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Economy-Finance-Environment-Society Interconnections
In a Stock-Flow Consistent Dynamic Model

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Abstract. This work takes inspiration from four theoretical strands: recent developments in ecological macroeconomics; the Schumpeterian framework of evolutionary economics that emphasises the entrepreneurial role of the State; the stock-flow consistent approach to macroeconomic modelling; and the supermultiplier model. Building upon these approaches, we develop a formal model that reproduces key interactions between the economy, the financial sector, the ecosystem and the society. We test and assess the effects of several fiscal policies. We find that, in principle, mission-oriented innovation policies are the most effective option in supporting innovation and growth, while reducing income inequality. However, lacking a 'green' and progressive taxation system, they are unlikely to reverse the current trend in atmospheric temperature.

Keywords: Supermultiplier, Mission-Oriented Policy, Stock-Flow Consistent Modelling, Climate Change, Rebound Effect

JEL codes: B51; B52; E12; Q57

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1. Introduction

The study of trade-offs and dilemmas is one of the most intriguing aspects of economic disciplines. Macroeconomics is no exception. The trade-off between full employment and price stability (that is, the Phillips curve) and the 'independent monetary policy – capital mobility – fixed exchange rate' trilemma (also called the 'impossible trinity') are well known, and quite controversial, examples. Price stability vs. economic growth and exchange rate stability vs. autonomous monetary policy decisions are not the only ones, however, since (market-based) economies unceasingly bring the policymakers face to face with hard choices. Expansionary fiscal policies aiming at enhancing economic growth might induce firms to increase their leverage ratio to fund investment, in a Minskian fashion, not to mention the potential complex interactions with income and, especially, wealth inequality. Broadening the landscape in order to include the ecosystem only makes the policymaker's tasks more complex. The pursue of environmental sustainability could come at the cost of a slowdown in economic growth and/or a reduced purchasing power for lower-class households. At the same time, the increase in ecological efficiency to be achieved through fiscal policy might be offset by indirect effects such as lower production costs and increases in activity levels (the so-called *rebound effect*), calling into question not only the extent but also the composition of government spending. While partial analyses of each sphere taken individually can shed light on important economic aspects, a general model is required to account for the complex interactions between the economy, the financial sector, the ecosystem and the society. This is the purpose of our work. We take inspiration from four theoretical strands:

i. recent developments in ecological macroeconomics that aim at applying post-Keynesian theories to ecological topics (e.g., Fontana and Sawyer 2016; Dafermos et al. 2017, 2018, 2019);
ii. the Schumpeterian framework of evolutionary economics that emphasises the entrepreneurial role of the State (e.g., Mazzucato 2013, 2016, 2018);
iii. the stock-flow consistent approach to macroeconomic modelling (e.g., Godley and Lavoie 2007);
iv. the supermultiplier model literature (e.g., Serrano 1995, Freitas and Serrano 2015).

Building upon these approaches, we develop a formal model that reproduces key interactions between the economy, the financial sector, the ecosystem and the society. We test and assess the effects of nine fiscal policies:

a) a reduction in the income tax rate for upper-class (UC) households;
b) a reduction in the income tax rate for lower-class (LC) households;
c) a selective tax on value added fostering green consumption relative to routine consumption;

d) an increase in routine government spending funded by issuing Treasury bills and/or monetary base;

e) an increase in government's mission-oriented innovation spending (MOIS) funded by issuing Treasury bills and/or money base;

f) an increase in green MOIS, that is, government innovation spending that aims at fostering the ecological transition to low-carbon techniques of production and is funded by Treasure bills and money base issues;

g) an increase in green MOIS funded by taxes on UC households;

h) an increase in green MOIS funded by selective taxation on consumption.

i) an increase in green MOIS funded by a carbon tax.

Therefore, our contribution to the current debate is fourfold. First, we focus on fiscal policy, which is usually neglected in ecological macroeconomics models. Second, we decompose it into a broad set of alternative options for policymakers, with a focus on public spending that aims to promote (public and private) innovation. Third, we factor in alternative sources of funding for government spending. Finally, we explicitly consider the interactions of the financial sector with the main macroeconomic variables, the society and the ecosystem.

We find that, in principle, MOIS policies are the most effective option in supporting innovation and growth, while reducing income inequality in the short to medium run. However, they may possibly increase wealth inequality. Furthermore, without a radical a radical change in government spending composition and a reform of the taxation system, MOIS policies are unlikely to reverse the current trend in atmospheric temperature. A carbon tax turns out to be the most efficient option from an environmental perspective, but its impact on short-term growth poses a political feasibility problem.

The rest of the paper is organised as follows. In section 2, we provide a short literature review. Section 3 is methodological and theoretical. We highlight assumptions, key features and possible drawbacks of the model. In section 4, our preliminary findings are presented and discussed. In section 5, we sum up the main policy implications.

2. Theoretical roots and literature review

As mentioned, our work is grounded in four theoretical strands: post-Keynesian ecological macroeconomics; the Schumpeterian school of evolutionary economics; the stock-flow consistent modelling approach; and the supermultiplier model.

i. *The post-Keynesian ecological macroeconomics (PKEM) approach*. This is a relatively recent strand in ecological economics (see, for instance, Foley 2012; Rezai et al., 2013; Rezai and Stagl, 2016; Sawyer and Fontana, 2013; Fontana and Sawyer, 2016; Taylor et al., 2016; Dafermos et al., 2017, 2018). PKEM theorists aim at analysing the macroeconomy as part of the broad ecosystem. Their approach is based on three principles: *a*) the main force driving economic growth is effective demand; *b*) supply-side constraints can emerge in the long-run due to environmental damages, the exhaustion of matter and energy reserves and climate change; *c*) there is a strong interconnection between the narrowly-defined economic system, the social environment, and the ecosystem. As a result, ecological feedbacks play a major role in determining both economic growth and policy effectiveness. PKEM authors usually focus on the effects of alternative monetary policies, selective credit policies and/or green bond markets (e.g., Jackson and Victor, 2015; Campiglio, 2016; Fontana and Sawyer, 2016; Dafermos et al., 2017, 2018). By contrast, seldom fiscal and innovation policies are examined.[1] Our paper is an attempt at bridging this gap.

ii. *The neo-Schumpeterian approach*. This strand of economic literature provides a theoretical framework to analyse the determinants of technical progress (see, among others, Nelson and Winter, 1982; Mowery et al., 2010; Mazzucato, 2013, 2014, 2018). We borrow, in particular, from the 'mission-oriented innovation spending' (MOIS) literature (e.g., Mazzucato, 2016, 2018). MOIS includes public spending on military and aerospace sectors, energy and clean-tech sectors, biotechnology and nanotechnology industries, and IT sectors (e.g., Block and Keller, 2011). MOIS policies aim at defining the direction of technical progress, thus creating market opportunities for the private sector (Mazzucato, 2013, 2016). Government spending stimulates and leverages private R&D investment in new areas, by allocating resources to find solution to societal challenges and technical problems (e.g., Mazzucato, 2016; Deleidi and Mazzucato, 2019, 2021). As a result, it accelerates the process of development and diffusion of innovation across the economy. Technical progress is regarded as endogenous with respect to both private firms' investment plans (e.g., Nelson and Winter, 1982) and government intervention (e.g., Mowery et al., 2010; Mazzucato, 2013; 2018).[2]

iii. *The stock-flow consistent (SFC) approach to macroeconomic modelling*. The SFC approach is grounded in both Copeland's pioneering works on national income identities and flow of funds in the 1940s and James Tobin's seminal work at Yale University. It was fully developed by Wynne Godley and Marc Lavoie in the 2000s (e.g., Godley and Lavoie, 2007), who paved the way for the flourishing of SFC models of the last decade (see Nikiforos and Zezza, 2017, Carnevali et al. 2019). SFC modellers use sound accounting principles to create the macroeconomic structure of a monetary economy of production, in which money supply is endogenous and behavioural equations are based on Kaleckian-Keynesian precepts.

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[1] There are a few exceptions, notably, Naqvi and Stockhammer (2018) and Dafermos et al. (2019).

[2] Examples of MOIS policies include the *Apollo Program* (EC, 2018a) and the *Energiewende Programme* (EC, 2018b; Mazzucato, 2018). The former is the US human spaceflight program carried out by the NASA, which led to the first manned landing on the moon in 1969. The latter is a German program aiming at reducing CO_2 emissions by developing a low-carbon energy system at the national level. The main purpose of the *Energiewende Programme* is to allow Germany to stop energy production from nuclear plants by 2022, and to rely on renewable energy resources only by 2050. The program is expected to create favourable conditions for the private sector, offering new opportunities to undertake green technological innovation (thanks to government-financed investment activities).

