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Fiscal policy and ecological sustainability: A post-Keynesian perspective

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Abstract: Fiscal policy has a strong role to play in the transition to an ecologically sustainable economy. This paper critically discusses the way that green fiscal policy has been analysed in both conventional and post-Keynesian approaches. It then uses a recently developed post-Keynesian ecological macroeconomic model in order to provide a comparative evaluation of three different types of green fiscal policy: carbon taxes, green subsidies and green public investment. We show that (i) carbon taxes reduce global warming but increase financial risks due to their adverse effects on the profitability of firms and credit availability; (ii) green subsidies and green public investment improve ecological efficiency, but their positive environmental impact is partially offset by their macroeconomic rebound effects; and (iii) a green fiscal policy mix derives better outcomes than isolated policies. Directions for future heterodox macroeconomic research on the links between fiscal policy and ecological sustainability are suggested.

Keywords: post-Keynesian economics, ecological economics, green fiscal policy, stock-flow consistent modelling

JEL Codes: E12, E62, Q54, Q57

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1. Introduction

Environmental problems are now more pressing than ever in human history. Climate change, biodiversity loss, ocean acidification, deforestation, ocean plastic pollution and water scarcity are only some examples of these problems. Human activity is almost entirely responsible for these environmental pressures. For instance, climate change is directly linked with the build-up of greenhouse gases (GHGs) in the atmosphere caused by industrial activity over the last decades. The accumulation of plastics in the oceans is a direct outcome of the inherent tendency of the current economic system to generate large amounts of non-recyclable hazardous waste, which is disposed into the environment. Deforestation is the result of urbanisation, cattle ranching, the use of trees for fuel and other human-related developments and activities.

There is, therefore, an urgent need to change fundamentally the way that our economies and societies produce and consume. Failure to do so could result in environmental collapse, harming fundamentally the future of humanity. Fiscal policy is one of the key tools that can be used in this direction. Green fiscal policy is not confined to the use of taxes as a means to incentivise more environmentally friendly production and consumption patterns. Green fiscal policy has also to do with government spending (for example, through subsidies and investment) that affects the use of renewables, energy efficiency, waste generation, recycling and other aspects of production and consumption that have an impact on the environment. Green fiscal policy also includes public investment in research and development of new green technologies.

Post-Keynesian economics has traditionally emphasised the importance of fiscal policy for achieving macroeconomic stability and high levels of employment (see, for example, Fazzari, 1994-5; Wray, 2007; Arestis and Sawyer, 2010; Hein and Stockhammer, 2010; Nikolaidi, 2014; Dafermos, 2018). This comes in contrast to the limited role fiscal policy is considered to play in the 'New Consensus Macroeconomics'. In this consensus, which continues to play a prominent role in modern macroeconomics, fiscal policy is not considered to be an effective instrument for regulating aggregate demand and higher government spending is postulated to have a neutral impact on long-run growth and an adverse effect on budget deficits (see Arestis and Sawyer, 2003; Lavoie, 2006; Arestis, 2012).

However, despite their emphasis on the positive economic and social effects of fiscal policy, post-Keynesian economists have not paid enough attention to the way that fiscal policy could be used to achieve ecological sustainability. This has largely to do with the fact that ecological sustainability has only very recently incorporated into post-Keynesian approaches (see Fontana and Sawyer, 2013, 2016; Jackson and Victor, 2016; Taylor et al., 2016; Dafermos et al., 2017). Therefore, the investigation of the environmental effects of fiscal policy from a post-Keynesian perspective is still at a very preliminary stage.

The aim of this paper is to critically discuss how green fiscal policy has been so far analysed within both conventional and post-Keynesian frameworks, placing particular emphasis on the assumptions that have been adopted in different types of models and the implications that these assumptions have for the results of the analysis. It also intends to explore how green fiscal policy could contribute to ecological sustainability, using a recently developed post-Keynesian ecological macroeconomic model that allows us to provide a comparative assessment of different types of green fiscal policies. Our evaluation, which relies on a scenario analysis, focuses both on the environmental effects of these policies (primarily climate change), and their key economic and financial implications. The green fiscal policies that we examine are carbon taxes, green subsidies and green public investment. We also discuss directions for future heterodox macroeconomic research in this area.

We proceed as follows. In Section 2, we briefly describe the main fiscal policies for ecological sustainability. In Section 3, we discuss how the effects of green fiscal policies have been analysed in mainstream and post-Keynesian models and we briefly analyse some key methodological issues. In Section 4, we outline the model used for our evaluation of green fiscal policies. In Section 5, we describe our scenario analysis and we present our simulation results. In Section 6, we summarise our key findings and provide directions for future research.

2. Which are the key green fiscal policies?

Carbon taxes remain the most popular green fiscal policy since today. The idea behind this policy is straightforward: by imposing such taxes on carbon emissions, firms have an economic incentive to rely less on fossil fuels and invest more in renewables and energy efficiency. Furthermore, carbon taxes can induce households to choose less carbon-intensive goods. Proponents of carbon taxes often argue that their beneficial effects are not confined to the reduction of carbon emissions. These taxes can be a source of significant revenues for the governments, allowing them to spend in areas that are highly important for the environment (such as low-carbon infrastructures) or reduce taxes on other economic activities or income sources, via the so-called 'revenue recycling' (High-Level Commission on Carbon Prices, 2017; OECD, 2017; World Bank, 2019).

However, carbon taxes are likely to have significant distributional effects (Zachmann et al., 2018). For example, a tax on carbon can lead to a rise in energy prices, which are more likely to hurt much more significantly poorer households whose electricity and heating costs constitute a significant proportion of their income. In addition, carbon taxes may affect those who work in carbon-intensive sectors or small and medium-sized enterprises that rely on carbon-related activities. Consequently, it is often argued that these policies have to be accompanied by offsetting measures that attenuate these adverse distributional effects.

Carbon taxes are not the only type of environmental taxes (World Bank, 2019). Environmental taxes include all the taxes that are imposed on a physical unit that has an adverse impact on the environment. Examples of other environmental taxes are the taxes on transport (e.g. heavy goods vehicle taxes), pollution taxes (e.g. air pollution and landfill taxes) and resource taxes (e.g. mineral resources extraction taxes). The idea behind these taxes is similar to that of carbon taxes: they are meant to create incentives for more environmentally friendly behaviours and can, at the same time, raise public revenues that can be used for other beneficial purposes.

Green subsidies are another green fiscal policy. They can take many forms. For example, they can be tax exemptions (as is the case, for example, with electric vehicles in many countries), feed-in tariffs for renewable energy production[1] or grants that fund part of investment projects that intend to have a positive environmental impact. Quite ironically, subsidies have not overall played a beneficial environmental role over the last decades. This is because a significant amount of subsidies has supported – and continues to support – energy consumption and production related to fossil fuels (High-Level Commission on Carbon Prices, 2017; Monasterolo and Raberto, 2019). The removal of fossil fuel subsidies is, thus, an essential part of any green fiscal policy mix.

However, green fiscal policies are not restricted to the use of taxes and subsidies. The spending decisions of governments also have a significant impact on ecological sustainability (Pollin et al., 2014). For example, instead of trying just to incentivise and fund green private investment, governments can also invest directly in low-carbon infrastructure (such as electricity transmission grids and electric vehicle charging facilities), energy efficiency retrofits for publicly-owned buildings as well as research and development in green technologies (like battery storage technologies and technologies for the electrification of the industrial sector). This investment can take place within the context of a mission-oriented approach (Mazzucato and McPherson, 2018). In addition, the government can employ people to work in the public sector in order to provide environment-friendly services through a jobs guarantee programme (Forstater, 2003) or via standard public sector employment contracts.

3. Modelling green fiscal policies

Carbon taxes constitute the green fiscal policy whose implications have been most extensively explored in the economic modelling literature. This has largely been done via Integrated Assessment Models (IAMs). These models include both economic and environmental modules, allowing the combined assessment of the economic and environmental effects of various types of policies. IAMs can be classified into two broad categories: (i) the Policy Optimisation Models (POMs) which identify optimal policies by relying on cost-benefit analysis; and (ii) the Policy Evaluation Models (PEMs) whose key aim is to identify a least-cost approach to achieve a specific goal; for example, a specific change in atmospheric temperature (Farmer et al., 2015).

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[1] Feed-in tariffs are long-term contracts, which allow green energy producers to receive a fixed payment for the electricity that they generate; these payments are independent of the market price of electricity.

The most well-known POM is the Dynamic Integrated Climate-Economy (DICE) model, which has been developed by the Nobel Prize-winning economist, William Nordhaus. The DICE model (Nordhaus, 2018) uses the standard neoclassical optimal growth framework whereby a social planner decides about the level of consumption and investment such that the discounted sum of per capita population-weighted utility is maximised. Within this framework, output is supply-determined and is affected by the level of investment, which builds up capital stock. Consumption and investment are substitutable. Lower consumption today leads to higher investment today, which in turn leads to higher output and higher consumption in the future.

Economic activity generates carbon emissions, which are considered a kind of externality. These emissions enter into the carbon cycle. The part of carbon that is not absorbed by oceans and the biosphere remains in the atmosphere contributing to climate change. Climate change in turn has adverse feedback effects on economic activity: the DICE model uses a damage function, which links atmospheric temperature with economic damages in a non-linear way. These damages reduce GDP and, thus, consumption and economic welfare. The *social cost of carbon* represents the decline in the discounted value of economic welfare caused by an increase in CO_2 emissions by 1 tonne. The rate that is used to discount economic welfare reflects social time preferences. The higher the discount rate the lower the value assigned to damages that will be experienced by future generations.

Firms can reduce emissions, and thus climate damages, by undertaking mitigation activities. However, mitigation has a cost: an increase in mitigation reduces the resources that are available for consumption and conventional investment. Therefore, the social planner weighs off the cost of mitigation against the benefit of reducing climate damages, and selects the optimal level of mitigation that equalises the cost with the benefit. At this optimal level, the social cost of carbon is equal to the incremental cost of mitigation. When the social cost of carbon is derived, based on this cost-benefit analysis, it is considered to reflect the optimal carbon price and, if a carbon tax is imposed, its value should be equal to this optimal price.[2]

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[2] Note that the carbon price derived by DICE and other IAMs is also compatible with cap-and-trade systems.

