example, Battiston et al. 2021; Dafermos/Nikolaidi 2021; Dunz et al. 2021; Lamperti et al. 2021; Svartzman et al. 2021). According to this approach, climate policies should not be assessed based only on one criterion (the maximisation of a narrowly defined welfare). Instead, in systems-based analysis the evaluation of policies depends on several criteria (minimisation of inequality and emissions, maximisation of employment, avoidance of financial crises, etc.) and the complex dynamic interactions between macroeconomic, financial, social and ecological variables are at the centre of policy assessment. Systems-based analysis also pays explicit attention to path dependency, disequilibrium phenomena and the endogeneity of risks.

In this paper, we first outline the key principles of the emerging systems-based analysis of climate policies. We then use the DEFINE (Dynamic Ecosystem-FINance-Economy) model, an ecological SFC model, to illustrate how a systems-based analysis can be used in practice to assess certain macroeconomic, financial and sufficiency policies for climate mitigation. A key conclusion of our analysis is that the multiple targets of macrofinancial stability, ecological sustainability and social stability might not be achieved without the simultaneous implementation of several climate policies, including policies that change our environmentally destructive consumption norms. Instead, isolated climate policies are unlikely to be sufficient for achieving the socio-ecological transformation of our economies and in some cases they might have too many side effects.

The paper is organised as follows. Section 2 explains how climate policies can be assessed using a systems-based analysis. Section 3 outlines the key features of the DEFINE model which we use to analyse climate policies. Section 4 presents several simulations about the effects of macroeconomic, financial and sufficiency policies and illustrates how they can be evaluated on the basis of a systems-based analysis. Section 5 concludes.

2 ASSESSING CLIMATE POLICIES: TOWARDS A SYSTEMS-BASED ANALYSIS

In integrated assessment models (IAMs), climate policies are typically evaluated through a cost–benefit analysis (for example, Nordhaus 2018). Climate policies are deemed to have costs because they result in more expenses (for example, firms have to pay carbon taxes or spend money to invest in energy efficiency capital). However, they also have benefits because they can lead to fewer climate damages that affect economic activity.[1] A climate policy is considered to be 'optimal' when the costs and benefits are balanced such that the discounted social welfare − which is typically captured by consumption and leisure − is maximised.

Cost–benefit analysis has two important limitations. First, it relies on a unidimensional approach that monetises costs and benefits. Other dimensions such as inequality, financial stability, employment, and the intrinsic value of the ecosystem are ignored. Second, through the use of a discount rate, it is implicitly assumed that consumption in the future

[1] From a post-Keynesian perspective, viewing spending on climate mitigation only as a cost is problematic. For example, more spending on wind farms and solar panels is a cost for the firms that buy them, but a source of income for the firms that produce them (see also Dafermos/Nikolaidi 2019).

will be higher than present consumption. This is not necessarily the case. For example, in the era of ecological breakdown, it is likely that people in the future will not be able to have higher levels of consumption compared to what is the case now. When their consumption is discounted in models, it is likely to end up supporting policies that benefit disproportionately the current generations compared to the future ones.[2]

A systems-based approach addresses these limitations. First, several dimensions are assessed at the same time. These dimensions include ecological, economic, financial and social factors. Crucially, these factors interact with each other through feedback loops that are at the heart of system dynamics. Policies can generate some positive outcomes (for example, increased employment and reduced inequalities), which can be considered as the 'opportunities' that these policies create. But policies can also generate negative outcomes (for example, increased debt defaults and inflation) which can be characterised as 'risks'. Researchers can identify policies or mixes of policies that seem to maximise opportunities and minimise risks (see Mercure et al. 2021).

Second, the short-run and long-run effects of specific policies are evaluated without having to discount the future values of variables. Specific attention is paid to path dependency: future outcomes are not independent of short-run developments. Issues of fragility are of particular importance − a policy might have some short-run positive effects, but might lead to instability in the long run. Therefore, researchers need to identify positive and negative outcomes over both a short-run and a long-run horizon.

Although a systems-based analysis provides a more holistic understanding of the implications of policies, the assessment of policies from a systems perspective faces challenges and has its own limitations. To begin with, it is not clear how many dimensions should be included in the analysis. In principle, the higher the number of dimensions, the more holistic the perspective will be. For instance, including gender and wealth inequality in the evaluation of policies is better than just focusing on income inequality. However, the higher the number of dimensions, the more difficult it is to draw clear conclusions.

In addition, a systems-based analysis does not allow for selecting between policies that have a similar number of positive and negative outcomes. This would require assigning weights to different outcomes based on their relative importance. This should not, however, be considered a drawback. Instead of having researchers arbitrarily assign weights to specific dimensions, it is best to leave it to policymakers to take such decisions based on their political legitimacy (Rose-Ackerman 2016; Mercure et al. 2021).

It is also important to point out that systems-based analysis relies on the development of policy scenarios whereby many unknowns exist. Being clear on the role of different types of uncertainty is, therefore, crucial. Moreover, modelling approaches to systems-based analysis need to be complemented by qualitative perspectives (Svartzman et al. 2021). For example, qualitative analyses can illustrate who benefits from different climate policies and what the political economy barriers to the implementation of specific climate policies might be.

3 THE 'DEFINE' MODEL: KEY FEATURES

[2] For a broader discussion of the limitations of cost–benefit analysis and discounting, see for example Ackerman/Heinzerling (2002), van den Bergh/Botzen (2015), Rose-Ackerman (2016) and Malik (2019).

Ecological stock–flow consistent (E-SFC) modelling has been increasingly used over the last years to analyse climate policies from a macroeconomic, financial and ecological perspective. Drawing on the standard SFC modelling approaches (see Nikiforos/Zezza 2017), E-SFC models are characterised by the explicit attention they pay to macrofinancial linkages and implications of the dynamic stock–flow interactions between macroeconomic and financial variables. But, on top of this, E-SFC models also analyse ecological issues, for example by making distinctions between different types of investment and loans (for example, green and dirty) or by combining the analysis of physical stocks and flows (for example, material reserves, carbon emissions, and waste) with the analysis of monetary stocks and flows, drawing on post-Keynesian and ecological economics. E-SFC models are dynamic models in which path dependency, non-linearities, and disequilibrium phenomena can play a key role. Hence, they can be easily deployed for a systems-based analysis of climate policies.