The use of this methodology is particularly appropriate for our research question. Although ecological aspects were not initially addressed by Godley and Lavoie (2007) and the early SFC research, recent developments in SFC literature demonstrate the flexibility and adaptability of this approach to studying the intertwined effects of economic development and technological progress on society and the natural environment (Naqvi 2015, Berg et al. 2015, Dafermos et al. 2017, 2018, Bovari et al. 2018, Monasterolo and Raberto 2018, Dafermos and Nikolaidi 2021, Dunz et al. 2021). As explained in detail in section 3, the standard way to account for the impact on the ecosystem and ecological feedbacks in SFC models is to couple the transactions-flow matrix and the balance sheet matrix with two additional matrices: the physical stock-flow matrix and the physical flow matrix of the society (see Table 3). The former can be regarded as an "extension of the matrix that Georgescu-Roegen used in his flow of fund model" (Dafermos et al. 2017, p. 192; see also, Georgescu-Roegen 1971, 1979, 1984).

iv. *The supermultiplier approach*. The main purpose of the supermultiplier model, originally proposed by Serrano (1995), is to link production with effective demand. It couples the traditional Keynesian multiplier with an investment function based on the flexible accelerator principle (e.g., Cesaratto et al., 2003; Freitas and Serrano, 2015). The supermultiplier model shows that the autonomous components of aggregate demand – among which the literature identifies government spending – are the main drivers of output growth.[3] The model displays some key properties, notably: the extension to the long-run of the 'Keynesian hypothesis', according to which output is essentially demand-driven and "the economic system may find itself in stable equilibrium with *N* [number of employed people] at a level below full employment" (Keynes 1936/1991, p. 30); an investment function that does not necessarily engender Harrodian instability; and the absence of any necessary relationship between the rate of accumulation and normal income distribution.[4] Our focus on fiscal and innovation policies led us to adopt a theoretical construction that models basic macroeconomic relationships. This construction has been used in recent literature to investigate the domain of fiscal and innovation policies.[5] We believe it can be fruitfully applied to our contribution. The model we use is a supermultiplier-like model, which provides an intuitive and simple treatment of capital accumulation. Specifically, it is based on the capital adjustment principle,

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[3] More precisely, "[p]ublic expenditure, exports, household residential investment, and consumption financed out of debt are considered autonomous components of aggregate demand in the literature and are the proximate cause of economic growth in the supermultiplier model. These components have two characteristics: they do not increase the (private) productive capacity of the economy and they are neither caused nor funded by domestic income" (Morlin et al., 2022, p. 5).

[4] Recently, supermultiplier-like models have been used by economists with different theoretical backgrounds (e.g., Allain, 2015; Lavoie, 2016; Hein, 2018; Fazzari et al., 2020, Nomaler et al., 2021).

[5] See, e.g., Freitas and Christianes (2020); Morlin (2022); Deleidi and Mazzucato (2019, 2021); Nomaler et al. (2021).

which means that private firms invest in order to adjust productive capacity to demand and production.[6]

3. Methodological aspects and main building blocks of the model

We test and discuss the effects of alternative fiscal policies on the economy, the society, the financial sector, and the ecosystem.

We use a supermultiplier approach, in line with recent PKEM literature that investigates the macroeconomic consequences of MOIS through this model (e.g., Deleidi and Mazzucato 2019, 2021), in a complete SFC discrete-time dynamic macro-economic model. For this purpose, we follow a three-step process. First, we define the basic behavioural (difference) equations, equilibrium conditions and accounting identities of the model. Second, we incorporate CO_2 emissions, climate change and the depletion of natural resources. Third, we further extend the model to account for the damages produced by global warming, which affect consumption, investment, capital depletion rates and labour productivity.

This section presents the most relevant equations for understanding the characteristics and dynamics of the model, as well as those that may require a detailed explanation due to their less intuitive rationale. The complete list of equations can be found in Appendix A. To facilitate cross-checking, we use the same numbering for the equations in the main text as in Appendix A.

3.1 Step one: defining economic identities and key behavioural equations

Table 1 and Table 2 display the sectoral balance-sheets and the transactions-flow matrix used to define the macroeconomic identities that assure the accounting coherence of the model. Five sectors are explicitly considered:

j) LC households (i.e., the recipients of labour incomes and a share of interest payments on bank deposits);

k) UC households (including firms’ owners, managers and rentiers, i.e., the recipients of entrepreneurial profits and financial incomes);

l) production firms (or non-financial corporations), which produce capital and consumer goods using two different techniques of production (notably, a high-carbon and a low-carbon technique);

m) the financial sector (including commercial banks, financial intermediaries and the central bank);

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[6] While firms' investment behaviour is more complex, we provide a stylized representation of capital accumulation in this article based on empirical literature that consistently finds a strong accelerator effect. A detailed analysis of this process is beyond the scope of this article.

n) the government sector (including both local and central government).

Both production firms and financial institutions are owned by UC households, who are the recipients of distributed profits. Whatever their class status, households' consumption is a function of disposable income, net wealth, price expectations and global warming. Therefore, LC household consumption function is:[7]

$$C_w = \left[c_w \cdot YD_w + c_{aw} \cdot NW_{w,-1}\right] \cdot \frac{E(p_w)}{p_w} \cdot \left(1 - d_{T,-1}\right) \tag{40}$$

where c_w is LC household propensity to consume out of income, YD_w is their disposable income, p_w is the (VAT inclusive) average price level faced by the LC households, $E(\cdot)$ stands for expected value in the current period (which was formulated in the previous period), c_{aw} is the propensity to consume out of wealth, NW_w is the stock of net wealth and d_T is a coefficient that defines the detrimental impact on consumption of climate change.[8] Finally notice that subscript '–1' marks lagged variables. Remaining variables are referred to the current period.

UC households' consumption is modelled in the same way (see equation 41). However, their disposable income includes price revaluation of shares' holdings (CG), in addition to entrepreneurial profits (F_{fd}), bank profits (F_b) and other net interest payments from financial assets (namely from deposits, D_π, and government bills, B_d. See equation 30 Appendix A).

Portfolio decisions of UC households have been modelled in line with SFC literature (based on Tobinesque principles, see Tobin, 1969). While the market of goods adjusts through quantities, a market-clearing price mechanism assures the equilibrium in the stock market (see equations 51 and 52 in Appendix A). In this model, the return rates on government bills are assumed to be steered by the central bank, who sets the policy rate (r_{cb}) and purchases government bonds in the secondary market to ensure financial conditions are consistent with its monetary policy stance (see equation 69 in Appendix A). While a complete yield curve with various interest rates related to different maturities is not included for the sake of simplicity, the model still provides a reasonable representation of the monetary policy conduct of contemporary central banks (Ihrig and Wolla, 2020). Notice that the risk premium on financial assets (μ_b) accounts for the *market-driven* component of government bond interest rate determination (see equation 94), and as such, can be viewed as a proxy for the slope of the yield curve.

Private investment plans are affected by firms' expectations concerning the output level, climate change-related damages and government policies. We assume that firms first choose the desired level of total investment (I_f) and then select its composition. Total investment is defined as a share of total estimated output ($E(Y_d)$). It is driven by firms' willingness to adjust

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[7] We maintain the same numbering of Appendix A, where the complete set of equations is reported.

[8] Adaptive expectations are assumed in our model. See equation (158) in Appendix A. For the sake of simplicity, we assume that $\psi = 0$ in our simulations, so that: $E(p_w) = p_{w,-1}$.

their productive capacity to the expected demand conditions, but it is also affected by climate change-related damages (d_T as defined in equation (144) in Appendix A). In formal terms:

$$I_f = h \cdot E(Y_d) \cdot \left(1 - d_{T,-1}\right) \tag{12}$$

$$u = u_{-1} \cdot \frac{1+g_Y}{(1+g_K)\cdot(1+g_{Af})} \qquad \text{with: } 0 < u \leq 1 \tag{13}$$

$$h = [1 + \phi \cdot (u_{-1} - u_n)] \cdot h_{-1} \tag{14}$$

where h is the share of investment to expected demand, u is the utilisation rate of plants, g_Y is the growth rate of output, g_K is the growth rate of the capital stock, g_{Af} is the growth rate of product per capital (see equation 138) and ϕ defines the speed of adjustment of the current utilisation rate to the normal utilisation rate (u_n).[9] Notice that equation (14) holds that firms adjust their investment plans to achieve the desired (cost-minimizing) capital intensity. Firms do that as long as they record discrepancies between the actual and the desired degree of capacity utilisation. At the macro level, these changes in investment plans arise as adjustments in the investment share.

As mentioned, green investment (I_{gr}) is simply defined as a share of total investment:

$$I_{gr} = \gamma_{gr} \cdot I_f \tag{17}$$

Green investment allows reducing CO_2 emissions and depletion rates of natural resources relative to conventional investment.[10] This beneficial effect is magnified by the choice of modelling investment in green capital as an imperfect substitute (not a complement) of conventional capital. The reason is that each type of capital implies a specific method of production, which, in turn, has a different impact on labour specialisation, the use of natural resources, and CO_2 emissions – think of skilled labour, dedicated machinery and/or alternative energy sources.[11]

We can now calculate the green investment share to total investment, γ_{gr}, as:

$$\gamma_{gr} = \gamma_0^{gr} + \gamma_1^{gr} \cdot \gamma_{gr,-1} + \gamma_2^{gr} \cdot \frac{G_{gr,-1}}{G_{-1}} + \gamma_3^{gr} \cdot d_{T,-1} + \gamma_4^{gr} \cdot \frac{C_{gr,-1}}{C_{-1}} + \gamma_5^{gr} \cdot \tau_{f,-1} \tag{18}$$

where γ_i^{gr} (with $i = 0,1,2,3,5$) are all positive coefficients. Intuitively, firms choose the share of green investment based on:

a) an autonomous or shock component $\left(\gamma_0^{gr}\right)$;

b) the past share of green investment $\left(\gamma_{gr,-1}\right)$;

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[9] See Brochier and Macedo e Silva (2019) for a similar approach.

[10] See equations (131) to (136) in Appendix A.

[11] Notice that hybrid technologies – say, an engine using both fossil fuel and wind as energy sources – are simply considered as involving a third type of capital (with respect to fossil fuel- and wind-based engines).

c) incentives created by the government (captured by the share of green spending to total government spending $\left(\frac{G_{gr,-1}}{G_{-1}}\right)$;

d) the proportion of climate-change related damages (d_T);

e) the share of household green consumption to total consumption $\left(\frac{C_{gr,-1}}{C_{-1}}\right)$;

f) the carbon tax rate $\left(\tau_{f,-1}\right)$.