According to the most recent estimates that rely on the DICE model (Nordhaus, 2017), the optimal carbon price for 2015 is \$31 per tonne of CO_2 in 2010 US\$.[3] Interestingly, such a price for carbon derives a 3.5 degrees global warming at the end of this century, which is much higher than 1.5 or 2 degrees threshold that has been set by the Paris Agreement. However, within the IAM community there is no consensus on what the right value for the optimal carbon price is. Many IAMs, which have modified key assumptions in the DICE model, have estimated different optimal carbon prices, which in most cases are higher compared to those estimated by Nordhaus. These higher estimates can, for example, be the result of the incorporation of climate tipping points, the use of a lower discount rate, the incorporation of a more pessimistic damage function, the assumption for a higher climate sensitivity to the increase in carbon concentration, or the introduction of intra-region inequality (see e.g. Botzen and van der Bergh, 2012; Lemoine and Traeger, 2014; Dennig et al., 2015; Dietz and Stern, 2015; Espagne et al., 2018).

Other well-known POMs that have been used to estimate optimal carbon prices are FUND (Anthoff and Tol, 2013), PAGE (Hope, 2011) and WITCH (Bosetti et al., 2006). FUND has a very detailed analysis of damages since it includes damage functions for a variety of effects of climate change, including the impact on health, agriculture, forestry, migration and water resources. It analyses a large number of world regions and endogenises many GHG emissions, not only the carbon dioxide ones, as is the case in DICE. However, the economic module in FUND is relatively simple and economic growth is exogenous. The social cost of carbon is estimated by monetising the welfare effects of climate change, including the value of life. PAGE is close to FUND in the sense that economic growth is exogenous and different type of damages in different regions are analysed. However, it is less complicated.[4]

In WITCH, economic growth is endogenously determined via a Ramsey-type neoclassical model. The model covers different regions around the world. In each region, a social planner determines the optimal path that maximises welfare. The distinguishing feature of the model is the endogeneity of technology and the emphasis on the role of learning processes and R&D investment. In addition, the strategy of each region is determined via an intertemporal game. The model has been used to

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[3] This price should increase by 3% every year.

[4] For a more detailed comparison of the two models and their similarities and differences with the DICE model, see Bonen et al. (2014).

explore the combined effects of carbon pricing and innovation policies, showing that innovation policies can reinforce the positive environmental effects of carbon pricing (Bosetti et al., 2011).

It is important to point out that although the primary aim of POMs is to estimate the social cost of carbon that corresponds to an optimal path, they have also been used to derive non-optimal paths. For example, Nordhaus (2017) has himself calculated the social cost of carbon that would result in no more than 2.5 degrees global warming. As expected, this social cost of carbon is much higher than the one that is derived based on the optimal path.

Contrary to POMs, PEMS do not use cost-benefit analysis since they do not typically include monetised damages from the environment. Generally speaking, they have a more detailed sectoral representation and a more detailed analysis of the energy system and emissions. This allows them to be employed for exploring how mitigation policies can affect different sectors of the economy, as well as the use of energy and the generation of GHG emissions in a more comprehensive way. This is why many PEMs have been used in the scenarios of the Intergovernmental Panel on Climate Change (IPCC) (see Krey et al., 2014). Some well-known PEMs are the Economic Projection Policy Analysis (EPPA) model (Chen et al., 2016), the Global Change Assessment Model (GCAM) (Shi et al., 2017) and the Model for Energy Supply Strategy Alternatives and their General Environmental impact model (MESSAGE) (Riahi et al., 2011).

The economic module of many IAMs (both POMs and PEMs) is often built based on CGE (Computable General Equilibrium) modelling techniques. CGE models are multi-sector models in which household and firms are assumed to maximise their utility and profits. In these models product and factor markets are typically postulated to be competitive and clear through changes in relative prices; the latter depend on the interaction between supply and demand. General equilibrium is achieved when all markets are in equilibrium.[5]

CGE models have been employed to analyse the effects of a wide range of green fiscal policies, including carbon taxes (e.g. Meng et al., 2013; Guo et al., 2014) and green subsidies or feed-in-tariffs (e.g. Kalkuhl et al., 2013; Wei et al., 2019). Many studies that rely on CGE models have also paid

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[5] For detailed discussions of the use of CGE models in the analysis of environmental policies, see Bergman (2005) and Babatunde et al. (2017).

particular attention to the distributional effects of carbon taxes (and carbon pricing more general), whereby a common finding is that carbon taxes are regressive. However, their adverse distributional effects can be offset if the associated tax revenues are used to compensate poorer households (e.g. Rausch et al., 2011; Liang and Wei, 2012).

In CGE models employment is determined via the interaction between labour supply and labour demand. In these models, a policy mix that increases environmental taxes and reduces labour taxes can increase employment, by raising both labour supply and labour demand, but it can also decrease it because of the impact of environmental taxes on prices. If the labour market is assumed to be perfect and no involuntary unemployment exists (which is the case in the vast majority of CGE models), it is less likely that such a policy mix will have a favourable employment effect. Positive employment effects become more likely when labour market is imperfect and involuntary unemployment exists (World Bank, 2019).[6]

Now, a crucial question arises: can IAMs and CGE models provide an appropriate framework for analysing environmental economic policies, including green fiscal policies? As the recent literature on economy-environment modelling has emphasised, these approaches have several limitations. Let us briefly refer to those of them that are more relevant for our analysis.[7]

First, in the vast majority of CGE models and IAMs it is assumed that economies function at full capacity and full employment. This is at odds with reality: modern economies are characterised by idle resources (see, for example, Chewpreecha et al., 2017), which means that an increase in aggregate demand always causes an increase in GDP.[8] In the standard IAMs and CGE models, this is not the case: if, for example, public green investment demand increases, the creation of new jobs should be accompanied by an equivalent reduction in jobs in other sectors of the economy. Although there are IAMs or CGE models in which involuntary unemployment is introduced (as mentioned above), aggregate demand still plays a negligible role.

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[6] For a CGE model that permits imperfections in the labour market, see Capros et al. (2013).

[7] For a detailed discussion of additional issues see, among others, Scrieciu et al. (2013), Farmer et al. (2015), van den Bergh and Botzen (2015) and Pollitt and Mercure (2017).

[8] Of course, the magnitude of this effect on GDP depends on some potential capacity constraints that have to do, for example, with skills and geographical location.

The lack of a role for aggregate demand is important for an additional reason. Climate damages are likely to affect consumption and investment demand significantly and hence GDP (Batten, 2018; and Dafermos et al., 2017, 2018). For example, in areas in which there will be a secular increase in the severity and frequency of climate-related events, firms might be less willing to invest is physical assets and households might increase their propensity to save. Without an explicit analysis of demand, these effects cannot be examined.

Second, the way that mitigation is modelled in CGE models and IAMs, is problematic. Mitigation in these models is considered to constitute only a cost. This violates the Keynesian principle that one person's spending is another person's income. For example, if a company buys some solar panels to reduce its carbon emissions, the spending on these panels will be an inflow for the company that produces the panels. This spending contributes to GDP and cannot be considered only as a cost. It is also problematic that green capital that is built via mitigation spending does not contribute to future GDP. Taking into account that mitigation can have a positive contribution to GDP would call into question the whole rationale of cost-benefit analysis.

Third, money in these models is not created endogenously as is the case in the real-world financial systems (see Arestis and Sawyer, 2006; McLeay et al., 2014). The financial system, if it appears in the models, plays merely an intermediary role. A direct implication is that environment-related spending (of the private or the public sector) always crowds-out other types of investment spending or leads to lower consumption. This is because credit cannot expand to support investment; prior savings can only fund the latter. This means that the possibility that climate policies are expansionary is ruled out (Pollitt and Mercure, 2017). Moreover, the expansion of green private investment is restricted since firms cannot acquire credit created out of 'thin air'. This is highly important as an assumption, given that credit can be a very crucial source of funding for green investments, like those linked to renewables, which tend to have high upfront costs.

The way that money and the financial system are treated in CGE models and IAMs has additional implications. In particular, it makes it very difficult to analyse the financial stability effects of climate change. As has been extensively discussed in the recent literature on climate-related financial risks (e.g. Scott et al., 2017), climate policies and climate change can lead to defaults and asset price deflation, disrupting the credit provision process through interconnected balance sheets. The effects cannot be properly explored in CGE models and IAMs. Moreover, these models are not suitable for the analysis of the effects of environmental financial policies that have been recently suggested, and whose aim is to reallocate credit and funds from brown investment towards green investment (Campiglio, 2016; Volz, 2017; Campiglio et al., 2018; D'Orazio and Popoyan, 2019).

Fourth, most IAMs and CGE models rely on the idea that the agents have a common understanding of the way that the economy works (which is captured by the model that is used by economists) and they know the data-generating process about the economy, which follows a pre-determined probability distribution. However, in reality fundamental uncertainty exists (Davidson, 1991, 2002; Fontana and Gerrard, 2004). The future path of the economy is unknown and unknowable, which stems from the fact that this path is determined based on the decisions of people today, which cannot be known by definition.[9] Consequently, in their decision-making process, agents follow norms and rules of thumb in line with the concept of 'procedural' rationality (Lavoie, 2014, chapter 2). Within that context, an 'optimal' path cannot be by definition identified. Needless to say, the importance of fundamental uncertainty is reinforced when the uncertainties about environmental issues are taken into account.[10]

Fifth, the idea of analysing the environmental problems simply as externalities, whose value can be priced, raises many questions. In practice, these prices are estimated using methodologies that often rely on subjective valuations of life and pollution, which cannot reflect the intrinsic value of nature and the actual social cost of environmental degradation (Neuteleers and Engelen, 2015; Berger, 2017). In addition, according to the tradition of ecological economics, the environmental problems should not be viewed as side effects of economic activity. Instead, the economy should be analysed as a sub-system of the wider ecosystem (Daly and Farley, 2011). An implication of this is that the stability of the ecosystem is a prerequisite for a stable society and economy. If the prices imposed on 'externalities' are not enough to prevent severe ecological disruptions, the economy will be destabilised as well. IAMs take implicitly that into account when they analyse, for example, how a higher than 2 degrees global warming can be prevented, instead of using cost-benefit analysis (which

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[9] This, in particular, relies on the concept of 'ontological' uncertainty, which is one of the two forms of fundamental uncertainty, the other one being 'epistemological' uncertainty. For the differences between ontological and epistemological uncertainty see Lavoie (2014, chapter 2).