The DEFINE model is an E-SFC model that has been widely used for the assessment of several types of climate policies (Dafermos et al. 2017; 2018; Dafermos/Nikolaidi 2019; 2021). Some key features of the model, which draws on the tradition of post-Keynesian and ecological economics, are as follows. First, in DEFINE demand drives economic activity, but supply-side constraints that might arise due to ecological limits can affect output. Second, money is endogenous and credit creation can both increase economic activity and financial fragility, in line with Minskyan perspectives. Third, agents in the economy are assumed to take their decisions based on heuristics. Fourth, material and energy inflows and outflows are included in the model in a way that is in line with the First and Second Laws of Thermodynamics. Monetary stocks and flows interact with physical stocks and flows. Fifth, environmental policies have both demand-side and supply-side effects and can attenuate the adverse effects of economic activity on the environment. This has feedback effects on the macroeconomy, for example through climate damages and the impact of hazardous waste on people's health.

For the simulations in this paper, we use DEFINE 1.1 (August 2022 version).[3] The model consists of firms, households, commercial banks, the government, and central banks. Firms' overall desired investment relies on their profitability and capacity utilisation, but also on supply-side factors. Firms invest both in green and conventional capital. Green investment can improve ecological efficiency indicators and, thus, reduce the ecological footprint for a given level of economic activity. Firms take out green and conventional loans from commercial banks. They also issue green and conventional bonds that are bought by households and central banks. Commercial banks provide only a proportion of the demanded loans (that is, there is credit rationing). Interest loan spreads are endogenous: they depend on the financial position of both firms and banks. The government sector invests in conventional and green capital. An increase in green government capital can improve ecological efficiency indicators as well. The government sector also collects carbon taxes and provides green subsidies. Central banks provide advances to commercial banks, issue high-powered money and buy conventional/green bonds issued by firms. Households purchase these bonds as well. Households' consumption depends on their income and wealth. The wage income share depends negatively on the unemployment rate due to the standard bargaining power channel.

[3] The manual of the model is available at: https://define-model.org/.

DEFINE is a global model. We econometrically estimate the parameters of specific behavioural equations by using panel data for several countries. The rest of the parameters are calibrated based primarily on previous studies, but also with the aim of generating the baseline scenario that we use as a reference in our simulations. The baseline scenario is constructed using the frameworks of shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs) that have been employed by the Intergovernmental Panel on Climate Change (IPCC) (see Riahi et al. 2017). Our baseline scenario is a combination of scenarios SSP2 and SSP3 6.0 W/m^2 whereby the transition to a low-carbon economy is very slow in the coming decades and, as a result, surface temperature becomes slightly higher than 3°C at the end of the century.[4]

4 SYSTEMS-BASED ANALYSIS OF CLIMATE POLICIES: AN ILLUSTRATION

We now turn to present some policy simulations that we have conducted using the DEFINE model.[5] We show the effects of three different types of climate policies: (i) green fiscal policies (carbon taxes, green subsidies, and green public investment); (ii) green monetary/financial policies (dirty penalising factor, green supporting factor, and green quantitative easing); and (iii) sufficiency policies (decline in consumption combined with less working hours). These climate policies are indicative and are used as examples to show how policies can be assessed through a systems-based analysis.[6] We use three sets of indicators to evaluate these policies:

- *ecological* indicators that include temperature as well as material use and waste;
- *macroeconomic–social* indicators that include the rate of unemployment and the wage share (which captures functional income distribution);[7] and
- *financial* indicators that include the default rate of firms, the leverage ratio of banks, and the public debt-to-output ratio.[8]

Our simulation period is 2021–2100. The starting year for the implementation of policies is 2024. In the baseline scenario, the surface temperature rises to about 3.2°C at the end of the century (Figure 1d). The continuous increase in global warming destabilises the macroeconomy and the financial system, especially after the middle of the century. For example, the profitability of firms has a declining trend (Figure 1e), the default rate of firms increases (Figure 1f) and the growth rate of output declines (Figure 1a).

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[4] For more details about our baseline scenario, see the manual of DEFINE 1.1. (August 2022 version), which is available at: https://define-model.org/.

[5] The R code used for the simulations of the model is available at: https://github.com/DEFINE-model.

[6] Due to the illustrative nature of our simulations, we have not conduced a sensitivity analysis to explore how robust our results are to changes in key parameter values. For such an analysis, see Dafermos et al. (2018) and Dafermos/Nikolaidi (2021).

[7] Generally speaking, a higher wage share is associated with lower income inequality – see, for instance, the empirical evidence in Daudey/García-Peñalosa (2007) and Bengtsson/Waldenström (2018).

[8] The use of the public debt-to-output ratio as a financial indicator for the assessment of climate policies needs to be treated with caution. For many high-income countries, an increase in public indebtedness does not pose risks to macrofinancial stability. However, in low-income countries, an increase in public indebtedness can create political, financial and economic pressures due to these countries' weak position in the global financial architecture. In addition, the potential adverse impact of certain climate policies on public debt is often used as an argument against their implementation. Including public debt in our assessment allows us to engage with these issues.

4.1 Green fiscal policies

We consider three fiscal policy scenarios. In the first scenario, we analyse the effects of an increase in *carbon taxes* (*CT*) in line with the SSP3 4.5 W/m^2 scenario. In the second scenario, we examine the combination of *carbon taxes* and *green subsidies* (*CT* + *GS*) whereby carbon taxes are recycled in the form of green subsidies that are provided to firms. The level of carbon taxes is the same as in the first scenario. In the third scenario, we focus on *green public investment* (*GPI*): we assume that green public investment increases from around 0.2 per cent to 0.8 per cent of GDP.[9] The evolution of some key variables under the different scenarios is shown in Figure 1.