There are three noteworthy aspects to mention here. First, although coefficients in equation (18) are not directly estimated, their values are derived from both the recent literature on the effects of green investment policies (Dafermos et al. 2017) and recent empirical findings about the impact of green government spending on private investment (Deleidi et al., 2020).

Second, the reason we consider the proportion of green spending to total government spending is that we contend that green government spending can have a positive impact on green private investment through externalities or market creation effects, as noted in Deleidi et al. (2020). In addition, to address negative externalities caused by brown production, we include a carbon tax in the model. By adjusting the profitability of the two sectors, the tax incentivizes firms to increase the volume of green investment, in line with conventional literature.

Third, the impact of climate change-related damages on green investment is not univocal, and negative feedback from these damages on green investment may occur. Nonetheless, the model can address these concerns. Specifically, as indicated in equation (12), climate change-related damages have a negative effect on total investment, which, in turn, has a negative impact on green investment as it is a fraction of total investment. Furthermore, these damages also decrease consumption – as per equation (40) – which negatively impacts total investment via the accelerator effect, and consequently, green investment.

3.2 Step two: modelling green spending and the ecosystem

Total output is demand-led both in the short and in the long run. However, firms' production plans can face labour force-, capital-, matter- and energy-constraints. A Leontief production function is used to determine potential output. In line with the von Neumann-Sraffa-Leontief tradition, we reject the neoclassical hypothesis of smooth substitutability between inputs. As a result, no adjustment in production techniques through changes in relative prices is allowed. This modelling choice rules out the possibility of countering natural reserves' depletion through a change in relative market prices. Consequently, socially and ecologically suboptimal results are possible and persistent in our model. Besides, fiscal and innovation policies play a crucial role.

We split government spending into two main components:[12]

i. routine spending (G_{rout}), meaning the purchase of goods and services from the private sector, which are necessary for the normal operation of the government sector;

ii. mission-oriented innovation spending (MOIS, represented by the variable G_{mois} in the equations in Appendix A), meaning the expenditures that stimulate structural change.

The former includes education and health spending, as well as expenditures in shovel-ready projects. The latter aims at fostering both technological innovation and low-carbon transition. Notice that MOIS focuses on big societal challenges, like climate change, which can only be addressed by involving many different sectors and institutions (Mazzucato, 2018). Therefore, MOIS is usually associated with a high multiplier effect, for it crowds-in private R&D investment.[13]

In our model, both conventional government spending and MOIS are assumed to grow at constant rates under the baseline scenario:

$$G_{rout} = G_{rout,-1} \cdot (1 + g_G^{rout}) \tag{87}$$

$$G_{mois} = G_{mois,-1} \cdot \left(1 + g_G^{mois}\right) \tag{88}$$

Green MOIS (G_{gr}), in turn, is just as a percentage of total MOIS:

$$G_{gr} = \alpha \cdot G_{mois} \tag{89}$$

where α is a positive coefficient. This type of green expenditure generates spin-offs through which green technologies are developed and diffused to the private sector. This effect is captured by equation (18) in our model (see section 3.1. In particular, this effect is captured by the third term of the equation: $\gamma_2^{gr} \cdot \frac{G_{gr,-1}}{G_{-1}}$).

Green MOIS accelerates the process through which innovation and new green technologies are introduced in the economic system (e.g., Deleidi and Mazzucato, 2019). Finally, like other aggregate demand components, it supports innovation spread and labour productivity growth through a Kaldor-Verdoorn mechanism (see equations 141 to 143 in Appendix A).

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[12] Equations (87) and (88) demonstrate that our model incorporates two distinct sources of autonomous demand. In this way, our contribution aligns with recent works that analyse the sub-components of autonomous demand, rather than treating it as a single entity. For example, Hein and Woodgate (2021) explore government spending and autonomous consumption, while Morlin (2022) examines exports and government spending. In Allain (2022) the two types of expenditure are not specified, while Freitas and Christianes (2020) focus on government and autonomous capitalists' consumption, and Pedrosa et al. (2021) analyze government and household consumption.

[13] We refer to Moretti et al. (2015), Deleidi et al. (2020), Ciaffi and Deleidi (2021), and Deleidi and Mazzucato (2021) for empirical analyses of the impact of government MOIS on private R&D spending. Furthermore, we refer to Ciaffi and Deleidi (2021) and Deleidi and Mazzucato (2021) for the empirical literature showing that MOIS produces larger multiplicative effects on GDP than more standard government expenditures.

Focusing on the ecosystem, green MOIS helps reduce the impact of production activities. It fosters private accumulation of green capital, which is marked by lower matter-, energy- and CO_2 emission-intensity coefficients and a higher share of renewable energy to total energy (see equations 131 to 133 in Appendix A for the effects of capital composition – green vs conventional – on matter, energy, CO_2-intensity coefficients, and equation 134 for the effects of the same ratio in the share of renewable energy sources).

Turning to narrowly-defined ecological variables, Table 3 shows the physical stock-flow matrix and the physical flow matrix of the society, respectively. The former allows defining the change in the stocks of things that directly influence human activities, namely, natural reserves and the socio-economic stock in our model.[14] The latter allows accounting for the First and the Second Law of Thermodynamics. Taken together, these two matrices provide the accounting structure for the ecosystem. The latter is defined as the physical environment with which individuals and groups interact. It determines the physical resources and constraints that human activities face. For the sake of simplicity, ecological variables are grouped in four blocks: material resources and reserves; energy resources and reserves; emissions and climate change; and ecological efficiency. Key behavioural equations are borrowed from Dafermos et al. (2017, 2018).

3.2.1. Material resources and reserves. The production of material goods (y_{mat}) is defined applying a matter-intensity coefficient (μ) to aggregate supply. The rationale behind this simple equation is that not all products and services generated by modern economies exist in a tangible form. For instance, software development results in an immaterial code written in a specific programming language. While this process demands human capital, energy, and hardware as inputs, the output is entirely intangible. The value of μ must fall between 0 and 1, and its precise magnitude varies according to the extent to which an economy has evolved from the initial stages of industrialization, when manufacturing consisted primarily of physical goods. In our model this value is determined by equation 131, that will be explained in section 3.2.4.

$$y_{mat} = \mu \cdot Y_s \tag{96}$$

The extraction of matter from the ground (mat) is the difference between the matter used in the production process, that can still be defined through y_{mat}, and the recycled socio-economic stock (rec , see equation 97). The latter is calculated as a percentage of demolished (or disposed) goods (des, see equation 98):

$$mat = y_{mat} - rec \tag{97}$$

$$rec = \rho_{rec} \cdot des \tag{98}$$

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[14] The socio-economic stock is made up of capital goods and durable (or yet-to-be-discarded) consumption goods.

In summary, not all production requires new raw materials or the creation of new components, as some components can be made from recycled materials and some raw materials can be extracted from goods that have completed their cycle of use. The value of ρ_{rec} in equation (98) depends on the level of recycling practices in a society. While the idea of a "circular economy" has spread in recent years, the level of ρ_{rec} varies greatly across the world, reflecting disparities in recycling infrastructure and culture. The value of ρ_{rec} used in the model is relatively conservative (0.24), as it aims to represent the global economy. This value is taken from Dafermos et al. (2017) for consistency with the literature in this field and to facilitate comparison with different models.

Demolished (or disposed) goods are defined through the following equation:

$$des = \mu \cdot \left(DA_f + \zeta \cdot DC_{-1}\right) \tag{99}$$

where:

$$DC = DC_{-1} \cdot (1 - \zeta) + C \tag{100}$$

is the amount of durable goods (that is, capital and consumer goods lasting more than one period) and ζ is the portion of them that gets discarded every year. DA_f is total depreciation of capital (green and conventional), meaning the portion of capital that must be replaced every year due to wear and tear. For sake of simplicity, and following Dafermos et al. (2017), equation (100) assumes that all new consumption goods contribute to the stock of durable goods.

As a result, the overall socio-economic stock at the end of the period is:

$$k_{se} = k_{se,-1} + y_{mat} - des \tag{101}$$

Additional waste generated by production activities can be derived from Table 3(b):

$$wa = mat + cen + o2 - emis - \Delta k_{se}$$

which, using equations (97), (101), and (111), becomes:

$$wa = des - rec \tag{102}$$

where wa is the annual level of waste, cen is the carbon mass of the non-renewable energy sources, $o2$ is the mass of oxygen, and $emis$ is total annual CO_2 emissions.

New hazardous waste (hws) is calculated using the parameter haz, which is the proportion of hazardous waste to total waste.

$$hws = hws_{-1} + haz \cdot wa \tag{103}$$

The hazardous waste ratio ($hratio$, in Gt/Km^2) is then calculated dividing the hazardous waste stock (hws) by the earth surface ($surf$):

$$hratio = \frac{hws}{surf} \tag{104}$$

which, in turn, affects the dynamics of the population, hence the labour force (see equation 148).

We can now to turn to the stock of material reserves (k_m), which is:

$$k_m = k_{m,-1} + conv_m - mat \tag{105}$$

where $conv_m$ are the material resources converted to reserves.

Equation (105) holds that k_m grows as resources are converted into reserves, and reduces as matter is extracted from the ground (mat).

Material resources are converted into reserves based on the following function:

$$conv_m = \max(\sigma_{m,-1} \cdot res_{m,-1}, mat_{-1}) \tag{106}$$

where σ_m is an endogenous rate, defined by equation (109). Equation (106) holds that converted material resources are always higher or equal to extractions in the previous period, which are used as a proxy of future extractions.