[10] See, for example, Aldred (2012) on the importance of climate change uncertainty and its links with fundamental uncertainty à la Keynes.

is the case in PEMs). However, IAMs and CGE models do not generally adopt a systems approach that could explicitly examine how the dynamic interactions between the ecosystem and the economic system could result in instability and collapse.

Over recent years, alternative models have been developed, which do not suffer from most of the above-mentioned problems. The majority of these models draw on the post-Keynesian tradition and they thereby postulate that output is demand-determined, money is created endogenously, finance plays a non-neutral role, economies do not operate at equilibrium and agents take decisions based on rules of thumb and norms. A few of these models also rely on agent-based methodologies, which provide an alternative to the representative agent approach of most IAMs (Lamperti et al., 2018).

Some of these heterodox macro models have recently been employed to examine the effects of green fiscal policies. Monasterolo and Raberto (2018) have explored the impact of green subsidies using a stock-flow consistent (SFC) model.[11] Their model does not include an environmental or climate module, but it has a detailed economic module in which an explicit distinction is made between green and brown capital. In their scenarios, subsidies are funded via sovereign green bonds or taxes. Their results show that green subsidies have a positive impact on green investment. However, the effects on employment and total capital accumulation depend on the type of funding. If green subsidies are funded via taxes, the economic effects are negative since taxation reduces disposable income. If, on the other hand, sovereign bonds are issued to finance green subsidies, employment and capital accumulation increase; however, in this scenario public indebtedness also increases. Monasterolo and Raberto (2019) have used an extended version of this model to examine the implications of phasing out fossil fuel subsidies. In their simulations, a smooth phasing out of these subsidies not only increases green investment, but also improves macroeconomic performance.

Godin (2012) has developed an SFC model that analyses the implications of a green employer of last resort (ELR) programme. According to this programme, all those who are unemployed do not receive unemployment benefits, but work instead in green jobs in the public sector. The simulation

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[11] For the stock-flow consistent approach to macroeconomic modelling, see Godley and Lavoie (2012), Caverzasi and Godin (2015) and Nikiforos and Zezza (2017).

analysis shows that such a programme can reduce both private unemployment and energy consumption.

D'Alessandro et al. (2018) have built a post-Keynesian model for the French economy, which is used to conduct projections for a variety of environmental policies. These policies include a carbon tax and a jobs guarantee programme that incorporates green jobs. In their simulations, carbon taxes do not have a very significant environmental effect because only a relatively small amount of emissions is affected by these taxes. The jobs guarantee programme has a positive effect on employment, but it also increases the fiscal deficit.

Bovari et al. (2018) have developed an SFC model in which a climate module à la DICE is incorporated. They analyse the effects of carbon taxes and green subsidies. Although carbon taxes have a beneficial effect on the path of atmospheric temperature, they decrease corporate profits, increasing thereby firms' reliance on private debt. When carbon taxes are implemented in combination with green subsidies, the reduction in atmospheric temperature is reinforced and the rise in private indebtedness is less severe. However, green subsidies cause a rise in public indebtedness.

Mercure et al. (2018) have used a large-scale global post-Keynesian macro-econometric model to analyse the effects of a wide range of climate policies, including green fiscal policies. They examine policies such as feed-in tariffs, subsidies for renewables and heating systems, carbon prices and fuel taxes. Their model also includes a climate module and the role of technology diffusion. Their results show that the combination of such policies can significantly reduce the pace of global warming. The economic effects of these policies are both positive and negative. On the one hand, electricity prices go up, reducing the real disposable income of households and slowing thereby economic activity. On the other hand, green public investment increases employment and household income. The impact on fiscal balances is typically positive since revenues from taxes are higher than the expenditures in each region of the world. The impact on trade balance varies. Regions that produce fossil fuels are adversely affected since their exports decline, while in regions in which fossil fuels are imported the impact is positive since their imports go down.

Deleidi et al. (2019) have investigated the way that government spending on both green innovation and green capital can affect ecological sustainability, using an SFC model. Their simulation analysis shows that this type of spending has positive effects on making the use of energy and matter more efficient, slowing down climate change and the depletion of energy and material resources.

Although the above-mentioned studies have examined various aspects of green fiscal policies from a post-Keynesian perspective, they have not systematically compared carbon taxes with other types of green fiscal policies (including green public investment) with explicit reference to their combined effects on the economic, financial and environmental variables. In what follows we provide such a comparative evaluation using the DEFINE (Dynamic Ecosystem-FINance-Economy) model developed by Dafermos et al. (2017, 2018). This model serves our purposes because it combines aspects of post-Keynesian and ecological economics and pays particular attention to the interactions between the ecosystem, the financial system and the macroeconomy. The aim of our analysis is to open the avenue for a more systematic examination of the links between fiscal policy and ecological sustainability in heterodox macroeconomics.

4. The DEFINE model

The DEFINE model portrays the economy as a subsystem of the broader ecosystem. The economy uses material and energy resources from the environment on a continuous basis. Production leads to the generation of waste (such as hazardous solid waste and carbon emissions), which causes the degradation of the ecosystem. This degradation has feedback effects on humans and the function of the macroeconomy and the financial system. These negative effects include, for example, (i) the destruction of capital stock due to climate-related events (like floods and hurricanes); (ii) global warming-related reductions in labour productivity; (iii) the negative impact of hazardous waste on the health of the population and the ability of people to work; and (iv) the adverse impact of climate damages on economic units' expectations that affect their consumption and investment decisions. These effects can worsen the financial position of households and firms and can result in financial instability via a large number of feedback loops related primarily with the process through which credit is provided via banks and the bond market.

The way that energy and matter are analysed draws on the tradition of Georgescu-Roegen (1971). The model uses material flow analysis, which ensures a consistent representation of material flows in and out the socio-economic system, in line with the First Law of Thermodynamics (according to which matter and energy are not created or destroyed). Special emphasis is placed on the interaction between material extraction, recycling and the generation of waste. The model reports how waste is accumulated and pays particular attention to the potential emergence of matter depletion problems. The model also captures a key implication of the Second Law of Thermodynamics: as fossil fuels are burned, low-entropy energy is transformed into high-entropy energy. The model shows the dynamic evolution of the stock of fossil-fuel energy in order to capture the depletion of low-entropy energy.[12]

Carbon emissions are generated when non-renewable energy is produced. These carbon emissions contribute to the accumulation of carbon dioxide in the atmosphere. This build-up of carbon leads to higher radiative forcing, which expresses the difference between the solar energy absorbed by the Earth and the energy that is radiated back to the outer space. In turn, the rise in radiative forcing causes an increase in atmospheric temperature.

The way that the macroeconomy and the financial system are analysed is broadly in line with the SFC literature. For example, (i) all financial inflows correspond to financial outflows and all financial assets correspond to financial liabilities; (ii) the interaction between financial stocks and flows are explicitly modelled and the accumulation of private debt can have important negative feedback effects on macroeconomic and financial stability; and (iii) money is endogenously created when loans are provided.

Some key features of the model that differentiate it from the majority of previous SFC models are the following. First, banks do not provide credit in a passive way. There is an explicit credit rationing procedure: banks reject a proportion of the loan applications or provide a lower amount of loans than those that are demanded by the potential borrowers. Banks decide about the level of credit rationing based on both their own financial position and the financial position of their potential

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[12] For a discussion of the First and the Second Law of Thermodynamics and their implications for economics, see Daly and Farley (2011).

borrowers. Lending interest rates are also endogenous; apart from being affected by central bank decisions, they also tend to increase when banks' financial position deteriorates.

Second, although output is demand-determined, supply constraints are also taken into account. This is crucial because environmental degradation, captured for example by climate change, is very likely to have significant supply-side effects, since it can reduce labour/capital productivity and labour force, and it can also destroy a large proportion of capital stock. In addition, the model uses a Leontief-type production function whereby energy and matter are essential for the production process. Thus, a potential depletion of energy and material reserves can restrict economic activity.

Environment-related technical change is endogenous. As green capital is accumulated (compared to conventional capital), the use of renewables increases, energy efficiency improves, material intensity declines and recycling increases. Technical change is governed by logistic functions, which capture learning effects; the latter are crucial for the way that green technology is developed and diffused.

DEFINE consists of two big blocks. The first block is the ecosystem block, which includes equations about (i) matter, recycling and waste, (ii) energy, (iii) emissions and climate change and (iv) ecological efficiency and technology. This block is built around a physical flow matrix and a physical stock-flow matrix that allow us to track explicitly the evolution of material and energy flows and stocks that play a key role for the stability of the ecosystem. The evolution of these physical stocks and flows is affected by human activity in both a negative and a positive way. On the one hand, higher economic activity leads to the accumulation of stocks that degrade the ecosystem (like carbon concentration and hazardous waste stock) and the depletion of useful resources. On the other hand, green technical progress can attenuate the adverse environmental impact per unit of GDP.

The second block is the macroeconomy and financial system block, which includes equations about (i) output determination, (ii) firms, (iii) households, (iii) banks, (iv) the government sector and (v) the central banks. This block is represented by the transactions flow matrix and the balance sheet matrix, as is the case in SFC models. Firms invest in conventional and green capital by using retained profits, loans and bonds. Commercial banks accumulate capital and distribute part of their profits to households. Firms can default on these loans. When this happens, there is an adverse effect on the capital of banks. In addition, firms can receive funding via the bond market. Households receive labour income, buy durable consumption goods and accumulate wealth in the form of deposits, corporate bonds and government securities (there are no household loans). Corporate bonds can be either green or conventional. When the demand for green bonds increases, the price of these bonds tends to go up, leading to a lower cost of borrowing for green projects.