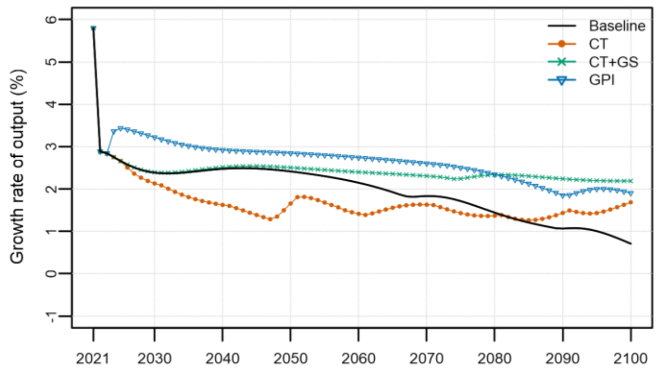
In the *CT* scenario, an increase in carbon taxes reduces the profitability of firms.[10] This reduction in their profitability negatively affects their desired investment. As a result, economic activity goes down (see Figure 1a). The reduction in economic activity leads to higher unemployment. This in turn reduces the bargaining power of workers, resulting in a lower wage share. At the same time, firms are induced to increase their green investment to reduce their carbon costs. This improves energy efficiency and the use of renewables. The combined reduction of economic activity and improvements in the use of energy leads to a reduction in emissions relative to the baseline scenario. As a result, temperature increases less relative to the baseline scenario (Figure 1d). Moreover, the reduction in economic activity in conjunction with the increase in green investment (which reduces the material intensity and increases recycling) leads to a lower generation of waste per person (Figure 1c).

[9] For a more detailed discussion of such policies, see Dafermos/Nikolaidi (2019). For an analysis of green fiscal policies in (i) IAMs and dynamic stochastic general equilibrium (DSGE) models, see Nordhaus (2018), Wei et al. (2019) and Diluiso et al. (2021); in (ii) E-SFC models, see Bovari et al. (2018), Mercure et al. (2018), Monasterolo/Raberto (2018; 2019) and Naqvi/Stockhammer (2018), Dafermos/Nikolaidi (2019), D'Alessandro et al. (2018) and Jackson/Victor (2020); and in (iii) agent-based models, see Lamperti et al. (2020).

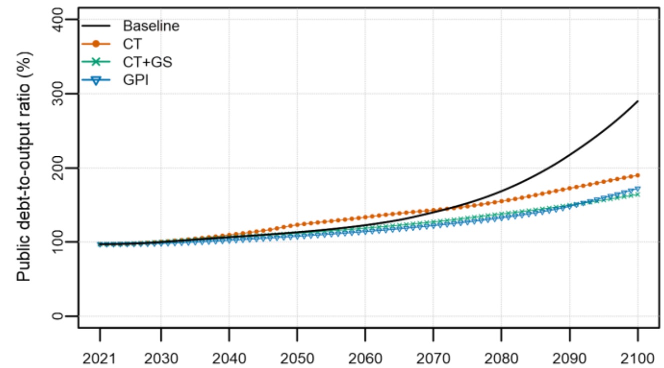
[10] It has been assumed that firms do not pass the higher carbon cost on to prices.

Figure 1 Effects of green fiscal policies

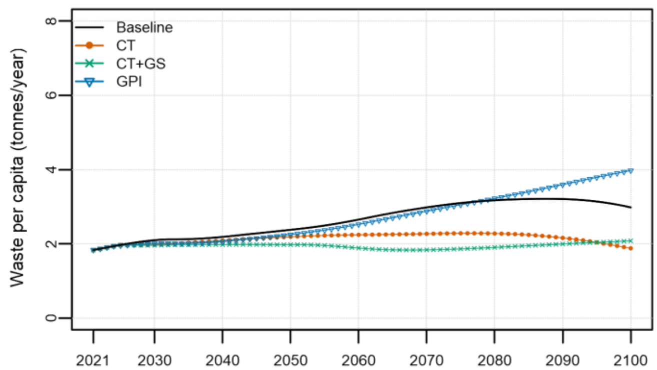
(a) Growth rate of output



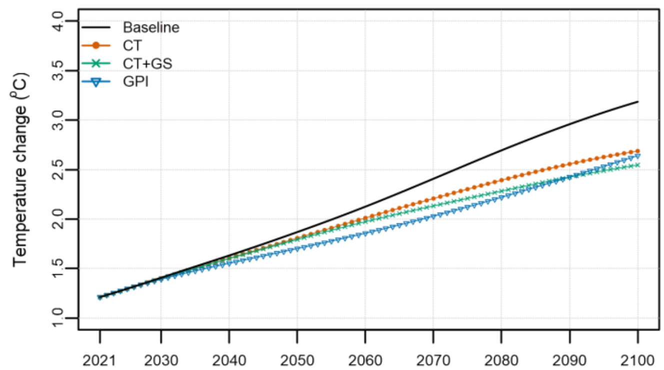
(b) Public debt-to-output ratio



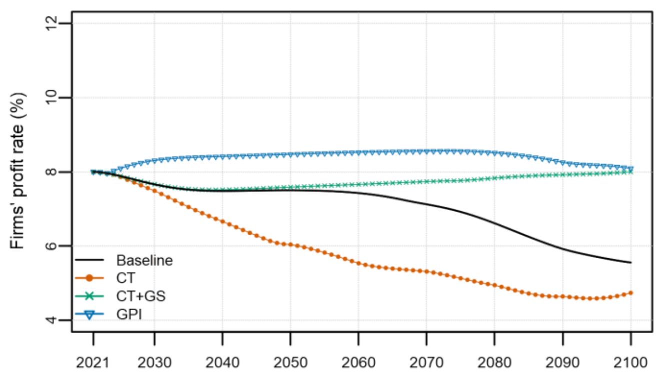
(c) Waste per capita



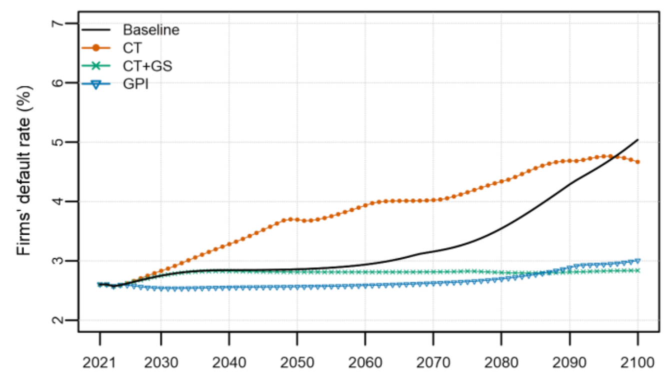
(d) Temperature



(e) Firms' rate of profit



(f) Default rate



Note: All policy shocks take place in 2024. The values used in the baseline scenario are reported in the manual of the model which is available at: https://define-model.org/. In the *CT* (carbon tax) scenario, the carbon tax becomes equal to the carbon price in the SSP3 4.5 W/m^2 scenario but the carbon tax revenues are not recycled; in the *CT* (carbon tax) + *GS* (green subsidies) scenario, the carbon tax becomes equal to the carbon price in the SSP3 4.5 W/m^2 scenario and green subsidies increase accordingly such that they are equal to the new carbon tax revenues; in the *GPI* (green public investment) scenario, green public investment increases to 0.8 per cent, as a proportion of GDP.