The stock of material resources is:

$$res_m = res_{m,-1} - conv_m \tag{107}$$

We assume the unit price of extracted matter (p_m) to be affected by the relative scarcity of extracted matter relative to its demand:

$$p_m = p_m^0 + p_m^1 \cdot \frac{mat_{-1}}{\sigma_{m,-1} \cdot res_{m,-1}} \tag{108}$$

where p_m^0 is the autonomous component of matter price, and p_m^1 is the sensitivity (or elasticity) of matter price to demand-supply gap.

In turn, the conversion rate of matter resources (σ_m) is driven by price expectations:

$$\sigma_m = \sigma_m^0 + \sigma_m^1 \cdot E(p_m) \tag{109}$$

where σ_m^0 is the autonomous component of matter conversion rate and σ_m^1 is the sensitivity of matter conversion rate to energy price. The higher the unit price of matter, the higher the pace of conversion.

Finally, the carbon mass of non-renewable energy and the mass of oxygen are defined, respectively, as:

$$cen = \frac{emis}{car} \tag{110}$$

$$o2 = emis - cen \tag{111}$$

where car is the conversion coefficient of Gt of carbon into Gt of CO_2.

The variables above are used into equation (102) to define the amount of waste.

3.2.2 Energy resources and reserves. Like matter, total energy required for production is defined using an energy-intensity coefficient to aggregate supply (see equation 112 in

Appendix A). Renewable energy is a share of total energy, whereas dissipated energy is the sum of renewable and non-renewable energy (equations 113-115). Energy resources and reserves are modelled in the same way matter resources and reserves are (equations 116-118). The same goes for the unit price of energy (equation 119) and the endogenous conversion rate of energy resources into reserves (equation 120).

3.2.3 Emissions and climate change. Industrial emissions of CO$_2$ ($emis_{in}$) are simply defined as a linear function of non-renewable energy (en):

$$emis_{in} = \beta \cdot en \tag{121}$$

where β is a CO$_2$-intensity coefficient determined by equation 133.

Emissions are also generated because of the use of land:

$$emis_l = emis_{l,-1} \cdot (1 - g_l) \tag{122}$$

where g_l is the exogenous rate of decline of land-use CO$_2$ emissions. Therefore, total emissions are the sum of industrial emissions and land emissions:

$$emis = emis_{in} + emis_l \tag{123}$$

The atmospheric temperature depends on both CO$_2$ emissions and the carbon cycle. The latter is defined by the following equations:

$$co2_{AT} = emis + \psi_{11} \cdot co2_{AT,-1} + \psi_{21} \cdot co2_{UP,-1} \tag{124}$$

$$co2_{UP} = \psi_{12} \cdot co2_{AT,-1} + \psi_{22} \cdot co2_{UP,-1} + \psi_{32} \cdot co2_{LO,-1} \tag{125}$$

$$co2_{LO} = \psi_{23} \cdot co2_{UP,-1} + \psi_{33} \cdot co2_{LO,-1} \tag{126}$$

where ψ_{ij} (with $i = 1,2,3$ and $j = 1,2,3$) are (estimated) parameters. More precisely, equation (124) defines the atmospheric CO$_2$ concentration ($co2_{AT}$), equation (125) defines the upper-ocean / biosphere CO$_2$ concentration ($co2_{UP}$), and equation (126) defines the lower-ocean CO$_2$ concentration ($co2_{LO}$). Overall, they hold that there is an exchange of carbon between the atmosphere, the upper ocean and the lower ocean.

The accumulation of CO$_2$ (and other greenhouse gases), in turn, fosters radiative forcing (F = Radiative forcing over pre-industrial levels measured in W/m^2):

$$F = F_2 \cdot \log_2\left(\frac{co2_{AT}}{co2_{AT}^{PRE}}\right) + F_{ex} \tag{127}$$

where F_2 is the increase in radiative forcing due to doubling of CO$_2$ concentration, $co2_{AT}^{PRE}$ is the pre-industrial level of CO$_2$ concentration, and F_{ex} is radiative forcing due to other greenhouse gases. The latter is defined as:

$$F_{ex} = F_{ex,-1} + fex \tag{128}$$

where fex is an exogenous increase.

The increase in radiative forcing puts upward pressure on the atmospheric temperature (T_{AT}, measured in degree Celsius over pre-industrial levels):

$$T_{AT} = T_{AT,-1} + t_1 \cdot \left[F - \frac{F_2}{sens} \cdot T_{AT,-1} - t_2 \cdot \left(T_{AT,-1} - T_{LO,-1}\right)\right] \tag{129}$$

where t_1 is is the speed of adjustment in atmospheric temperature, t_2 captures the heat loss from the atmosphere to the lower-ocean, T_{LO} is the lower-ocean temperature (measured in degree Celsius over pre-industrial levels), and $sens$ is the equilibrium climate sensitivity.

In turn, the lower-ocean temperature is defined by the following equation:

$$T_{LO} = T_{LO,-1} + t_3 \cdot \left(T_{AT,-1} - T_{LO,-1}\right) \tag{130}$$

where t_3 measures the heat loss from the atmosphere to the lower-ocean.

3.2.4 Ecological Efficiency. Intensity indices are all calculated as weighted averages of green and conventional production intensity indices. For example, the matter-intensity coefficient is defined as:

$$\mu = \mu_{gr} \cdot \frac{K_{gr}}{K_f} + \mu_c \cdot \frac{K_c}{K_f} \tag{131}$$

where μ_{gr} is the matter intensity coefficient on green production, μ_c is the matter intensity coefficient on conventional production, K_f is the total capital stock, K_{gr} is the green capital stock, and K_c is the conventional capital stock.

The energy-intensity coefficient, the CO_2-intensity coefficient, and the average share of renewable energy sources, are calculated in the same way (see equations 132 to 134 in Appendix A).

Depletion ratios of matter (ρ_m) and energy (ρ_{en}) are defined, respectively, as:

$$\rho_m = \frac{mat}{k_{m,-1}} \tag{135}$$

$$\rho_{en} = \frac{en}{k_{en,-1}} \tag{136}$$

where k_{en} is the stock of energy reserves.

3.3 Step three: modelling climate change feedbacks and production

The last step is to add the effects of climate change and natural resources' depletion on economic, social and financial variables. These effects are highlighted by green arrows in Figure 1. While government policies can help reduce depletion rates and address climate change by inducing a modification in the production structure, the opposite may also occur. It is well known that global warming can affect both the level and composition of output. Four main channels have been identified within our model:

i. climate change can undermine the existing capital stock through the increase and intensification of natural catastrophes (that is, through an increase in capital depreciation rates δ_c and δ_g. See equation 137 in Appendix A and equation 138 below);

ii. climate change can slow down the process of accumulation of capital, as it reduces desired investment. This effect is captured by the variable d_T, which was firstly introduced in equation 12 in section 3.1. d_T is the proportion of gross damage due to changes in atmospheric temperature, and it is given by equation 144 in Appendix A);

iii. climate change increases the risk premium (μ_b) on financial assets, notably, Treasury bills (see equations 94 and 95 below);

iv. climate change (and the depletion of natural resources) can also affect consumption patterns of households by:

   – rising ecological awareness, thus modifying the population's consumption plans (c_{gr}^{w} and c_{gr}^{π}, which are the green consumption share of LC and UC households, are both affected by d_T: see equation 46 below and 47 in Appendix A);

   – increasing uncertainty, thus triggering hoarding behaviours. These behaviours affect the dynamics of the model via the term $\left(1 - d_{T,-1}\right)$, which multiplies the whole consumption equation of both LC households (as we have seen in equation 40 in section 3.1) and UC households (see equation 41 in Appendix A).

All these channels are explicitly factored in the model.

Focusing on the stock of green capital (K_{gr}), its change equals gross green investment minus green capital depreciation (DA_{gr}):

$$K_{gr} = K_{gr,-1} + I_{gr} - DA_{gr} \tag{19}$$

$$DA_{gr} = \delta_{gr} \cdot K_{gr,-1} \tag{21}$$

The depreciation rate of green capital, δ_{gr}, depends on climate change-related gross damages and firms' adaptation to the new conditions:

$$\delta_g = \delta_g^0 + \left(1 - \delta_g^0\right) \cdot \left(1 - ad_K^g\right) \cdot d_{TF,-1} \tag{138}$$

where $0 < \delta_g^0 \leq 1$ is a positive coefficient, ad_K^g captures firms' adaptation to global warming and d_{TF} is the percentage of climate-related damages to funds. We have modelled the stock of conventional capital in the same way (see equations 11 and 16 in Appendix A).

Global warming also affects capital and labour productivity rates. The former is defined as:

$$a_f = a_{f,-1} \cdot \left(1 + g_f\right) \cdot \left[1 - (1 - ad_P) \cdot d_{TP,-1}\right] \tag{139}$$

$$g_f = g_{f0} + g_{f1} \cdot g_{BE,-1} \tag{140}$$

where g_f is the normal growth rate of the product per unit of capital (if there were no climate-related damages), d_{TF} is the percentage of climate-related damages to productivity (see equation 145 in Appendix A), g_{f0} is a constant coefficient and g_{f1} is the sensitivity of the capital productivity growth rate to firms' non-green innovative spending.

Similarly, labour productivity is defined as:

$$a_n = a_{n,-1} \cdot (1 + g_n) \cdot \left[1 - (1 - ad_P) \cdot d_{TP,-1}\right] \tag{141}$$

$$g_n = g_{n0} + g_{n1} + g_{n2} \cdot g_{y,-1} \tag{142}$$

$$g_{n0} = g_{n0,-1} \cdot (1 - g_{n3}) \tag{143}$$

where g_n is the growth rate of labour productivity (if there were no climate-related damages), g_{n1} is a positive coefficient, g_{n2} is labour productivity's sensitivity to the size of the market (that is, the so-called Kaldor-Verdoorn effect), whereas g_{n0} is its rate of deceleration. In other words, the technical progress-driven growth rate of labour productivity is assumed to decrease over time (we refer again to Dafermos et al. 2017, 2018).