Central banks determine the base interest rate; they also provide liquidity to commercial banks and purchase government securities and corporate bonds. The government sector collects taxes (including carbon taxes), decides about the level of government consumption and government investment (the latter can be green or conventional) and can implement bailout programmes, if there are financial problems in the banking sector.

In what follows, we use the new version of the model, DEFINE 1.1. Compared to DEFINE 1.0, the latter version has various additional features that have to do with the role of fiscal and financial policies. The new features that are relevant for our analysis here are the following. First, carbon taxes are explicitly incorporated, which means that firms have to pay taxes based on the carbon emissions that they generate. The implication of this is that carbon taxes reduce the profitability of the firm sector. Since investment depends on profits, carbon taxes have an adverse effect on economic activity and accumulation of capital. Note that the adverse effect on economic activity is magnified by the fact that lower profitability also reduces loan provision. However, the adverse effect of carbon taxes on firms' profitability induces them to replace conventional investment with green investment. This tends to reduce carbon emissions.

Second, the government sector covers a proportion of green private investment spending via green subsidies. This has the opposite effect on profitability compared to carbon taxes. This policy also incentivises firms to invest more in green capital.

Third, the government sector undertakes public investment, which can be either green or conventional. As a result of this investment, public capital is accumulated. The evolution of green public capital compared to conventional capital affects ecological efficiency. For example, the building of public electricity grids can increase the use of renewables and improve energy efficiency.

In the model, the decision of the government about the level of green investment is exogenously determined based on its policy priorities. In addition, the government decides about the level of its green and conventional investment separately.

We have made the simplifying assumption that the government decides about this spending without taking into account the potential effects on public debt. We have assumed so because we wish to focus on the implications of green government spending, instead of exploring the drivers of fiscal decisions, which are quite complex, differ around the world and depend significantly on political factors.

Fourth, the firm sector has been disaggregated into four broad sectors ('mining and utilities', 'manufacturing and construction', 'transport' and 'other sectors')[13] whose conventional capital stock is assumed to have a different 'degree of brownness'. This degree of brownness is proxied by the carbon dioxide emissions that each sector produces compared to its gross value added. Hence, the higher this value, the higher the brownness of the capital of the sector, and the larger thereby the adverse environmental effect of the conventional investment of this sector.

A detailed description of these extensions as well as an analysis of all the equations of the model and its technical details can be found on the website of the model.[14] The website also includes information about the data that has been used to calibrate the model and estimate some of its key behavioural equations. Our econometric estimations rely on panel data for a large number of countries and refer to (i) the consumption function, according to which the spending of households depends on their disposable income and financial wealth; (ii) the investment equation which portrays the investment of firms as a function of the profit rate, the rate of capacity utilisation and the unemployment rate; (iii) the labour productivity function whereby labour productivity depends on the growth rate of output in line with the Kaldor-Verdoorn law; (iv) the credit rationing function,

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[13] This disaggregation relies on ISIC (International Standard Industrial Classification of All Economic Activities) rev. 3.1. The 'mining and utilities' sector includes ISIC C ('mining and quarrying') and ISIC E ('electricity, gas and water supply'), the 'manufacturing and construction' sector includes ISIC D ('manufacturing') and ISIC F ('construction'), the 'transport' sector corresponds to ISIC I ('transport, storage and communications') and the 'other sectors' include ISIC A, B, G, H and J-P.

[14] Available at: www.define-model.org

which is indirectly estimated via an econometric equation that refers to the determinants of corporate loan growth; and (v) the equation about the endogenous spread on corporate loans.

The evaluation of policies in DEFINE does not rely on any cost-benefit analysis, despite the fact that damages are taken into account. Mitigation, which takes the form of green investment, does not represent just a cost, as in traditional IAMs. Instead, green investment contributes to GDP and is not necessarily financed by prior savings; it can also be financed by newly created public or private debt. This is not in line with the rationale of the cost-benefit analysis used by IAMs.

In DEFINE we, instead, adopt a systems approach. Policies are evaluated based on their ability to achieve high well-being in a way that does not cause a collapse of the highly interconnected macroeconomic, financial and ecological systems (in both the short run and the long run). In other words, when the model is used for policy analysis, the purpose is to identify a mix of policies that permits the socio-economic system to function within the environmental limits and achieve the highest possible welfare.

5. A comparative evaluation of green fiscal policies

The model is run for the period 2017-2120. The reason why such a long period has been selected is because we wish to evaluate how green fiscal policy could alter the long-run trends in key environmental variables (and the feedback effects of these trends on the stability of the economic and financial systems). We first develop a baseline scenario for this period. In this scenario, the global economy continues to expand in broad line with recent trends and ecological efficiency improves slowly, due to green technical progress and some moderate mitigation action. However, this action is not enough to avoid a significant rise in atmospheric temperature by the end of this century.

Table 1 describes the main features of this scenario. The economy grows on average at a rate close to 2.5% until 2050; in other words, we postulate an economic expansion a little bit slower than the one observed over the last two decades or so. Crucially, economic growth has a declining trend, partially because of demographic changes. In 2050 population becomes equal to about 9.77 billion people (based on United Nations, 2017). The unemployment rate remains, on average, slightly lower than 6% until 2050. Moreover, the default rate on corporate loans is assumed to remain, on average, close to its current level, which is slightly higher than 4%.

Table 1: Key features of the baseline scenario

Variable	**Value/trend**
Economic growth till 2050	Approximately 2.5% (on average)
Unemployment rate till 2050	Slightly lower than 6% (on average)
Population in 2050	9.77 billion
Labour force-to-population ratio in 2050	0.45
Default rate on corporate loans till 2050	Slightly higher than 4% (on average)
Carbon tax	Increases by 3% per year
Green public investment	Remains stable as a proportion of GDP
Green subsidies	Remain stable as a proportion of green investment
CO_2 intensity in 2050 as a ratio of CO_2 intensity in 2017	Around 0.9
Share of renewable energy in total energy in 2050	Around 25%
Energy intensity in 2050 as a ratio of energy intensity in 2017	Around 0.7
Annual total green investment in the period 2017-2050	Around US$ 1.5 trillion
Yield of conventional bonds	Quite stable till around 2050
Yield of green bonds	Declines slightly in the next decade or so

In terms of environmental policies, the carbon tax is assumed to increase by 3% per year. In our model, the carbon tax has been calibrated to US$ 1 per tonne of CO_2 in 2017. This is derived by dividing the global total revenue from carbon taxes (available from World Bank, 2018) by the total industrial carbon emissions. This figure is relatively low since in reality only a small proportion of carbon emissions (about 20%) is taxed (World Bank, 2018), while in our model all the industrial emissions are taxed. Thus, the carbon tax should be low enough in our simulations in order for the value of carbon tax revenues in our model to match the data for 2017.

The subsidy rate on green investment remains unchanged, close to 28% according to our calibration for 2017. Green public investment increases, but remains constant as a proportion of GDP. For 2017, this has been calibrated at about 0.25%. It is implicitly assumed that environmental regulation becomes gradually stricter, contributing to the moderate rise in green investment as a proportion of conventional investment. Overall, annual total (private and public) green investment during the period 2017-2050 is equal to around US$ 1.5 trillion.[15]

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[15] Note that in the reference scenario of IRENA (2018, p. 41) the annual investment in renewables and energy efficiency over the period 2015-2050 is close to US$ 1.3 trillion. Recall that green investment in our model does not only include

The accumulation of green capital leads to an improvement in ecological efficiency indicators. The share of renewable energy increases to about 25% until 2050 (from about 14%, which is the current level), while energy intensity is assumed to become approximately 30% lower in 2050 compared to its 2017 level. Material intensity and recycling rate also improve moderately.

We also assume that the yield on conventional bonds remains relatively stable until 2050, while the yield of green bonds improves in the next decade or so. The latter is a result of an increasing demand for green bonds that outstrips their supply, in line with recent trends (Climate Bonds Initiative, 2017, 2018a, 2018b).

Figure 1 illustrates how some key variables of the ecosystem, the financial system and the macroeconomy evolve under our baseline scenario. Since the rise in green investment is moderate (see Figure 1b, which refers to the desired investment in the 'mining and utilities' sector), the share of renewable energy does not increase sufficiently by the end of the century (Figure 1c). The improvement in energy efficiency is also moderate (not shown in the figure). This fact, combined with the continuous rise in GDP (Figure 1a), results in a continuous rise in carbon emissions in the next 4-5 decades (Figure 1d) that ultimately leads to an increase in atmospheric temperature by about 3.8°C (compared the pre-industrial levels) in 2100 (Figure 1e).

Global warming has adverse effects on the economy and the financial system. There is a long-run decline in the profitability of firms (Figure 1f), which is driven both by the climate-related destruction of capital and the fall in aggregate demand due to climate change. This decline becomes more pronounced once the 2 degrees threshold is passed, at the mid of this century. The fall in profitability triggers liquidity problems that cause a rise in the default rate on corporate loans (Figure 1g). Consequently, the capital of banks is hurt and their capital adequacy ratio follows a downward trend (Figure 1h). At some point, bank capital is not enough in order for banks to comply with the minimum capital requirements, so the government sector steps in and bailouts the banking sector.

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investment in renewables and energy efficiency; it also includes investment that improves material intensity and the recycling rate.

Bank bailouts have an adverse effect on the public debt-to-output ratio (Figure 1i). However, this is not the only reason why public indebtedness deteriorates. Public indebtedness primarily goes up because of the decline in economic activity that reduces tax revenues. Note that in our model we have not incorporated the financing of adaptation measures to climate change. If this were the case, the adverse impact of climate change on public indebtedness would be magnified.

Climate change is not the only environmental issue. The combination of continuous economic expansion with an insufficient improvement in material efficiency and recycling leads to a continuous rise in the waste produced by the socio-economic system (Figure 1l). This has negative feedback effects on the health of the population since a proportion of this waste is hazardous and can lead to chronic diseases. These diseases reduce the ability of people to work, inducing a fall in labour force.