Importantly, the increase in carbon taxes affects the ability of firms to repay their debt. Since the available inflows to cover debt repayments become lower, the default rate of firms increases (Figure 1f). The higher default rate depletes the capital of banks and leads to a higher bank leverage ratio.

As far as government finance is concerned, the increase in carbon taxes increases government revenues. This tends to improve the fiscal balance. However, the reduction in economic activity leads to lower tax revenues. This, in combination with the lower GDP, increases public indebtedness relative to the baseline scenario. However, in the long run, the public debt-to-output ratio is lower in comparison with the baseline scenario due to the lower climate damages.

Having presented the main effects of carbon taxation, we are now in a position to provide an overall evaluation of this policy from a systems-based perspective. Table 1 shows the indicators that we use for the systems-based analysis. For each indicator, we identify whether the policy affects the indicator favourably or not (compared to the baseline scenario). We highlight in green the cases in which the policy has a favourable impact on the indicator, and in red/pink the cases in which the policy has an adverse effect on the indicator. We make a distinction between short-run and long-run outcomes. Due to the long horizon of our simulation period, the 'short run' and the 'long run' refer to longer periods than what is typically the case: the 'short run' refers to the first 2–3 decades after the introduction of the policy, while the 'long run' captures the rest of the simulation period, that is, the period after the middle of the century.

Table 1 Effects of green fiscal policies on indicators selected for a systems-based analysis

Type of indicator	Indicator	Carbon Tax		Carbon Tax+Green Subsidy		Green Public Investment	
		Short run	Long run	Short run	Long run	Short run	Long run
Ecological	Temperature	Mildly declines	Declines	Mildly declines	Declines	Mildly declines	Declines
	Waste per capita	Mildly declines	Declines	Mildly declines	Declines	Mildly declines	Mildly increases
Macroeconomic-social	Unemployment rate	Mildly increases	Increases	Mildly declines	Declines	Mildly declines	Declines
	Wage share	Mildly declines	Declines	Mildly increases	Increases	Mildly increases	Increases
Financial	Default rate	Increases	Mildly declines	Mildly declines	Declines	Mildly declines	Declines
	Banks' leverage ratio	Increases	Mildly declines	Mildly declines	Mildly declines	Mildly declines	Declines
	Public debt-to-output ratio	Increases	Declines	Declines	Declines	Declines	Declines

Note: Comparisons are made with reference to the baseline scenario. 'Short run' refers to the first 2–3 decades after the introduction of the policy. 'Long run' captures the rest of the simulation period (circa 2050–2100). Green panels depict improvements in the indicators. Red/pink panels capture deteriorations.

The increase in carbon tax has overall favourable effects on ecological indicators both in the short run and in the long run. However, the macroeconomic, financial and social effects are unfavourable. An increase in the carbon tax that is not accompanied by other climate policies increases unemployment and inequality, makes banks more fragile and increases financial instability in the short run. It also deteriorates public debt in the short run. Therefore, an isolated implementation of a carbon tax is not recommended from a macrofinancial and social point of view.

In the *CT* + *GS* scenario, the adverse macrofinancial and social effects are prevented. Since firms receive green subsidies when they invest in green capital, their profitability does not deteriorate as is the case in the *CT* scenario (Figure 1e). Consequently, the growth rate of output remains unchanged in the first years of the simulation period (Figure 1a). At the same time, firms that receive green subsidies are induced to increase their green investment. Therefore, the share of non-fossil energy improves substantially since there is a double incentive for firms to invest in green capital. As a result, emissions and temperature decline more compared to the scenario in which carbon taxes are implemented individually (Figure 1d).

In the first years of the simulation period the default rate, the public debt-to-output ratio and the rate of profit of firms remain almost unchanged compared to the baseline scenario. However, as time passes, there are fewer emissions in the economy and, hence, fewer climate damages. As a result, in the long run, the default rate, the public debt-to-output ratio and the rate of profit of firms improve compared to the baseline scenario.

Overall, as shown in Table 1, the combination of carbon taxes with green subsidies is a desirable policy based on all the indicators that we use in our systems-based analysis. The macrofinancial system is not hit by an adverse shock, as is the case with the *CT* policy, and in the long run all systems are characterised by higher stability since the adverse environmental effects are milder relative to the baseline scenario.

In the *GPI* scenario, economic activity improves since the rise in green public investment directly increases output: this investment takes place on top of existing investment (Figure 1a). The expansionary effects of green public investment result in a lower unemployment rate, a higher wage share, higher firm profitability, and a lower rate of default in the short run, relative to the baseline scenario. In the long run, this is still the case due to the reduction in climate damages that attenuates the adverse climate effects on economic activity.

The increase in green public investment initially increases the deficit-to-output ratio of the government. However, as time passes, the government can collect more taxes from firms and households due to the increase in economic activity, compared to what is the case in the baseline scenario. Therefore, the public debt-to-output ratio is, in the long run, lower relative to its baseline value (Figure 1b).

However, the stimulation of economic activity induced by green public investment has some adverse long-run ecological implications. As shown in Figure 1c, the waste per capita becomes higher in the long run: the additional instalment of green capital reduces emissions but increases the extraction of materials and the generation of waste. This illustrates the importance of not confining our attention to climate issues when ecological implications are analysed.

Overall, based on the information that is summarised in Table 1, it can be argued that an increase in green public investment is a policy that generates several positive outcomes from a macrofinancial and social point of view. However, there are some ecological trade-offs: on the one hand, higher green investment reduces emissions but, on the other hand, it increases the extraction of materials and the generation of waste in the long run.