Recall equations (12), (17), (18) and (40). It is clear that global warming affects both firms' investment decisions and household consumption plans. The *level* of total investment decreases as global warming-related damages increase.[15] Investment *composition* is also affected, because firms are more prone to *green investment* relative to conventional investment as the frequency of damages increases. Besides, firms adapt their production plans to consumers' tastes. As a result, the higher the share of green consumption to total consumption, the greener investment and production. Similarly, climate-related damages affect *total consumption* of households. We assume that global warming can affect the *composition* of consumption too:

$$C_{gr}^{w} = c_{gr}^{w} \cdot C_w \tag{42}$$

$$c_{gr}^{w} = c_0^{w} + c_1^{w} \cdot d_{T,-1} + c_2^{w} \cdot \left(vat_c - vat_{gr}\right) \tag{46}$$

where c_{gr}^{w} is the percentage of LC household green consumption to total LC household consumption, c_0^{w} is a positive coefficient, c_1^{w} defines the sensitivity of green consumption to climate-related damages, and c_2^{w} captures the sensitivity of green consumption to the tax rate gap between conventional and green goods. The same goes for UC households.

Finally, the impact of global warming on the return rate of government bills is also considered by linking the risk premium to climate-related damages:

$$r_b = r_{cb} + \mu_b \tag{94}$$

$$\mu_b = \eta \cdot d_{T,-1} \tag{95}$$

where η is the sensitivity of the risk premium to the climate-related damages.

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[15] Private investment is not directly influenced by matter and energy prices instead. However, there is an indirect effect, for changes in prices affect the rates of extraction (or use) of natural reserves. These rates, in turn, affect the price level, real output, hence investment decisions.

As mentioned, potential output is determined by a Leontief function using stock-flow resources (matter and energy) and fund-serve resources (total capital and labour force). In formal terms, input-constrained potential output levels are:

$$Y_f^* = a_f \cdot K_{f,-1} \tag{154}$$

$$Y_n^* = a_n \cdot LF_{-1} \cdot H_{-1} \tag{155}$$

$$Y_m^* = \frac{k_{m,-1} + rec}{\mu} \tag{156}$$

$$Y_{en}^* = \frac{k_{en,-1}}{\varepsilon} \tag{157}$$

where Y_f^* is capital-determined potential output, a_f is the real product per unit of capital, Y_n^* is labour-determined potential output, a_n is hourly labour productivity, LF is the labour force, H is the annual amount of labour hours per worker, Y_m^* is matter-determined potential output, k_m is the stock of matter reserves, rec is the recycling rate of socio-economic stock, μ is the matter-intensity coefficient of output, Y_{en}^* is the energy-determined potential output, k_{en} is the stock of energy reserves and ε is the energy-intensity coefficient of output. Total potential output is therefore:

$$Y^* = \min\left(Y_f^*, Y_n^*, Y_m^*, Y_{en}^*\right) \qquad (160)^{16}$$

Figure B1(a) in Appendix B shows that capital is the main constraint in our model's baseline scenario. Labour force availability is only a constraint for low levels of output, while matter and energy reserves are still relatively abundant – Figure B1(b). Unlike natural inputs and labour force, green capital is not a complement but a substitute for conventional capital. Both the level and the growth rate of the labour force are determined endogenously:

$$LF = LF_{-1} \cdot (1 + g_{LF}) \cdot \left[1 - (1 - ad_{LF}) \cdot d_{TF,-1}\right] \tag{147}$$

$$g_{LF} = lf_0 + lf_1 - lf_2 \cdot un_{-1} - lf_3 \cdot hratio_{-1} \tag{148}$$

$$lf_0 = lf_{0,-1} \cdot (1 - lf_4) \tag{149}$$

$$N = \frac{Y_S}{H \cdot a_n} \tag{150}$$

where LF is the labour force level, g_{LF} is its growth rate, un_{-1} is the unemployment rate, $hratio$ is the hazardous waste ratio (Gt/Km^2), lf_i (with $i = 1,2,3,4$) are positive coefficients and lf_0 defines the deceleration rate of labour force (that is, the expected reduction in population growth rate). Climate change-related damages d_{TF} and adaption (ad_{LF}) also affects labour force availability. Actual demand for labour (employment, N) is calculated by dividing total output (Y_S) by the product per worker ($H \cdot a_n$).

The change in the annual working time is defined as a positive function of the employment rate, signalling relative scarcity of labour inputs:

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[16] See equations (154) to (157) in Appendix A.

$$H = H_{-1} + h_1 \cdot (em_{-1} - h_2) \tag{151}$$

where h_1 and h_2 are positive coefficients, while $em = N/LF$ is the employment rate.

Finally, notice that current production is demand-led. Potential output only affects current output indirectly, through the effect of price expectations on spending decisions. We use the output gap to capture the effect of demand pressure and supply-side constraints on the general price level. In formulas, the unit price of output is:

$$p_y = \frac{w}{a_n} \cdot (1 + mk) \tag{161}$$

where w is the wage rate and mk is the mark-up over labour costs. The wage rate is defined as

$$w = w_{-1} \cdot \left(1 + w_a \cdot \frac{d(a_n)}{a_n}\right) \tag{162}$$

where w_a defines the percentage of labour productivity growth that is captured by the growth rate of the money wage rate.

The mark-up over labour costs is defined as a function of the output gap:

$$mk = mk_0 + mk_1 \cdot \frac{Y_{S,-1}}{Y^*_{-1}} \tag{163}$$

where mk_0 and mk_1 are positive coefficients. The higher current production relative to potential production, the higher will be the price charged by the firms, given the unit cost of labour.

Finally, the general price level is obtained as a weighted average of the unit price of output, the unit price of matter and the unit price of energy:

$$p = \pi_1 \cdot p_y + \pi_2 \cdot p_{en} + \pi_3 \cdot p_m \tag{164}$$

where $0 \leq p_i \leq 1$ and $\sum_i p_i = 1$, with $i = 1,2,3$.

3.4 Model calibration

The complete model is made up of 169 equations, including identities, equilibrium conditions and behavioural equations. Table B1 in Appendix B features all symbols, descriptions, and values of the model. The sources of data are indicated too.

Coefficients of behavioural equations have been calibrated for the global economy. Parameters defining the main output components (total consumption, investment, government spending, and intermediate consumption), the price level and the labour force have been defined based on World Bank annual data. Ecological parameters and initial values for ecosystem variables have been taken from, or based on, Dafermos et al. (2017) and IPCC (2018). NASA/GISS data and Ritchie and Roser (2020)’s figures have also been used to calibrate ecological parameters and initial values. Remaining coefficients have been set in such a way to match baseline values of main endogenous variables with their observed values. For this reason, the baseline scenario has been validated through a correlation analysis (see below), whereas the robustness of our findings has been double-checked by running several sensitivity tests (which are presented at the end of section 4).

The model was run from 2010 to 2100 on an annual basis.[17] Figure 2 displays the development of selected variables, under the baseline scenario, up to 2100. Blue shaded areas mark long-run values. Green shaded areas show that the model's key variables are anchored to observed time series up until 2018. Conversely, pure out-of-sample predictions are displayed starting from 2019. For instance, global real output is expected to reach 1.475 trillion dollars in 2100 (Figure 2(b)), with an average predicted growth rate of 3.45% over the period 2019-2100. The temperature level in 2100 (Figure 2(j)) is consistent with the consensus forecast in the absence of climate policies (see Ritchie and Roser 2020).

Potential output is only constrained by labour force availability and capital accumulation under the baseline. This is shown by Figure 2(e), which is the 2D dynamic counterpart of Figure B1 in Appendix B. The average wage share is slightly above 64% during the same period, although it shows a clear decreasing trend (Figure 2(c)). Inequality indices increase over time (Figure 2(c)). Bank deposits are around two thirds of total asset holdings of households. Cash is approximately 15%. The rest is uniformly distributed between treasury bills and equity and shares (Figure 2(q)). The total financial assets held by the private sector are approximately 4 times world output. Both aggregate profits from sales made by production firms and banks' profits grow over time (Figure 2(h)). The unemployment rate fluctuates around 6.5% (Figure 2(d)). The average working time is almost 1,700 hours per year. The average utilisation rate of plants is approximately 88% and increases over time (Figure 2(o)). Inflation is very low and stable (less than 1%), but the price level accelerates as global warming hits the economy (Figure 2(g)). The average nominal interest rate on loans is 7% (Figure 2(s)). The average income tax rate is 14%, while government spending, net of interest payments, is approximately 13% of total income. As a result, the government deficit to output ratio is 2.3%, while the stock of government debt to output ratio is 67% (Figure 2(t)). Total CO_2 emissions are predicted to exceed 80 billion Gt in 2050 (and keep growing) despite higher ecological efficiency ratios (Figure 2(i)). The socio-economic stock for the world economy in 2020 is roughly 1,600 Gt. As mentioned in section 3.3, total stocks of natural resources (matter and energy) are still abundant, meaning that they do not constrain firms' production plans. However, they decline at an annual rate of approximately 1% (Figure 2(p)).