We now examine how the above mentioned trends could be modified if different types of green fiscal policies are introduced at the global level in 2022. The green fiscal policies that we analyse are the following:

- *Carbon tax*: The carbon tax increases to US$ 16 per tonne of CO_2 in 2022 and grows by 3% per year thereafter. The increase in carbon tax to US$ 16 per tonne of CO_2 in 2022 corresponds to a carbon tax of US$ 80 per tonne of CO_2, if the latter is imposed only on those emissions that are currently covered by carbon pricing schemes (20% of total emissions). Note that US$ 80 per tonne of CO_2 is the upper limit for the carbon price suggested by High-Level Commission on Carbon Prices (2017) for 2020.
- *Green public subsidies*: The green subsidies provided by the government increases from 28% to 60% as a proportion of green investment in 2022 and remain constant thereafter.
- *Green public investment*: The green investment of the government increases from 0.25% to 1% (as a proportion of GDP) in 2022 and remains constant thereafter.

Note that each one of these policies corresponds to US$ 0.6-0.7 trillion. This amount is either the increase in government revenues (in the case of carbon tax) or the increase in government spending (in the case of green subsidies or green public investment) after the introduction of the policies.

The effects are shown in Figure 1. Let us first focus on the impact of a rise in carbon tax. This rise has a direct adverse effect on the profitability of firms (Figure 1f): since they cannot directly cut carbon emissions substantially, they have to pay a significant amount of money in the form of taxes, which causes a fall in profits. This has various implications for macroeconomic performance and financial stability.

To begin with, since firms have fewer profits, they cut their desired investment and their access to finance is distorted. The latter happens because lower profits increase the debt service ratio of firms, and this makes banks less willing to approve applications for corporate loans. The decline in desired investment, in conjunction with the increase in credit rationing, triggers an overall decline in private investment. Consequently, economic activity slows down (Figure 1a) and the unemployment rate increases significantly (Figure 1j). Moreover, lower profitability deteriorates the liquidity position of firms, causing a rise in the default rate, which affects adversely the stability of the financial system. Therefore, in our simulations the increase in carbon tax increases the so-called climate-related transition financial risks. In the related literature (e.g. Scott et al., 2017), these risks refer, among others, to the adverse impact that an abrupt implementation of climate policies could have on the financial system.[16]

However, these risks are not confined to the direct negative effect of a higher carbon tax on loan defaults. The interaction between the macroeconomy and the financial system generates second-round effects that exacerbate these risks and influence the evolution of macroeconomic activity. In particular, as the default rate remains high, the capital adequacy ratio of banks declines. Since banks have less capital, the cut in lending is reinforced.[17] This keeps economic growth at a low level for a prolonged period, magnifying financial instability.

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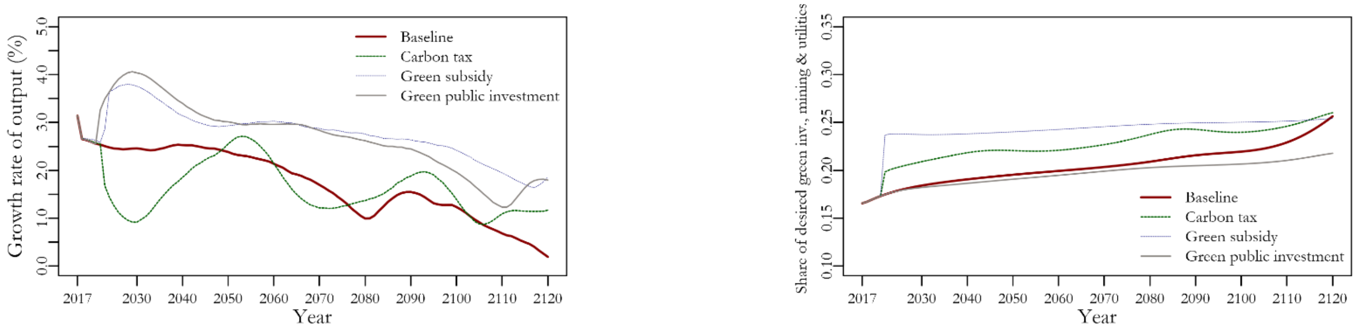
[16] Other causes of climate-related transition financial risks include rapid green technical progress that might render carbon-intensive assets unprofitable and abrupt changes in environmental preferences.

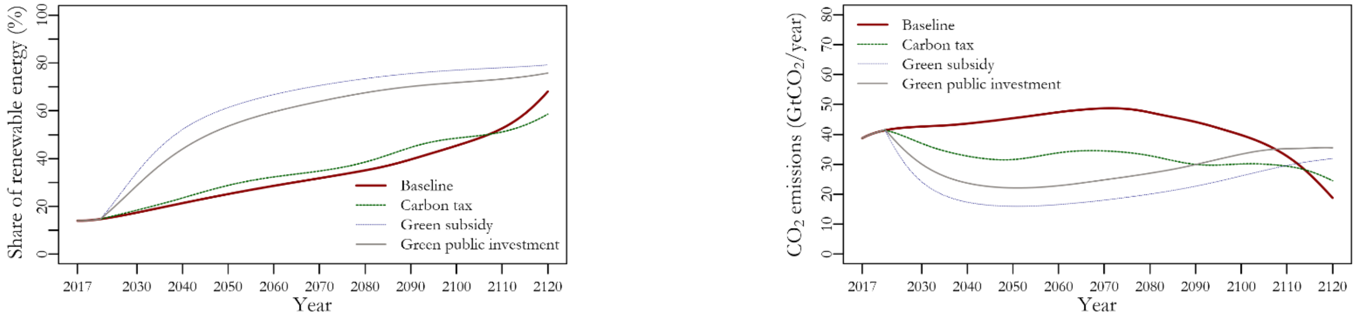
[17] Note that the effect of bank capital on bank lending, which is incorporated explicitly in our model, is in line with the recent empirical literature. The latter shows that changes in the capital adequacy ratio affect loan supply (see e.g. Aiyar et al., 2016; Gambacorta and Shin, 2018).

Fig. 1: Effects of carbon tax, green subsidy and green public investment policies, selected variables



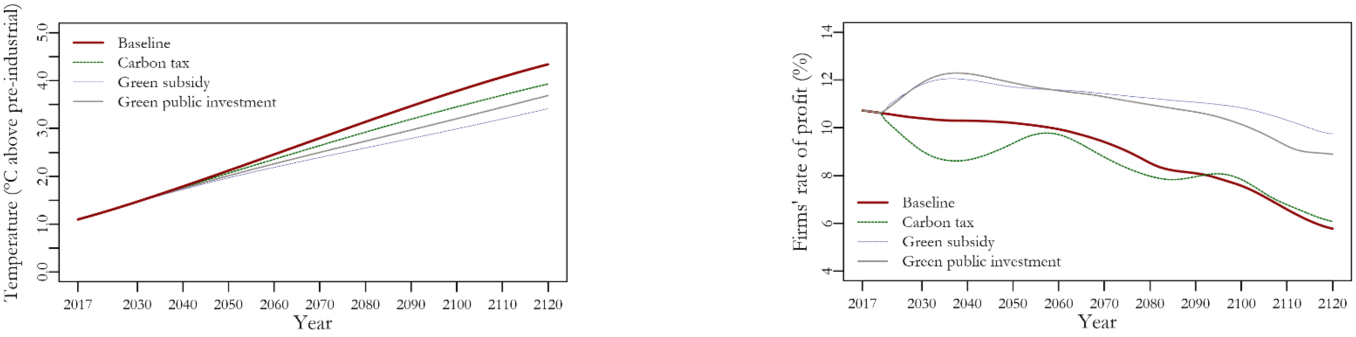
(a) Growth rate of output

(b) Share of desired green investment in total investment, mining and utilities



(c) Share of renewable energy in total energy

(d) CO_2 emissions



(e) Atmospheric temperature

(f) Firms' rate of profit

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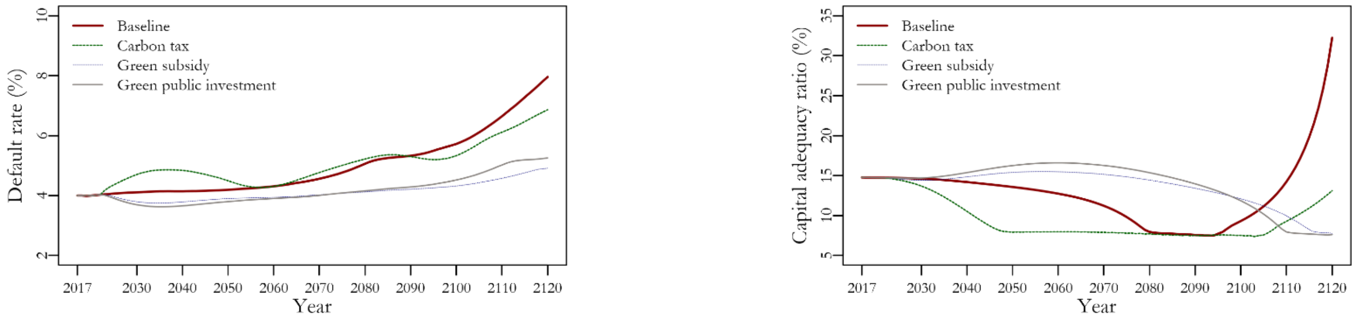
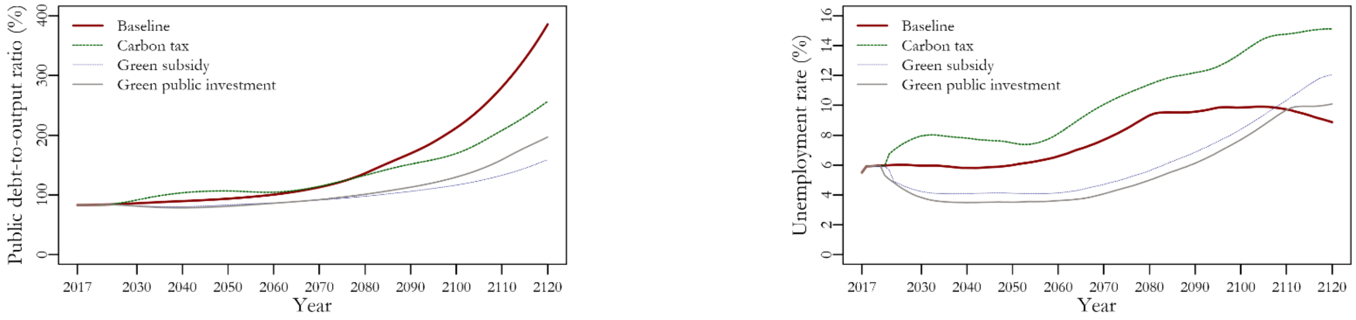
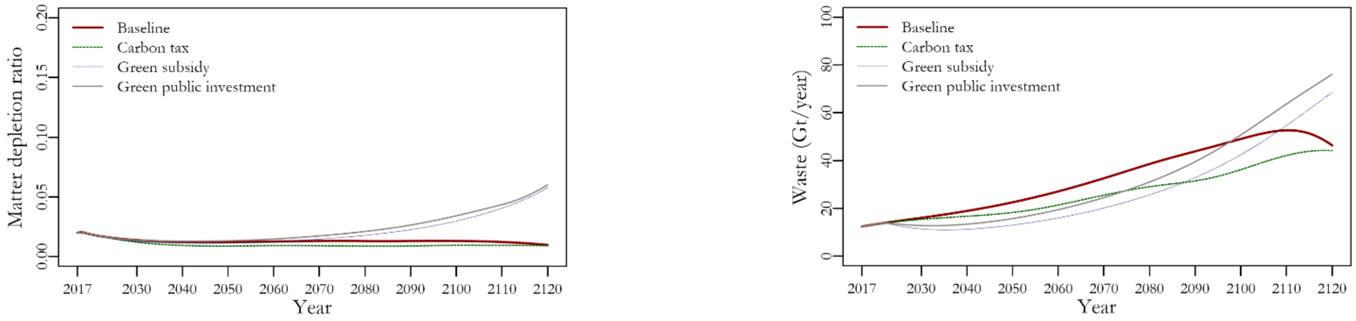