4.2 Green monetary/financial policies

Next, we turn to the effects of green monetary/financial policies. In the first scenario, we examine a *dirty penalising factor* (*DPF*) scenario whereby the risk weight on dirty loans increases by 25 percentage points. In the second scenario, there is a reduction in the risk weight on green loans by 25 percentage points. This is the so-called *green supporting factor* (*GSF*). In the third scenario, we analyse the effects of a *green quantitative easing* (*GQE*) by assuming that central banks increase the green corporate bonds that they hold under their quantitative easing (QE) programmes.[11]

In the short run, the introduction of the dirty penalising factor reduces the capital adequacy ratio of banks (Figure 2b). This is because the risk weight on dirty loans increases. The decline in the capital adequacy ratio induces banks to increase their overall credit rationing and interest rates, creating recessionary effects (Figure 2a). At the same time, banks are prompted to reallocate their loans away from dirty investments and to increase the interest rate on dirty loans compared to the rest of the loans. In response to banks' modified behaviour, firms increase their green investment compared to conventional investment. This brings about a reduction in emissions and, hence, a reduction in temperature relative to the baseline scenario (Figure 2d). Nevertheless, the decline in temperature is quantitatively small. Moreover, the reduction in GDP observed shortly after the dirty penalising shock leads to a slight increase in the unemployment rate and, as a result, to a decline in the wage share. At the same time, the higher credit rationing and the lower level of economic activity adversely affects the liquidity of firms, leading to a small increase in the rate of default (Figure 2f).[12]

As time passes, the effects of the reduction in climate damages become more visible. In the long run, the growth rate of output and the profitability of firms are at a higher level compared to the baseline scenario, while the default rate of firms is lower.

[11] For a more detailed discussion of these policies, see Dafermos et al. (2018) and Dafermos/Nikolaidi (2021). For the analysis of green financial and monetary policies in E-SFC and agent-based models, see Monasterolo/Raberto (2018), Dunz et al. (2021) and Lamperti et al. (2021). For analyses that rely on environmental dynamic stochastic general equilibrium (E-DSGE) models, see Ferrari/Nispi Landi (2020) and Diluiso et al. (2021). Note that in our *green QE* scenario central banks do not reduce the dirty bonds that they hold. For a detailed proposal on how a decarbonised QE programme (that combines an increase in the holdings of environmentally friendly bonds with a decline in the holdings of dirty bonds) could be implemented in practice, see Dafermos et al. (2022a).

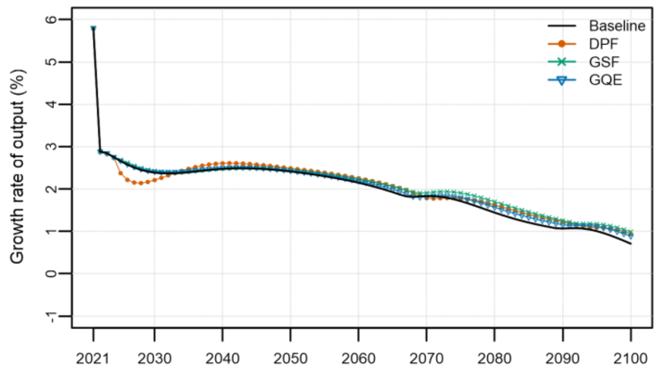
[12] Due to the large scale of the vertical axis in Figure 2f, this small increase is not easily visible.

Table 2 shows that the overall effects of the dirty penalising factor are positive (but mild) in the long run. This is so because the policy leads to a reduction in climate damages which is beneficial both for the macroeconomic and the financial system. However, in the short run, there are some adverse transition effects on unemployment, income distribution, and the default rate on corporate loans.

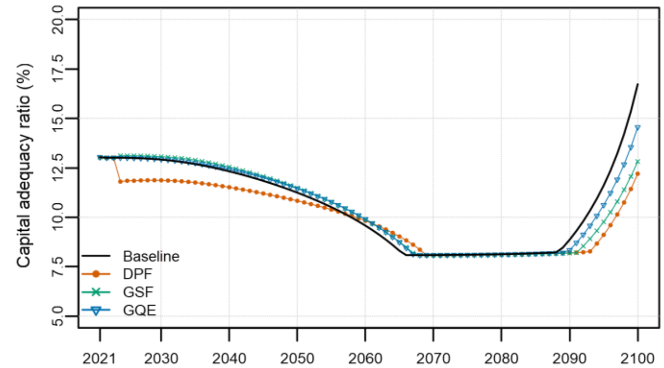
In the *GSF* scenario, the capital adequacy ratio of banks improves since there is a decline in the risk weight of green loans (Figure 2b). The increase in the capital adequacy ratio induces banks to increase credit availability and reduce the interest rates on loans. This has a mild expansionary effect (Figure 2a), which is beneficial for the employment performance and inequality. Banks are also induced to reduce the credit rationing and the interest rate on green loans compared to conventional loans. The overall outcome is a small decline in global warming (Figure 2d) which has beneficial macrofinancial effects in the long run. However, the higher provision of credit increases the leverage of banks in the first years after the green supporting factor shock.