Model's ability to capture statistical properties of key (observed) time series was tested by calculating and comparing auto- and cross-correlations of observed and predicted values (baseline validation). Figure B2 in Appendix B shows that patterns of the predicted series under the baseline scenario look reasonably coherent with patterns of the observed series. Notice, however, that the aim of the baseline scenario is not to provide the best possible prediction of future trends. Rather, we have used it as a reasonable benchmark to compare

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[17] Simulations have been performed using *EViews*. We are happy to provide the programming code.

alternative policy scenarios, starting from 2020. Relative impacts of shocks on selected variables are displayed by figures 3 to 6, whereas their quantitative dimensions after 30 years are listed in Table 4.

Lastly, we did not consider the recent global economic shock caused by the Covid-19 pandemic nor the energy crisis arising from the Russian-Ukraine conflict in our baseline scenario. While these events have undoubtedly had a significant economic impact, analysing their long-term effects goes beyond the scope of this paper. In fact, the multidimensional crisis that the pandemic and war have created globally could accelerate efforts to promote a green transition of economies. Arguably, this makes the topic of this paper even more relevant now than ever before.

4. Simulations and main findings

While several studies have been published about the link between economic policies and the ecosystem, they typically deal with monetary policies. Fiscal and industrial policies are usually neglected, the main exceptions being Naqvi and Stockhammer (2018), Dafermos and Nikolaidi (2019) and Valdecantos (2021). This is the reason we focus on the level and composition of government spending and taxation. For this purpose, the world economy is considered as a fully integrated and consolidated system, where monetary and fiscal policies are perfectly coordinated across nations.[18] In other words, cooperation issues are assumed away. While this is certainly a strong assumption, it allows us to test alternative measures *as if* there were a worldwide consensus surrounding them, so that policy decisions were fully effective. More specifically, we test the impact of nine fiscal policies on four sets of variables, defining alternative scopes for the policy makers: i) the economy; ii) the financial sector; iii) the society; iv) the broader ecosystem. For instance, the policy makers may want to support employment, assure financial stability, reduce inequality and/or counter global warming. To achieve these targets, they have several options. We consider the following:

a) *An income tax cut for UC households*. This is sometimes invoked to boost output growth (under profit-led economies) and assure financial stability. The expected impact on the ecosystem is negative, as the higher consumption boosts production, hence natural resources' depletion and CO_2 emissions. We test a 1% cut in the tax rate.

b) *An income tax cut for LC households*. This is usually argued to reduce inequality and support output growth (under wage-led economies). Once again, the impact on the ecosystem is expected to be negative. We test a 1% cut in the tax rate.[19]

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[18] We refer to Carnevali et al. (2021), who use an open-economy ecological SFC model prototype to analyse cross-border policy coordination problems.

[19] Notice also that LC households are usually assumed to have a higher propensity to consume relative to UC households. However, their consumption is usually *greener*, as green intentions of the upper classes are crowded

c) *Selective taxation on consumption*. Higher indirect taxes depress consumption and economic activity. However, they can be tuned in such a way to foster green consumption and discourage high-carbon consumption, thus leaving output and employment unaffected. We test a 2% cut in the VAT rate on green consumer goods.

d) *An increase in routine government spending funded by issues of Treasury bills and/or money base*. This is the standard (Keynesian) way to support employment and stabilise financial markets. However, it can bring remarkable side effects on the ecosystem. We test a 1.5% increase in routine government spending growth rate.

e) *An increase in overall MOIS funded by issues of Treasury bills and/or money base*. MOIS policies are alternative to routine spending. They aim at generating an innovation cascade in the private sector, enhancing both conventional and green investment. We test a 1.5% increase in MOIS growth rate.

f) *An increase in green MOIS funded by issues of Treasury bills and/or money base*. The policymakers must target low-carbon technologies if they want to limit the impact of the higher growth rate of output on industrial emissions. We test a 1.5% increase in MOIS growth rate coupled with a change in its composition.

g) *An increase in green MOIS funded by levying taxes on UC household incomes*. We check whether a mix of expansionary and restrictive policies can be more effective in tackling global warming, while reducing social inequality. We test a 1.5% increase in MOIS growth rate coupled with a change in its composition and a 1% increase in UC household income tax rate.

h) *An increase in green MOIS funded by green taxes on consumption*. Increasing the VAT rate on non-green consumption goods can be seen as an alternative way to fund government spending. We test a 1% increase in the VAT rate on non-green products (to fund green MOIS policies).

i) *An increase in green MOIS funded by a carbon tax*. Government spending can also be funded by a carbon tax, that is, a tax on firms' carbon emissions. We test a tax rate leading to a 30 million USD tax revenue per 1 Gt of industrial emissions of CO_2.

Scenarios (a) to (i) are all tested as permanent shocks to government spending growth rates and/or tax rates.[20] Absolute levels of selected variables after 30 years, under different scenarios, are summarised by Table 4, which shows that the policy makers always face a four-fold predicament when making their decisions. We name it the *Economy-Finance-Environment-Society (E.F.E.SO.) problem*. The point is that, *ceteris paribus*, economic growth is an important precondition for supporting employment and assuring financial stability.

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out by wealth. In other words, ecological impacts are best predicted by people's income level (e.g., Moser and Kleinhückelkotten, 2017). As a result, the change in emissions due to policy (b) relative to policy (a) is ambiguous.

[20] See notes under Table 4 for further details.

However, it also boosts industrial CO_2 emissions. Income inequality can be either boosted (e.g., if economic growth arises from lower tax rates for the upper class) or reduced (if growth results from measures enlarging LC household disposable income). Wealth inequality usually grows as the economy grows. As a result, a corrective mechanism seems paramount to cope with social and ecological side effects of expansionary policies.

i) *The economy.* Variables trends over time are displayed by figures 3 to 6. Light green-shaded areas highlight the pre-shock period. The vertical dashed lines mark the inception of the shock. Light blue-shaded areas highlight the approximation to full employment, due to expansionary measures. Figure 3(a) shows that world output is 11 to 21 pp higher in 2030 (and 28 to 39 pp higher in 2050) relative to the baseline scenario (i.e., relative to the *status quo*) when MOIS and green MOIS options are chosen. The impact of routine spending is lower than that of non-tax funded MOIS (scenario e), but higher relative to MOIS policies funded by higher taxes (scenarios g and h). Unsurprisingly, a selective taxation system (favouring green over routine consumption) and a tax cut for the UC households are the less effective options in supporting output growth. Tax cuts on income rather affect output level than its growth rate. The reason for the last result is mainly to be found in the high propensity to save of rich households. Still, the limited growth which characterizes this scenario avoids triggering excessive environmental damages which would have implied an even higher drag on the level of investment and growth. As “expansionary austerity” struggled to find empirical evidence in recent years, equally no perspective of “austere expansion” seems to emerge by the simulations with our model. An increase in green MOIS funded by a carbon tax has initially a negative impact on output. By 2040 its effect turns positive, and its order of magnitude is comparable with the ones of other MOIS policies. Notice that this feature can possible jeopardise its political feasibility: any policy that implies a cost today in exchange for uncertain benefits in the future is usually difficult to “sell”. Figure 3(b) shows that the price level grows following expansionary fiscal policies, particularly for MOIS policies. Inflation does not look remarkable (relative to the baseline) and tends to reduce. Figure 3(c) shows that the impact of expansionary fiscal policies on government bills’ return rate is usually low but positive. It can even turn negative if government policies slow down global warming, thus reducing uncertainty. Higher output growth rates coupled with low interest rates allow the additional government deficit to be reabsorbed in the medium run – Figure 3(d).

ii) *The financial sector.* Looking at the stock market, the valuation ratio of production firms (i.e., the Tobin’s *q*) usually increases in the short run following expansionary policies relative to the baseline scenario – Figure 4(a). The reason is that the market value of the firms outgrows their capital stock value, even though the latter is also positively affected. However, green policies have usually a negative impact, through a change in the composition of firms’ investment plans. Figure 4(b) shows that expansionary fiscal policies may induce firms to increase their leverage ratios to fund additional investment. This Minskian effect is supported by the increase in the return rate on equity and shares – Figure 4(c). The strong pro-cyclical effect of expansionary fiscal policies on firms’ leverage ratio can possibly lead to financial fragility in the medium to long run. However, green MOIS policies can temporarily reduce firms' leverage ratio. Turning to households, the lower-class benefits from expansionary policies. Their disposable income increases, while the interest rate is almost unchanged. As a result, their debt burden reduces.[21] Notice that the effect of government spending policies is usually more persistent than that of tax reforms – Figure 4(d). Besides, the effect is mostly driven by the reduction in the unemployment rate. Once the full employment is achieved, the relative effect of expansionary policies on household debt burden reverses. The intertemporal trade-off between short-run costs and long-run benefits of an increase in green MOIS funded by a carbon tax is particularly apparent for the return rates on equity and shares and the household debt burden. In both cases, the initial deterioration and the subsequent recovery are explained by the cycle of deceleration-acceleration triggered by the policy.

iii) *The society.* Bill-funded MOIS is the most powerful option also in terms of social wellbeing. Figure 5(b) shows that the unemployment rate is approximately 6 pp lower in 2040 relative to the baseline scenario. This leads to full employment, despite the increase in the labour force level. Figure 5(c) shows that income inequality reduces thanks to government spending policies, quite independently of the way they are funded – up to -17 pp in 2040. However, income inequality restart growing once full employment is achieved. Besides, Figure 5(d) shows that wealth inequality may well increase, due to the higher amount of assets held by UC households. This can possibly affect income inequality too in the long run.[22] Funding MOIS policies by levying taxes on UC household income or with a carbon tax are by far the most effective option in reducing income inequality. It can also reduce wealth inequality in the short to medium run. However, unemployment hovers above the baseline level in the short run, due to the contractionary effect of the tax hike. The cost of the carbon tax in terms of short-run unemployment is particularly severe.

iv) *The Ecosystem.* A well-known issue with fiscal policies, even when they aim at supporting low-carbon transition, is the so-called *rebound effect*: the adoption of green technologies and/or the increase in ecological efficiency can be offset by other systemic effects, e.g., higher consumption of goods, lower costs of production and higher production levels (e.g., Greening et al. 2000). Our experiments confirm that incentivising low-carbon investment is not enough to reduce industrial CO_2 emissions and tackle climate change. Figure 6(a) shows that annual emissions increase following five out of nine scenarios (ten years after the implementation of the new policy). Annual emissions can be 11 pp higher (relative to the baseline) after ten years if spending policies are undertaken. The percentage increase becomes 28 pp in 2040. Similarly, annual emissions are 2 pp higher in 2030 when taxes are cut. Not even a selective tax system enables *per se* to reduce emissions. As a result, the average atmospheric temperature is unchanged or higher relative to its baseline value. On the one hand, ecological

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[21] We refer the reader to equations (34) and (35), defining household debt level and ratio, respectively.