(g) Default rate

(h) Capital adequacy ratio


(i) Public debt-to-output ratio

(j) Unemployment rate


(k) Matter depletion ratio

(l) Waste per capita

Note: The figure reports across-run averages from 200 Monte Carlo simulations. The values used in the baseline scenario are available at www.define-model.org. All policy shocks take place in 2022. Under 'carbon tax', the tax on total carbon emissions increases to \$16/tCO$_2$ and grows at 3% thereafter. Under 'green subsidy', the subsidies as a proportion of green investment increase to 60%. Under 'green public investment', green public investment increases to 1%, as a proportion of GDP.

This higher financial instability is reflected, more precisely, in two developments. First, the capital adequacy ratio of banks continues to decline for many years, reaching the minimum level required by regulatory authorities (which in our simulations is assumed to be 8%). This induces the government sector to bailout banks. Second, lower macroeconomic activity reduces the financial wealth of households and, hence, their demand for corporate bonds goes down. The overall result is that the price of corporate bonds declines, causing an increase in the yield of bonds, which affects the cost of borrowing for firms (not shown in the figure). Thus, we overall have that in our simulations the sudden increase in carbon tax brings about a kind of *climate Minsky moment* that has prolonged adverse effects on the economy.[18]

These effects of the rise in carbon tax have an additional important implication. The conventional wisdom is that such a rise benefits public indebtedness because it increases tax revenues. The argument is that, if these revenues are not 'recycled', the government deficit goes down and this can improve the financial position of the government. However, this conventional wisdom ignores the aggregate demand and financial effects of carbon taxes, described above. These effects make carbon taxes have adverse implications for the long-run financial position of the government. In particular, in our simulations the increase in the carbon tax initially reduces the public deficit, as expected by the conventional wisdom (not shown in the figure). However, the reduction in aggregate demand, amplified by the adverse financial conditions, reduces the revenues that the government receives from taxes. Hence, the deficit gradually gets back to its initial level. At some point, the contractionary effects make the public debt-to-output ratio higher than its value in the baseline scenario (see Figure 1i).

The carbon tax-induced stagnation does not continue forever. The increase in carbon tax incentivises firms to invest more in green capital and reduce their brown investment. This is reflected in the rise of the share of desired green investment in total investment. Figure 1b shows how this share in the 'mining and utilities' sector increases due to the increase in the carbon tax. A similar increase takes place in other sectors, generating an improvement in the use of renewables (Figure 1c) and a decline in energy efficiency (not shown in the figure).

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[18] This term was first used by Carney (2015).

As a result, carbon emissions go down and, hence, firms have gradually to pay less carbon taxes. This improves their profitability and liquidity position, producing an increase in desired investment and loan supply. These positive economic developments are reinforced by the fact that the prolonged stagnation has declined the level of private debt, making firms and banks more willing to participate in new debt contracts that stimulate economic activity. Hence, although the increase in carbon tax triggers important contractionary effects, these effects are gradually faded away and economic growth bounces back.

How about the impact of the increase in carbon taxes on the environment? As alluded to above, an important implication of this policy is that firms start reducing their carbon emissions since they now have to pay more for the adverse environmental impact of their activity. However, the decline in emissions is not only caused by the change in firms' investment mix. Quite ironically, the contractionary effects of carbon taxes also drive this decline; this is so since economic activity slows down, and, thus, the emissions that the economy generates decline too. Hence, a more integrated approach to the environmental effects of carbon taxes needs to take explicitly into account the adverse impact that such taxes might have on economic activity.

The reduction in carbon emissions, compared to the baseline scenario, slows down global warming. However, atmospheric temperature is still high at the end of this century (close to 3.5^{o}C according to Figure 1e). A higher decline in global warming would be possible by imposing a higher carbon tax. However, the side effect of doing so would be an even higher decline in economic activity in the first years after the introduction of a stricter carbon tax policy.

Importantly, other environmental variables are also positively influenced by the rise in carbon tax. The induced increase in green investment, in combination with the reduction in economic activity, leads to a lower extraction of matter for production purposes. Hence, the depletion of material reserves slows down, compared to the baseline scenario (Figure 1k). The waste per capita that is generated by the socio-economic system is also reduced (Figure 1l).

However, the overall restriction of environmental problems is not sufficient to prevent a new round of severe economic and financial problems. This time the physical effects of climate change primarily cause these problems, as it was the case in the baseline scenario. Climate damages increase the default rate of firms (Figure 1g), reinforcing the under-capitalisation of banks (Figure 1h). At some point, the economy somehow recovers once debt levels have fallen sufficiently and credit expansion slightly bounces back. However, since this economy is constantly hit by climate shocks, it is not possible for the default rate to get back to levels that ensure financial stability. Therefore, climate-induced financial volatility becomes the new norm.

Overall, the increase in carbon tax in our model initiates a process that generates two long cycles in which climate and financial factors interact. The first cycle is induced by a partial transition to a low-carbon economy that takes place via the increase in carbon taxes. The carbon tax-related stagnation lasts until carbon emissions and private debt decline sufficiently. However, relatively shortly after the recovery of the economy a new cycle begins. This cycle starts because of the physical effects of climate change that bring the economy into a period of constant volatility.

Next, we turn to the impact of green subsidies. The rise in the green subsidy rate has quite the opposite effects compared to those of carbon taxes: since firms now receive money from the government, their profitability and liquidity increases. Hence, all those macrofinancial dynamic interactions described in the case of carbon taxes now work in the opposite direction, leading to an increase in economic activity (Figure 1a), a fall in unemployment (Figure 1j), a decline in loan defaults (Figure 1g) and an improvement in the financial position of banks (Figure 1h). This implies that green subsidies do not pose transition risks to the financial system. Quite the contrary: they improve financial stability.

However, do they harm the financial position of the government? As shown in Figure 1i, the public debt-to-GDP ratio does not increase, compared to the baseline scenario. Actually, after a few years it becomes lower than what it was the case in the baseline scenario. This is due to the positive expansionary effects of this policy on growth and thus on tax revenues. Hence, the impact of higher green subsidies on public indebtedness should not be the primary concern for those policy makers worrying about the government financial position.

Of particular interest are the environmental effects of green subsidies. As in the case of carbon taxes, green subsidies motivate firms to invest more in green capital. Hence, there is a reduction in atmospheric temperature (see Figure 1e). This improvement in temperature is higher in comparison with the carbon taxes scenario. This is so basically because the green subsidy policy (i) affects green investment in all sectors (not only in the sectors that produce the majority of carbon emissions) and (ii) has a positive impact on green credit availability.

One would might expect an even higher reduction in atmospheric temperature. However, this is not the case because of the macroeconomic rebound effect that refers to the adverse environmental impact of the increase in macroeconomic activity.[19] In other words, although green subsidies reduce the carbon emissions per GDP, the rise in GDP weakens the decline in these emissions. Moreover, the rise in green subsidies leads to a higher material depletion ratio and a higher generation of waste in the long run, compared to the baseline scenario (see Figures 1k and 1l, respectively).

We now consider the impact of an increase in public green investment. As in the case of green subsidies, such an increase leads to more economic activity (Figure 1a). Note that green public investment affects directly GDP; the government sector builds infrastructure by demanding directly investment goods produced by the private sector. On the contrary, when green subsidies are provided, the impact on investment is indirect (via the profitability of firms). Moreover, ecological efficiency now improves without observing an increase in the share of desired green private investment in total private investment (Figure 1b). This improvement in ecological efficiency stems now directly from the increase in green public capital. Actually, it is interesting that the share of desired green investment in the 'mining and utilities' sector goes down. This happens because the reduction in overall carbon emissions (due to green public infrastructure) makes this sector pay less carbon taxes, and thus disincentivises it to undertake more green investment.