Figure 2 Effects of the implementation of green monetary/financial policies

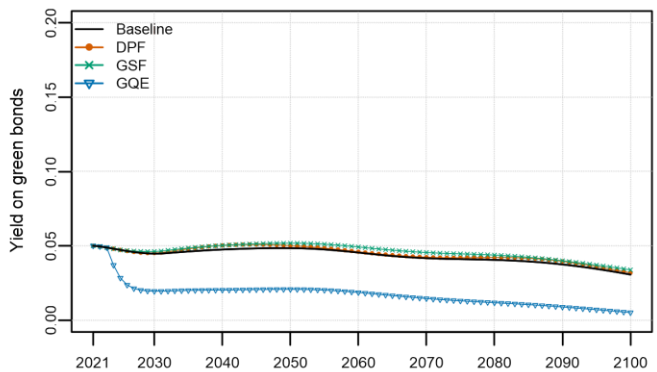
(a) Growth rate of output



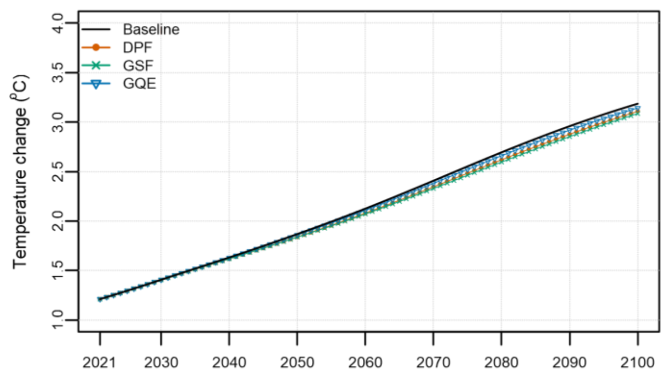
(b) Capital adequacy ratio



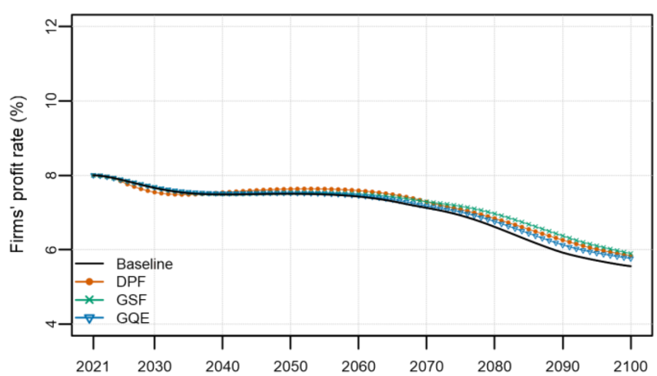
(c) Yield on green bonds



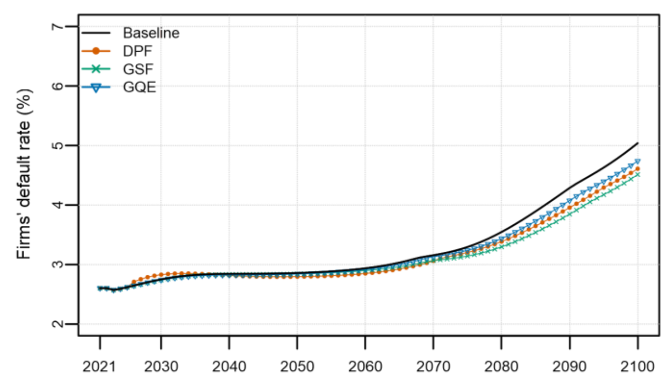
(d) Temperature



(e) Firms' rate of profit



(f) Default rate



Note: All policy shocks take place in 2024. The values used in the baseline scenario are reported in the manual of the model which is available at: https://define-model.org/. Under DPF (dirty penalising factor) the risk weight on conventional loans decreases by a maximum of 25 percentage points. Under GSF (green supporting factor) the risk weight on green loans increases by 25 percentage points. Under GQE (green quantitative easing), the share of the total corporate green bonds held by central banks increases to 40 per cent.

All in all, our systems-based analysis, illustrated in Table 2, suggests that the green supporting factor can slightly improve most of our indicators both in the short run and in the long run. Nevertheless, in the short run, it can adversely affect the financial fragility of banks.

We now turn to the case of a green QE. The increase in the demand for green bonds by central banks increases the price of green bonds and reduces their yield (Figure 2c). The reduction in the yield of green bonds induces firms to increase their green investment, which, in turn, reduces emissions, generating a small decline in temperature relative to the baseline scenario (Figure 2d). The green QE also stimulates economic activity, since it leads to a reduction in the cost of borrowing. However, this effect is small.

As Table 2 shows, the implementation of a green QE is beneficial for all the indicators that we use in our systems-based analysis. Nevertheless, the beneficial effects are small in quantitative terms. A caveat is also in order: we have not used a wealth inequality indicator in our analysis. The increase in the price of green bonds can adversely affect wealth inequality since bonds tend to be held by richer households.

Table 2 Effects of green financial and monetary policies on indicators selected for a systems-based analysis

Type of indicator	Indicator	Dirty Penalising Factor		Green Supporting Factor		Green Quantitative Easing	
		Short run	Long run	Short run	Long run	Short run	Long run
Ecological	Temperature	Mildly declines	Mildly declines	Mildly declines	Mildly declines	Mildly declines	Mildly declines
	Waste per capita	Mildly declines	Mildly declines	Mildly declines	Mildly declines	Mildly declines	Mildly declines
Macroeconomic-social	Unemployment rate	Mildly increases	Mildly declines	Mildly declines	Mildly declines	Mildly declines	Mildly declines
	Wage share	Mildly declines	Mildy increases	Mildy increases	Mildy increases	Mildy increases	Mildy increases
Financial	Default rate	Mildly increases	Mildly declines	Mildly declines	Mildly declines	Mildly declines	Mildly declines
	Banks' leverage ratio	Mildly declines	Mildly declines	Mildly increases	Mildly declines	Mildly declines	Mildly declines
	Public debt-to-output ratio	Mildly increases	Mildly declines	Mildly declines	Mildly declines	Mildly declines	Mildly declines

Note: Comparisons are made with reference to the baseline scenario. 'Short run' refers to the first 2–3 decades after the introduction of the policy. 'Long run' captures the rest of the simulation period (circa 2050–2100). Green panels depict improvements in the indicators. Red/pink panels capture deteriorations.

4.3 Sufficiency policies and climate policy mixes

We characterise as sufficiency policies those policies that restrict individual consumption in a way that is in line with sufficiency practices. These policies can include regulatory interventions that put a cap on the consumption of carbon-intensive goods, policies that restrict the advertisement of specific products, or policies that improve public provisioning and make thereby less necessary specific types of consumption, such as the purchase of cars (see

Dafermos et al. 2022b). In our *sufficiency* scenario, we do not explicitly model such policies. Instead, we assume that they can lead to a reduction in the average propensity to consume out of income and wealth. We assume that sufficiency policies are introduced gradually over the period 2024–2100 and reduce the propensities to consume by 15 per cent in 2100 compared to their 2024 levels.[13]

As is well known in the degrowth literature, policies that reduce economic activity can lead to higher unemployment (for example, Kallis 2011; Hickel 2019; Jackson/Victor 2020; Mastini et al. 2021). In order to prevent that, working hours need to decline. Hence, we include the reduction of working hours in our sufficiency policies (for example, Jackson/Victor 2020; Cieplinski et al. 2021; Dafermos et al. 2022b). In particular, working hours decrease whenever the unemployment rate becomes higher than a reference value, which is set equal to about 6 per cent.[14]

In our *sufficiency* scenario, the growth rate of output goes down by construction (Figure 3a). Despite this decline in economic activity compared to the baseline scenario, the rate of unemployment increases only mildly (Figure 3e). This is due to the working hours reduction policy. As a result, the wage share is only slightly affected.