[22] Income inequality is measured as UC household income (including *capital gains*) to total income *after taxes*. Similarly, wealth inequality is measured as UC household net wealth to total net wealth.

efficiency gains generated by fiscal policies can be offset by the increase in the growth rate of output if policymakers do not target low-carbon investment. On the other hand, ecological efficiency losses (not gains) are recorded as long as the accumulation of conventional capital outstrips the accumulation of green capital. This is the case portrayed by Figure 6(c) for the first four scenarios.

A possible way to counter the side effects of higher economic growth on climate change is to modify the *composition* of government spending plans (in such a way to foster private firms' green investment relative to routine investment) and/or partially fund them through taxation. In principle, higher taxes could be levied on UC households, LC households or both. However, as we have mentioned above, if the policymakers are also interested in tackling inequality, they should primarily target non-labour incomes. Alternatively, they can fund green MOIS policies by means of higher taxes on non-green consumption, which we named 'selective VAT', or via a carbon tax. Tax-funded MOIS policies allow reducing emissions, while still delivering and higher equality ratios relative to both the baseline and tax cuts. Unsurprisingly, their influence on ecological variables is beneficial when spending is partially funded by higher taxes on UC household income and/or taxes on routine consumption (relative to green consumption). A carbon tax produces the best outcome in terms of emissions and atmospheric temperature reduction, but, as mentioned above, these results come at a cost of a higher short-run unemployment.

Although experiments involving tax rate changes are only qualitatively (not quantitatively) comparable with experiments involving changes in the rate of government spending, our model suggests that a radical redefinition of the composition of MOIS is by far the most important precondition to *counter* climate change. From this perspective, our findings support the conclusions of previous studies that explore strategies to reconcile economic growth with ecological sustainability by advocating for a shift in government spending priorities (Dunz et al., 2020; Monasterolo and Raberto, 2018; Yajima, 2021).

In Figure 6, green MOIS is assumed to increase from 44% to 73% of total MOIS, that is, from approximately 22% to 37% of total government spending (or 3.5% to 5.8% of GDP). By contrast, the effect on the average atmospheric temperature is negative if the share of green spending to total spending is low – see Figure 6(b). Notice that, while industrial CO_2 emissions fall in absolute terms and the atmospheric temperature reduces relative to the baseline, the change is not dramatic. It amounts to –0.012C (after thirty years) when the policy "MOIS plus higher taxes for the rich" which is the second most effective strategy, is implemented. Similarly, the policy "MOIS plus carbon tax", which is the most effective strategy, is only associated with a temperature reduction of –0.024C (relative to the baseline).

One may wonder whether our results are robust or rather depend on the chosen values for key parameters and exogenous values. We have checked the robustness of our model using two sets of sensitivity tests. Figure 7 displays four univariate sensitivity tests on MOIS policies. Quadrant (a) shows the impact, on the atmospheric temperature, of different growth rates of innovative spending (g_G^{mois}). Our qualitative findings are not affected by the specific value chosen for the experiment. The same applies when we test alternative values for the income tax rate paid by UC households (quadrant c) and the VAT rate on "brown" consumption (quadrant d). Obviously, different percentages of green spending to total spending (quadrant b) are associated with different trends in atmospheric temperature instead. Figure 8 shows several multivariate sensitivity tests on crucial parameters defining the green share of consumption and investment, respectively. Once again, MOIS-based policies are considered both alone and coupled with different types of taxation. Parameters are all assigned random values in the range (0,1). Monte Carlo simulations are then used to generate stochastic predictions on policy effects. Overall, our findings about the impact on output, leverage ratio, atmospheric temperature and income inequality are confirmed. The only partial exception is the atmospheric temperature, because CO_2 emissions are quite sensitive to the total share of green spending. Although the change in temperature is never dramatic, it may have a positive sign if such share is small enough. However, this should be no surprise.

Figure B3 in Appendix B provides 5D scatterplots of the differential effects of fiscal policies on real output, firms' leverage ratio, atmospheric temperature and income inequality. Variables are all expressed as ratios to, or differences with, the baseline scenario.[23] It is shown that real output growth is frequently associated with a reduction in income inequality. However, regressive (and, possibly, indirect) taxation reduce LC households' disposable income relative to the UC households'. The average atmospheric temperature usually grows as output grows, but green options (f, g, h) can reduce it relative to the baseline scenario. No *necessary* correlation direction between firms' aggregate leverage ratio and output exists instead. Summing up, our model shows that direct support to green investment, coupled with a more progressive taxation system, is paramount to relax the E.F.E.SO. problem. Government spending funded by a selective VAT system is also an effective tool to tackle CO_2 emissions and global warming. All in all, the question of whether it would be possible to invert the current trend in atmospheric temperature, while maintaining a positive rate of growth and improving income distribution, remains open.

5. Final remarks

We took inspiration from four different strands of economic thought (ecological macroeconomics, the Schumpeterian approach to innovation, the SFC modelling, and the supermultiplier literature) to study the interaction between government policies, green innovation, the economy and the ecosystem. For this purpose, we developed an ecological stock-flow consistent model calibrated for the world economy. We used the model to assess and compare nine different types of fiscal policies. Our experiments display a 'lights and

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[23] The same experiment can be replicated using alternative variables and/or composite indices for the four main spheres of our artificial world.

shadows' picture. Expansionary fiscal policies are effective in supporting economic growth and delivering financial stability. Furthermore, their effect on income equality is usually beneficial. However, wealth inequality worsens. Besides, these policies are unlikely to reduce CO_2 emissions and counter global warming, because they are associated with high multipliers. A carbon tax can be relatively effective in reducing industrial CO_2 emissions and the atmospheric temperature relative to the baseline, but it comes with a high unemployment cost in the short to medium run. The only way for the policy makers to address this fourfold predicament is to associate a progressive and/or green taxation system with a radical change in the *composition* of government spending. This allows relaxing, although not solving, the Economy-Finance-Environment-Society problem.

References

Allain, O. (2015). Tackling the instability of growth: A Kaleckian-Harrodian model with an autonomous expenditure component. *Cambridge Journal of Economics*, 39 (5), 1351-1371.

Allain, O. (2022). A supermultiplier model with two non-capacity-generating semi-autonomous demand components. *Structural Change and Economic Dynamics*, 63 (C), 91-103.

Berg, M., Hartley, B., and Richters, O. (2015). A Stock-Flow Consistent Input–Output Model with Applications to Energy Price Shocks, Interest Rates, and Heat Emissions. *New Journal of Physics*, 17(1), 1–21.

Block, F. and Keller, M.R. (2009). Where do innovations come from? Transformations in the US economy, 1970–2006. *Socio-Economic Review*, 7 (3), 459-483.

Bovari, E., Giraud, G., & Mc Isaac, F. (2018). Coping with collapse: a stock-flow consistent monetary macrodynamics of global warming. *Ecological Economics*, 147, 383-398.

Brochier, L. and Macedo e Silva, A.C. (2019). A Supermultiplier Stock-Flow consistent model: the "return" of the paradoxes of thrift and costs in the long run? *Cambridge Journal of Economics*, 43 (2), 413-442.

Carnevali, E., Deleidi, M., Pariboni, R. and Veronese Passarella, M. (2019). SFC Dynamic Models: Features, Limitations and Developments. In: Arestis, P. Sawyer, M. (eds.), *Frontiers of Heterodox Macroeconomics*. London (UK): Palgrave Macmillan, pp. 223-276.

Carnevali, E., Deleidi, M., Pariboni, R. and Veronese Passarella, M. (2021). Cross-Border Financial Effects of Global Warming in a Two-Area Ecological SFC Model, *Socio-Economic Planning Sciences*, 75, article 100819.

Campiglio, E. (2016). Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy. *Ecological Economics*, 121 (C), 220-230.

Cesaratto, S., Serrano, F. and Stirati, A. (2003). Technical change, effective demand and employment. *Review of Political Economy*, 15 (1), 33-52.

Ciaffi, G., and Deleidi, M. (2021). Generic and public R&D fiscal policies: An empirical assessment for OECD Countries. *Conference Proceedings*: 25th Conference of the Forum for Macroeconomics and Macroeconomic Policies (FMM), 28–30 October 2021, Berlin. Available from: https://www.boeckler.de/pdf/v_2021_29_10_ciaffi.pdf

Dafermos, Y., Nikolaidi, M. and Galanis, G. (2017). A stock-flow-fund ecological macroeconomic model. *Ecological Economics*, 131 (C), 191-207.

Dafermos, Y., Nikolaidi, M. and Galanis, G. (2018). Climate change, financial stability and monetary policy. *Ecological Economics*, 152 (C), 219-234.