As in the scenario of green subsidies, the increase in economic activity is not beneficial to the environment. The decline in atmospheric temperature is less impressive than one would might expect (Figure 1e). In addition, as shown in Figure 1k and Figure 1l, the high economic growth caused by the increase in public green investment amplifies the material depletion and waste generation problems. Therefore, although an increase in public investment appears to be an

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[19] For a description of the rebound effects, see Barker et al. (2009). Our analysis captures the macroeconomic aspects of these rebound effects since a rise in investment induced by a climate policy leads to higher economic activity that results in a rise in carbon emissions, waste and the use of energy and matter.

attractive policy in terms of economic and employment effects, it does not have very strong effects on improving environmental sustainability, when it is implemented in isolation.

As is clear from Figure 1, the rebound effects on green public investment should be of a much larger concern than any effects on public indebtedness. Actually, the higher economic growth caused by the rise in green public investment reduces after some years the public debt-to-GDP ratio, compared to the baseline scenario (similarly to what happens when the green subsidies increase).

Table 2 summarises the main similarities and differences between the effects of all green fiscal policies described above. A common feature of all these policies is that they reduce global warming. In the case of green subsidies and green public investment, this happens primarily because of the rise in green investment compared to conventional investment. In the case of carbon taxes, the reduction in global warming is also caused by the slowdown that it causes to the global economy. Since all these policies reduce the pace of climate change, they also reduce the climate-related physical financial risks.

Table 2: Key similarities and differences between the effects of the three green fiscal policies

	Increase in carbon tax	**Increase in green subsidy rate**	**Increase in public green investment**
Economic growth	Declines	Increases	Increases
Transition financial risks	Yes	No	No
Physical financial risks	Decline moderately	Decline	Decline
Public indebtedness	Increases	Declines moderately	Declines moderately
Global warming	Declines moderately	Declines	Declines

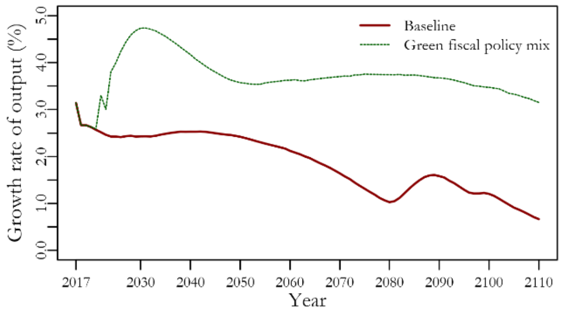
Note: The policies are compared with the baseline scenario

Both green subsidies and green public investment policies stimulate economic activity. This is beneficial to the economy, but has adverse effects on the environment due to the macroeconomic rebound effects described above. On the contrary, the carbon tax policy hits the profitability of firms and, thus, the transition to a low-carbon economy is accompanied by financial instability and a deterioration in macroeconomic performance. A side effect of this is that public indebtedness increases. This is not the case under the policies of green subsidies and green public investment: their positive economic and financial effects cause a decline in public indebtedness, compared to the baseline scenario.

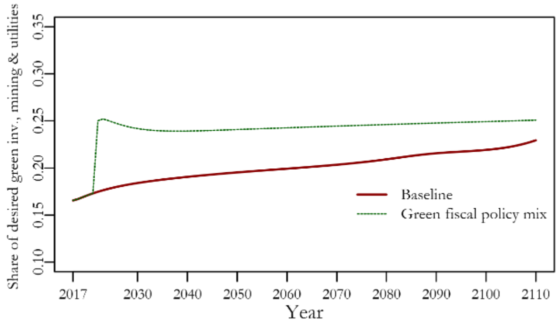
We now ask what the effects are of a combined implementation of all the above-mentioned policies. Figure 2 shows that this fiscal policy mix has several advantages. First, the combined implementation of the three policies represents a very large positive economic shock, which affects the economy on a constant basis. The contractionary effects of a higher carbon tax are overcompensated by the expansionary effects of the green subsidy and green public investment policies. Thus, economic growth increases (Figure 2a) and unemployment declines substantially (Figure 2j). Note that the stimulating effect of the shock continuously increases since, as time passes, private green investment goes up (and thus green subsidies) and carbon emissions go down (and thus carbon taxes). Second, the boost in green investment is now much stronger, producing a pronounced improvement of ecological efficiency indicators. For example, the share of renewable energy increases much more rapidly by the mid of this century (Figure 2c). Consequently, there is a significant decline in carbon emissions (Figure 2d) that restricts the rise in atmospheric temperature to about 2.6°C by the end of this century (Figure 2e). Third, the lower pace of climate change makes the climate damages much less pronounced. This, in conjunction with the rise in economic activity, improves substantially firm profitability compared to the baseline scenario (Figure 2f); the same holds for the default rate (Figure 2g), the capital adequacy ratio (Figure 2h) and the public debt-to-GDP ratio (Figure 2i).

Fig.2: Effects of a green fiscal policy mix, selected variables

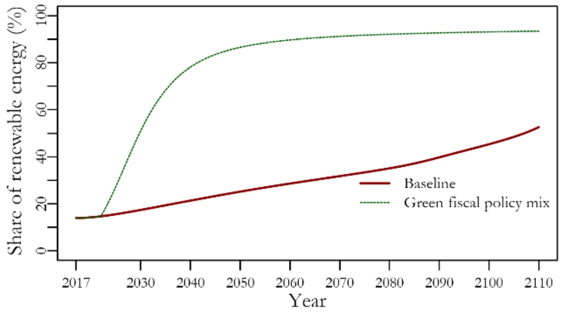
(a) Growth rate of output



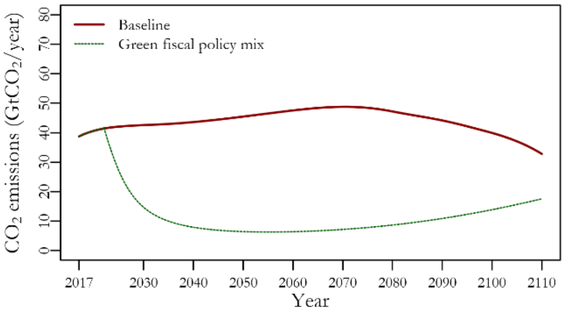
(b) Share of desired green investment in total investment, mining and utilities



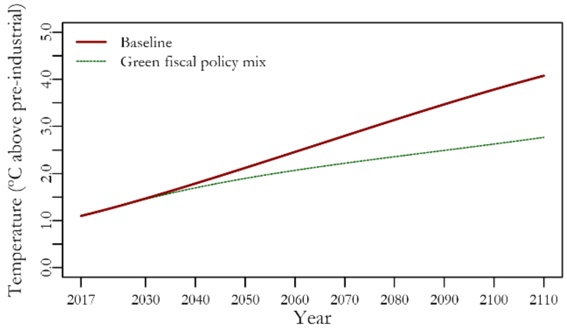
(c) Share of renewable energy in total energy



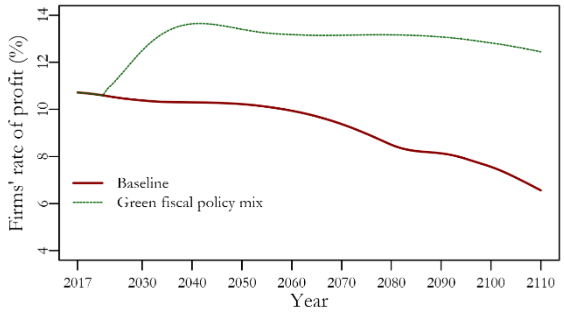
(d) CO_2 emissions



(e) Atmospheric temperature



(f) Firms' rate of profit



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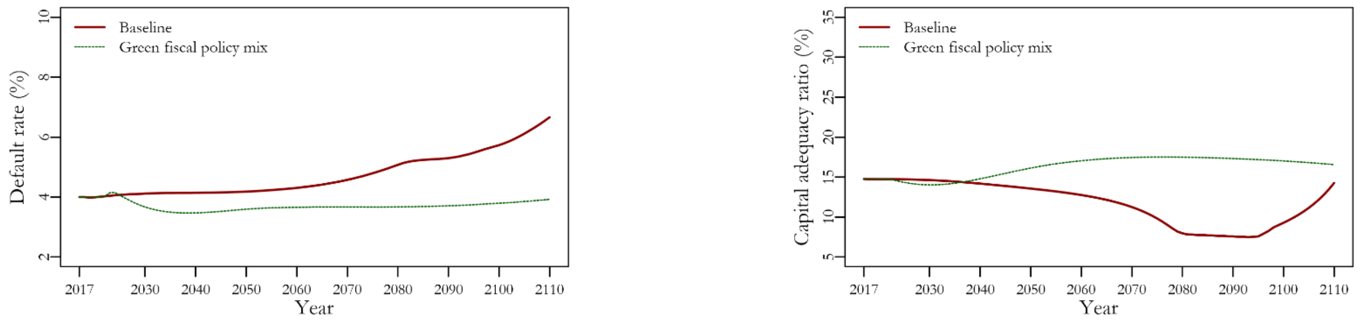
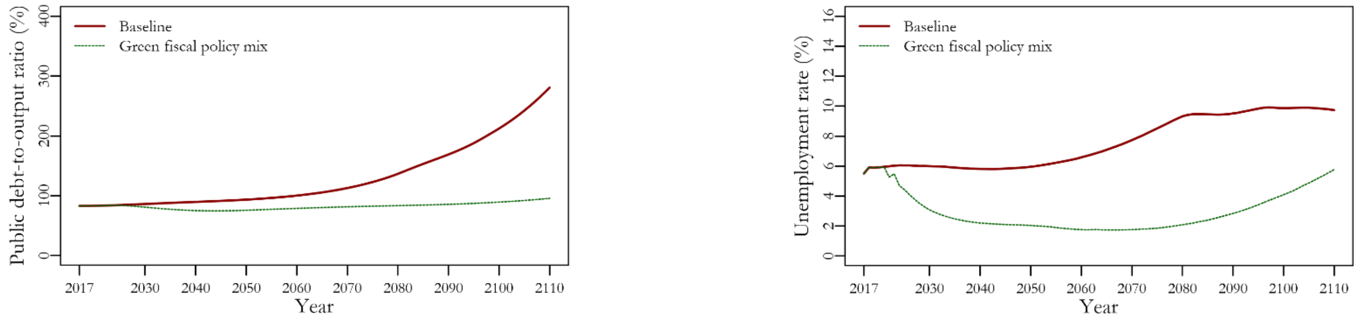