The reduction in economic activity is beneficial for the ecosystem: temperature declines (Figure 3d) and the waste per capita becomes lower compared to the baseline scenario (Figure 3c). However, the sufficiency policies have some adverse financial implications. Due to the initial decline in economic activity, the government revenues decline and, as a result, the public debt-to-output ratio becomes higher relative to its baseline value (Figure 3b).[15] At the same time, firms experience a decline in their sales. Therefore, their profitability goes down and the rate of default on loans increases (Figure 3f).

Table 3 summarises the evaluation of sufficiency policies from a systems-based perspective. These policies are clearly beneficial for our ecological indicators both in the short run and in the long run. In the short run, there are some negative transition effects since financial and macroeconomic/social indicators deteriorate. However, in the long run, the reduction in global warming compared to the baseline scenario is generally conducive to higher macrofinancial and social stability. The only exceptions are the leverage of banks and the public debt-to-output ratio which are higher than the baseline scenario.

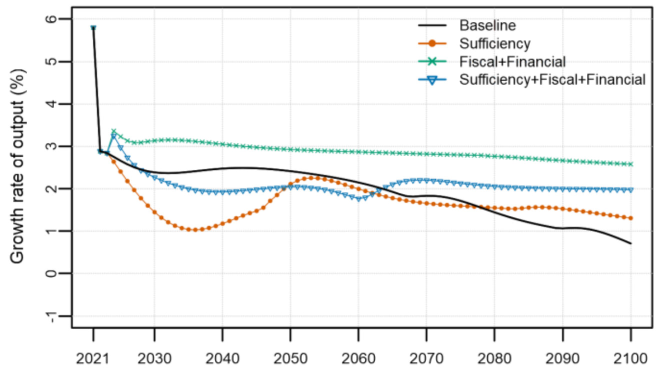
We now turn to present climate policy mixes. We first focus on the combined implementation of all the green fiscal policies and the green monetary/financial policies described in the previous sub-sections (*fiscal + financial* scenario). The main advantage of this policy mix is that it leads to a significant reduction in temperature compared to the baseline scenario: global warming becomes close to 2°C at the end of the century. At the same time, the combined

[13] Although our global model does not make a distinction between the Global North and the Global South, we implicitly assume that the reduction in the propensities to consume will primarily take place in the Global North.
[14] We assume that the reduction in working hours is not accompanied by a change in the exogenous component of the wage share.
[15] This increase in public indebtedness could potentially be restricted if the reduction in consumption were accompanied by an increase in tax rates.

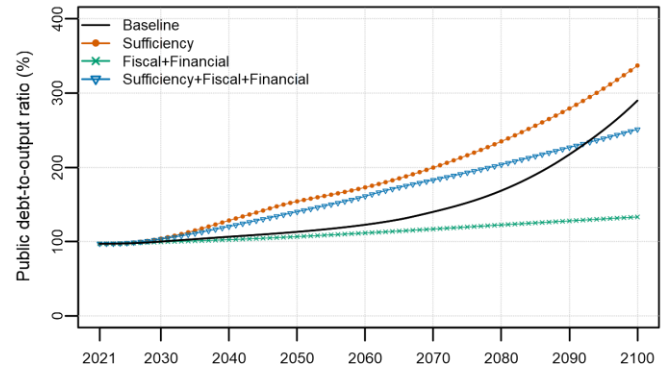
implementation of several green macroeconomic and financial policies improves all the macroeconomic, financial and social indicators included in Table 3.

Figure 3 Effects of sufficiency, green fiscal and green monetary/financial policies