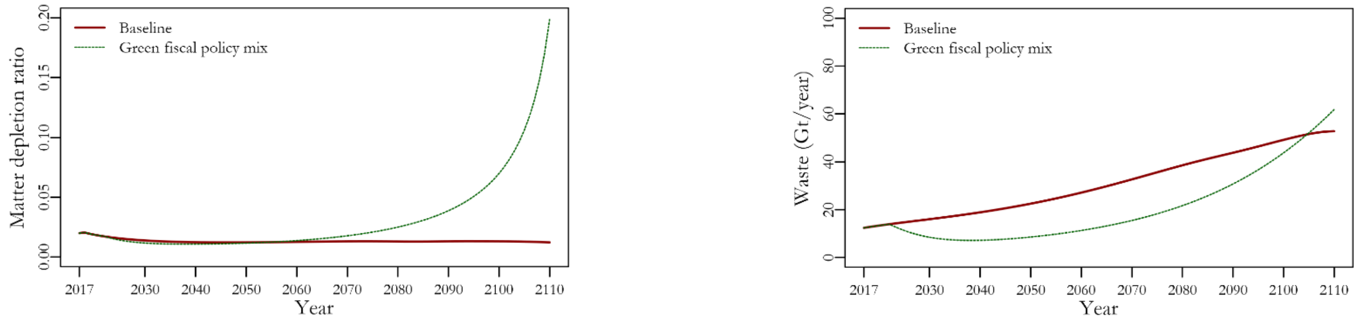
(g) Default rate

(h) Capital adequacy ratio



(i) Public debt-to-output ratio

(j) Unemployment rate



(k) Matter depletion ratio

(l) Waste per capita

Note: The figure reports across-run averages from 200 Monte Carlo simulations. The values used in the baseline scenario are available at www.define-model.org. The 'green fiscal policy mix' is implemented in 2022. It combines a 'carbon tax', a 'green subsidy' and a 'green public investment' policy. Under 'carbon tax', the tax on total carbon emissions increases to \$16/tCO_2 and grows at 3% thereafter. Under 'green subsidy', the subsidies as a proportion of green investment increase to 60%. Under 'green public investment', green public investment increases to 1%, as a proportion of GDP.

However, the high level of economic activity comes at an environmental cost. Although green investment reduces material intensity and increases recycling, this is not sufficient to prevent an increase in the waste per capita generated by the socio-economic system (Figure 2l). Moreover, there is a substantial rise in the material depletion ratio (Figure 2k). This happens, in particular, at the beginning of the next century and poses a significant challenge to macroeconomic stability. Actually, with the values that we have used in our simulations for the parameters and variables that refer to material flows and stocks, it turns out that the economy exhausts most of its material reserves until 2110. This results in severe economic instability.[20]

Regarding the global warming effects of the green fiscal policy mix, several additional points are worth mentioning. First, the path of atmospheric temperature shown in our simulations is significantly affected by the assumptions made about the climate system. Our assumptions follow those that Nordhaus (2018) has made in the recent version of the DICE model. Two key parameters of the climate system are the climate sensitivity and the carbon absorption capacity of the upper ocean and the biosphere. The climate sensitivity shows how much the equilibrium temperature of the atmosphere increases when carbon concentration doubles compared to pre-industrial levels. The carbon absorption capacity of the upper ocean and the biosphere reflects how much carbon is absorbed by these reservoirs. The lower the value of climate sensitivity and the higher the value of the carbon absorption capacity, the lower the adverse effects of carbon emissions on global warming. Under more optimistic assumptions about the value of these parameters, our green fiscal policy mix could produce a temperature path closer to 2 degrees.

Second, our analysis does not consider the case of 'negative emissions' technologies, like the carbon capture and storage ones. The inclusion of such technologies could significantly affect the path of atmospheric temperature in our scenarios. Note that these technologies play a key role in the IPCC scenarios that produce 1.5 or 2 degrees (IPCC, 2018).

Third, even if optimistic assumptions about the reaction of the climate system are adopted and 'negative emissions' technologies are introduced, it might well still be the case that our green fiscal policy mix, or more aggressive versions of it, are insufficient to keep climate change close to the targets set by the Paris Agreement. This means that many other policies need to accompany our green fiscal policy mix. These could include stricter environmental regulation, policies that reduce the growth of carbon-intensive consumption and financial policies that support actively the

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[20] This is why we do not report the value of variables after 2110 in Figure 2.

transition to a low-carbon economy. Actually, a key message of our analysis is that the complex interactions between the ecosystem, the macroeconomy and the financial system make it almost impossible for isolated policies to achieve stability in all systems simultaneously. The environmental and social challenges facing humanity in the next decades will require an innovative combination of different types of policies, as well as a fundamental change in our consumption patterns.

6. Conclusions and directions for future research

Fiscal policy has a crucial role to play in the fight against environmental problems. Contrary to conventional wisdom, this role moves beyond environment-related taxation; the spending decisions of the government can also have important implications for ecological sustainability. The main purpose of this paper has been to provide a comparative evaluation of different types of green fiscal policies, drawing on some recent developments in post-Keynesian ecological macroeconomic modelling. In our assessment, we focused on the role of carbon taxes, green subsidies and green public investment.

Our analysis has produced various interesting results. We have shown that carbon taxes can reduce global warming, as is the case in conventional environment-economy models. However, the explicit incorporation of the financial system in our model has allowed us to pay particular attention to an additional aspect of this policy, which has so far been neglected in conventional approaches: the implications of carbon taxes for the stability of the financial system. In particular, we have illustrated that the adverse effect of carbon taxes on the profitability of firms can give rise to a type of *climate Minsky moment* whereby the default rate of firms increases, with negative effects on the capital position of banks and the availability of credit. The rise in financial instability exacerbates the negative effects of carbon taxes on economic growth and employment. However, quite ironically, these economic and financial adverse effects of higher carbon taxes reinforce their positive environmental impact, since lower economic activity leads to less carbon emissions.

Green subsidies and green public investment also have positive environmental effects since they increase green capital compared to conventional capital. However, their positive impact on economic activity has as a result that their beneficial environmental effects are partially offset by macroeconomic rebound effects. The latter refer to the fact that the rise in green private and public investment leads to higher use of natural resources. This does not only have a negative impact on the dynamics of atmospheric temperature. It also causes some quite significant matter depletion problems at the beginning of the next century and it places upward pressures on the waste generated by the socio-economic system. Another interesting result is that, quite paradoxically from a conventional point of view, higher spending on public green investment and green subsidies reduces public indebtedness. This happens because of the positive effects of higher growth on tax revenues, but also because these policies reduce climate damages, which have an adverse impact on public indebtedness.

Combined implementation of higher carbon taxes, green subsidies and green public investment turns out to be more beneficial compared to the case in which these policies take place in isolation. Since green public investment and green subsidies boost the profitability of firms and growth, the financial instability effects of higher carbon taxes do not materialise. At the same time, the contractionary effect of higher carbon taxes counterbalances to some extent the adverse impact of the macroeconomic rebound effect on carbon emissions and other environmental variables. Therefore, a green fiscal policy mix is more effective from both an environmental and an economic/financial point view. This, however, does not mean that such a policy mix solves the environmental problems: the rise in atmospheric temperature is not so pronounced and high economic growth causes some material depletion and waste generation problems in the very long run. Hence, a green fiscal policy mix should be viewed as only one of the tools of a broader set of policies that are essential for achieving ecological sustainability.

There are various aspects of green fiscal policies that have not been accounted for in our model and can be the subject of future research. First, we have not explored the distributional effects of carbon taxes. These effects can be investigated by disaggregating the household sector into different types of households (see e.g. Dafermos and Papatheodorou, 2015) or by using agent-based techniques (e.g. Dosi et al., 2013; Russo et al., 2015). This needs to be accompanied by an analysis of the pricing policies of the carbon-intensive sectors in order to study how income distribution is affected by different pricing policies, depending on whether higher carbon taxes are passed on to consumers or not. This would provide some additional insights into our transition-related *climate Minsky moment*. For example, one could expect that if carbon taxes are passed on to consumers, such a moment could be triggered not by higher firm financial fragility, but by higher household financial fragility. For a preliminary analysis of the distributional effects of carbon taxes within a post-Keynesian framework, see Monasterolo and Raberto (2018).

Second, we have not analysed green public R&D expenditures. Nowadays, the risk of investing in innovative green technologies is relatively high and the private sector does not seem sufficiently willing to take that risk. Therefore, future research should investigate how public spending on innovative research in green technologies could facilitate the transition to a low-carbon economy and accelerate the change in the technological paradigm. Deleidi et al. (2019) have conducted a preliminary investigation of the impact of green public spending on green innovation.

Third, public green employment has not been incorporated into our model. This is a crucial aspect of green fiscal policy. By hiring public sector employees to work in green jobs, the government can both support environmental targets and reduce the unemployment rate. Nonetheless, higher green public employment can have macroeconomic rebound effects, as it was the case with green subsidies and green public investment in our model. The implications of these rebound effects need to be explored in detail.

Fourth, we have adopted a global perspective for the analysis of the implications of green fiscal policies. However, regional- and country-level approaches are a prerequisite for a well-informed implementation of such policies. Although some post-Keynesian analyses have been conducted in along these lines (e.g. Barker et al., 2012; Pollin et al., 2014), a deeper look into the financial aspects and implications of green fiscal policies is in order. The incorporation of environmental aspects into the recently developed country-specific empirical SFC models (see Burgess et al., 2016; Zezza and Zezza, 2019) would be a significant step in this direction.

Finally, in our analysis we have restricted our attention to a small subset of environmental problems: climate change, material/energy depletion and waste generation. However, fiscal policy can also affect many other aspects of the environment, including biodiversity, forests, fisheries and oceans. A broad research programme on green fiscal policy needs to pay attention to these aspects of the environment as well. This is particularly important due to the highly interconnected ecological sub-systems of the global ecosystem. The systems approach adopted in our analysis would be the natural starting point for such an interdisciplinary research programme.

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