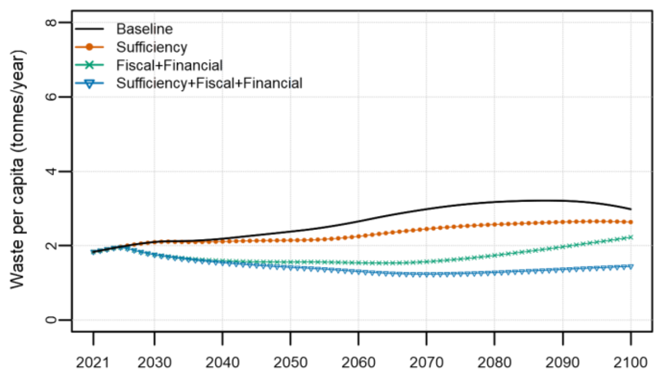
(a) Growth rate of output



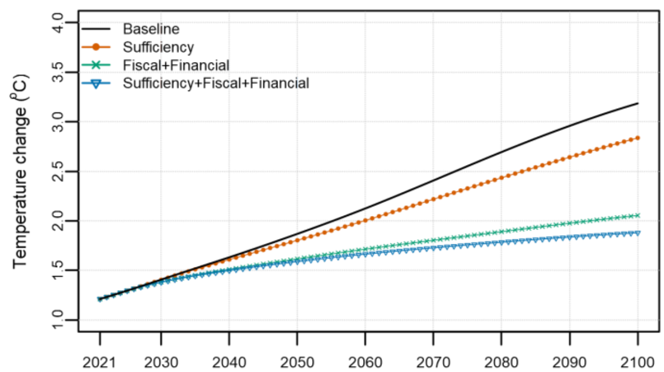
(b) Public debt-to-output ratio



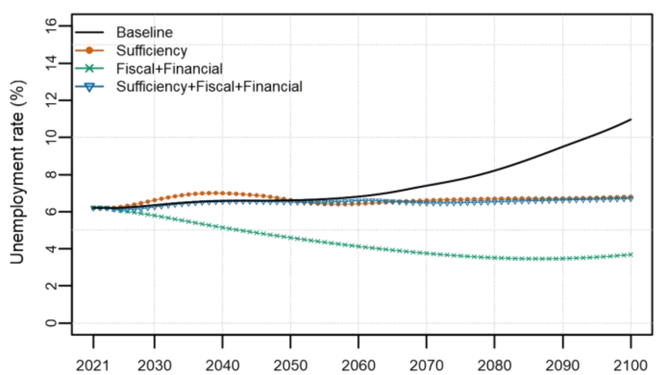
(c) Waste per capita



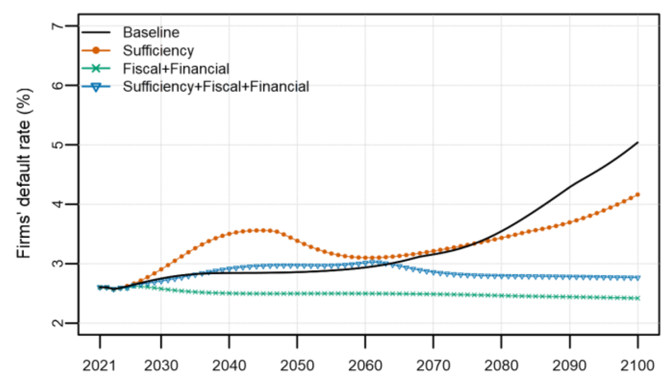
(d) Temperature



(e) Unemployment rate



(f) Default rate



Note: All policy shocks take place in 2024. The values used in the baseline scenario are reported in the manual of the model which is available at: https://define-model.org/. Under the *sufficiency* scenario the propensity to consume out of income and the propensity to consume out of wealth gradually decline by 15 per cent by 2100 and working hours decline whenever the unemployment rate increases compared to a reference value (close to 6 per cent). Under the *fiscal + financial* scenario, all the green fiscal policies and green monetary/financial policies depicted in Figures 1 and 2 are implemented at the same time. Under the *sufficiency + fiscal + financial* scenario, these green fiscal and green monetary/financial policies are implemented in conjunction with sufficiency policies.

Table 3<em>Comparative evaluation, sufficiency, green fiscal policies, and green monetary/financial policies

Type of indicator	Indicator	Sufficiency policies		Fiscal+Financial policies		Sufficiency +Fiscal+Financial policies	
		Short run	Long run	Short run	Long run	Short run	Long run
Ecological	Temperature	Mildly declines	Declines	Declines	Declines	Declines	Declines
	Waste per capita	Mildly declines	Declines	Declines	Declines	Declines	Declines
Macroeconomic-social	Unemployment rate	Mildly increases	Declines	Mildly declines	Declines	Mildly declines	Declines
	Wage share	Mildly declines	Increases	Mildly increases	Increases	Mildly increases	Increases
Financial	Default rate	Increases	Declines	Mildly declines	Declines	Mildly increases	Declines
	Banks' leverage ratio	Mildly increases	Increases	Mildly declines	Declines	Mildly increases	Mildly increases
	Public debt-to-output ratio	Mildly increases	Increases	Mildly declines	Declines	Mildly increases	Mildly increases

Note: Comparisons are made with reference to the baseline scenario. 'Short run' refers to the first 2–3 decades after the introduction of the policy. 'Long run' captures the rest of the simulation period (circa 2050–2100). Green panels depict improvements in the indicators. Red/pink panels capture deteriorations.

Nevertheless, relying solely on such policies to reduce even more the pace of global warming (close to 1.5°C) would face several limitations. A first option would be for some of these policies to be calibrated such that they become more ambitious from a climate perspective. For example, the size of green public investment and green public subsidies could increase to further stimulate the shift to renewables and the use of energy efficiency practices. However, increasing the magnitude of expansionary fiscal policies would face some real resource constraints: material resources might not be sufficient to support an additional increase in economic activity and the labour force might not be sufficient to generate the additional GDP. These constraints are exemplified in Figure 3c, which shows that in the *fiscal + financial* scenario the waste per capita exhibits a rising trend towards the end of the simulation period (a reflection of the higher use of material reserves), as well as in Figure 3e, which shows that the unemployment rate becomes pretty low in the same scenario. Therefore, adopting more ambitious expansionary green policies might not be feasible in practice.

A second option would be to make policies such as carbon taxes and the dirty penalising factor more ambitious. However, as explained above, such policies can deteriorate specific macroeconomic, financial and social indicators. Hence, increasing even further the carbon taxes and the risk weight on dirty loans might be unfeasible in practice as well.

This means that we need to move beyond such policies to achieve a socio-ecological transformation of our economies that is in line with the limits of a finite planet. The *sufficiency*

+ *fiscal* + *financial* scenario illustrates that. In this scenario, we combine the sufficiency policies with the macroeconomic and financial policies of the previous scenario. The combination of these policies allows the surface temperature to get closer to 1.5°C at the end of the century. This is combined with lower use of matter and a lower generation of waste. However, in the *sufficiency* + *fiscal* + *financial* scenario, there are some mild adverse effects on the leverage ratio of banks and public indebtedness both in the short run and in the long run (see Table 3). Designing a policy mix that can address these adverse effects and can improve ecological indicators even further is left for future research.

5 CONCLUSION

We urgently need to design and implement a socio-ecological transformation of our economies. In this paper, we showed how E-SFC modelling can help in identifying climate policy mixes for this transformation. We did so by illustrating how different types of climate policies can be evaluated using what we have called a 'systems-based analysis', which constitutes an alternative policy assessment approach to cost–benefit analysis.

We showed that the simultaneous achievement of ecological sustainability and macrofinancial and social stability requires the combination of several climate policies. Some policies (such as carbon taxes and sufficiency policies), which are likely to create trade-offs when they are implemented in isolation, can have a positive contribution to a smooth socio-ecological transformation when they are combined with other climate policies. Importantly, our results also show that ecological instability is unlikely to be prevented if we solely rely on a green transformation of macroeconomic and financial policies, without at the same time taking action to change our environmentally destructive consumption patterns.

For future research, we would like to highlight the following. First, although E-SFC modelling provides an appropriate framework for assessing policies from a systems-based perspective, it is not the only type of modelling that can be used for a systems-based analysis of climate policies. Other modelling approaches that focus on out-of-equilibria phenomena, the endogeneity of risks, and path dependency (such as agent-based modelling) are also suitable for systems-based assessments (see for example Lamperti/Roventini 2022). Second, climate justice and gender issues have received limited attention in the assessment of climate policies from a modelling perspective. This needs to be addressed in future modelling works, for example by using gender equality and climate justice indicators in the systems-based assessment of climate policies. Third, in the systems-based analysis of this paper, we compared policies without setting specific targets for certain indicators. In the era of ecological breakdown, a different way of performing the systems-based analysis would be to: (i) set specific ecosystem thresholds that should not be passed to ensure a stable ecosystem; (ii) identify policy mixes that can meet these thresholds; and (iii) compare the policy mixes according to their performance with respect to macroeconomic, financial and social indicators. This would be in line with the precautionary principle (Chenet et al. 2021) and the planetary boundaries approach (Steffen et al. 2015). Fourth, it is highly necessary for quantitative systems-based assessments of climate policies to be accompanied by political economy analyses that focus on the distribution of power and the political barriers to the implementation of climate policies.

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