Dafermos, Y. and Nikolaidi, M. (2019). Fiscal policy and ecological sustainability: A post-Keynesian perspective. *Post Keynesian Economics Society (PKES)*, Working Paper No. 1912.

Dafermos, Y., and Nikolaidi, M. (2021). How can green differentiated capital requirements affect climate risks? A dynamic macrofinancial analysis. *Journal of Financial Stability*, 54, 100871.

Deleidi, M. and Mazzucato, M. (2019). Putting austerity to bed: Technical progress, aggregate demand and the supermultiplier. *Review of Political Economy*, 19 (3), 315-335.

Deleidi, M. and Mazzucato, M. (2021). Directed innovation policies and the supermultiplier: An empirical assessment of mission-oriented policies in the US economy. *Research Policy*, 50 (2), 104151.

Deleidi, M., Mazzucato, M. and Semieniuk, G. (2020). Neither crowding in nor out: Public direct investment mobilising private investment into renewable electricity projects. *Energy Policy*, 140 (C), article 111195.

Dunz, N., Monasterolo, I. and Raberto, M. (2020). Assessing Macro-Financial and Distributive Impacts of Climate Policies: a Stock-Flow Consistent Model with Portfolio Choice. Working paper presented at the 18th International Conference on Credit Risk Evaluation. Available at: https://www.greta.it/old/credit/credit2019/papers/Thursday/08_Dunz_Monasterolo_Raberto_.pdf

Dunz, N., Naqvi, A., and Monasterolo, I. (2021). Climate sentiments, transition risk, and financial stability in a stock-flow consistent model. *Journal of Financial Stability*, 54, 100872.

European Commission (EC) (2018a). Mission-oriented R&I policies: In-depth case studies. Case Study Report Apollo Project (US). *European Commission, Directorate-General for Research and Innovation*, DOI: 10.2777/568253

European Commission (EC) (2018b). Mission-oriented R&I policies: In-depth case studies. Case Study Report Energiewende. *European Commission, Directorate-General for Research and Innovation*, DOI: 10.2777/835267

Fazzari, S., Ferri, P. and Variato, A.M. (2020). Demand-led growth and accommodating supply. *Cambridge Journal of Economics*, 44 (3), 583-605.

Foley, D.K. (2012). Dilemmas of economic growth. *Eastern Economic Journal*, 38 (3), 283-295.

Fontana, G. and Sawyer, M. (2016). Towards a post-Keynesian ecological macroeconomics. *Ecological Economics*, 121 (C), 186-195.

Freitas, F. and Christianes, R. (2020). A baseline supermultiplier model for the analysis of fiscal policy and government debt. *Review of Keynesian Economics*, 8 (3), 313-338.

Freitas, F. and Serrano, F. (2015). Growth rate and level effects, the stability of the adjustment of capacity to demand and the Sraffian supermultiplier. *Review of Political Economy*, 27 (3), 258-281.

Georgescu-Roegen, N. (1971). *The Entropy Law and the Economic Process*. Cambridge: Harvard University Press.

Georgescu-Roegen, N. (1979). Energy Analysis and Economic Valuation. *Southern Economic Journal*, 45(4), 1023–1058.

Georgescu-Roegen, N. (1984). Feasible Recipes Versus Viable Technologies. *Atlantic Economic Journal*, 12(1), 21–31.

Godley, W. and Lavoie, M. (2007). *Monetary Economics: an integrated approach to credit, money, income, production and wealth*. New York: Palgrave.

Greening, L.A., Greene, D.L. and Difiglio, C. (2000). Energy efficiency and consumption—the rebound effect – a survey. *Energy policy*, 28(6-7), 389-401.

Hein, E. (2018). Autonomous government expenditure growth, deficits, debt, and distribution in a neo-Kaleckian growth model. *Journal of Post Keynesian Economics*, 41 (2), 316-338.

Hein, E. and Woodgate, R. (2021). Stability issues in Kaleckian models driven by autonomous demand growth—Harrodian instability and debt dynamics. *Metroeconomica*, 72 (2), 388-404.

Ihrig, J., Wolla, S. (2020). The Fed’s new monetary policy tools. *Page One Economics Newsletter*, Available at: https://research.stlouisfed.org/publications/page1-econ/2020/08/03/the-feds-new-mone-tary-policy-tools

Jackson, T. and Victor, P.A. (2015). Does credit create a ‘growth imperative’? A quasi-stationary economy with interest-bearing debt. *Ecological Economics*, 120 (C), 32-48.

Keynes, J. M. (1991). *The General Theory of employment, interest and money*. New York (US): Harcourt (original work published in 1936).

Lavoie, M. (2016). Convergence towards the normal rate of capacity utilization in Neo-Kaleckian models: The role of non-capacity creating autonomous expenditures. *Metroeconomica*, 67 (1), 172-201.

Mazzucato, M. (2013). *The Entrepreneurial State: Debunking the Public vs. Private Myth in Risk and Innovation*. London: Anthem Press.

Mazzucato, M. (2014). A mission-oriented approach to building the entrepreneurial state, paper commissioned by Innovate UK Technology Strategy Board November 2014T14/165. Available at: https://www.gov.uk/government/publications/a-mission-oriented-approach- to-building-the-entrepreneurial-state

Mazzucato, M. (2016). From market fixing to market-creating: a new framework for innovation policy. *Industry and Innovation*, 23 (2), 140–156.

Mazzucato, M. (2018). Mission-oriented innovation policies: challenges and opportunities. *Industrial and Corporate Change*, 27 (5), 803-815.

Monasterolo, I., and Raberto, M. (2018). The EIRIN flow-of-funds behavioural model of green fiscal policies and green sovereign bonds. *Ecological Economics*, 144, 228-243.

Moretti, E., Steinwender, C., and Van Reenen, J. (2015). The Intellectual Spoils of War? Defense R&D, Productivity and International Technology Spillovers. *LSE mimeo*.

Morlin, G. S. (2022). Growth led by government expenditure and exports: Public and external debt stability in a supermultiplier model*. Structural Change and Economic Dynamics*, 62 (C), 586-598.

Morlin. G. S., Passos, N. and Pariboni, R. (2022). Growth theory and the Growth Model perspective: Insights from the Supermultiplier. *Review of Political Economy*, doi.org/10.1080/09538259.2022.2092998.

Moser, S. and Kleinhückelkotten, S. (2018). Good Intents, but Low Impacts: Diverging Importance of Motivational and Socioeconomic Determinants Explaining Pro-Environmental Behavior, Energy Use, and Carbon Footprint. *Environment and Behavior*, 50 (6), 626–656.

Mowery, D.C., Nelson, R.R., and Martin, B.R. (2010). Technology policy and global warming: Why new policy models are needed (or why putting new wine in old bottles won’t work). *Research Policy*, 39 (8), 1011–1023.

Naqvi, S. A. A. (2015). Modeling Growth, Distribution, and the Environment in a Stock-Flow Consistent Framework. *Working Paper No. 2015/02*. Institute of Ecological Economics.

Naqvi, A. and Stockhammer, E. (2018). Directed technological change in a post-Keynesian ecological macromodel. *Ecological Economics*. 154 (C), 168-188.

Nelson, R.R., and Winter, S.G. (1982). *An evolutionary theory of economic change*. Harvard University Press.

Nikiforos, M. and Zezza, G. (2017). Stock-Flow consistent macroeconomic models: A survey. *Journal of Economic Surveys*, 31 (5), 1204-1239.

Nomaler, Ö., Spinola, D. and Verspagen, B. (2021). R&D-based economic growth in a supermultiplier model. *Structural Change and Economic Dynamics*, 59 (C), 1-19.

Pedrosa, Í, Brochier, L. and Freitas, F. (2021). Debt hierarchy: autonomous demand composition, growth and indebtedness in a Supermultiplier model, paper presented at the 25th FMM Conference. Available at https://www.boeckler.de/pdf/v_2021_10_29_pedrosa.pdf.

Rezai, A. and Stagl, S. (2016). Ecological Macroeconomics: Introduction and Review. Institute for Ecological Economics Working Paper 9.

Rezai, A., Taylor, R. and Mechler, R. (2013). Ecological macroeconomics: An application to climate change. *Ecological Economics*, 85 (C), 69-76.

Ritchie, H., and M. Roser (2020). CO_2 and Greenhouse Gas Emissions. Published online at OurWorldInData.org. Available from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Sawyer, M.C. and Fontana, G. (2013). Post-Keynesian and Kaleckian thoughts on ecological macroeconomics. *Intervention: European Journal of Economics and Economic Policies*, 10 (2), 256-267.

Serrano, F. (1995). Long period effective demand and the Sraffian Supermultiplier. *Contributions to Political Economy*, 14, 67-90.

Taylor, L., Rezai, A. and Foley, D.K. (2016). An integrated approach to climate change, income distribution, employment, and economic growth. *Ecological Economics*, 121 (C), 196-205.

Tobin, J. (1969). A General Equilibrium Approach to Monetary Theory. *Journal of Money, Credit and Banking*, 1 (1), 15-29.

Valdecantos, S. (2021). Grasping Argentina’s Green Transition: Insights from a Stock-Flow Consistent Input-Output Mode. *Macroeconomic Methodology, Theory and Economic Policy (MaMTEP). Working Paper Series*, No. 4.

Yajima, G. T. (2021). The employer of last resort scheme and the energy transition: A stock-flow consistent analysis. *Levy Economics Institute, Working Papers Series*.

Tables and figures

Table 1. Nominal balance sheets

	Households		**Production firms**	**Commercial banks**	**Central bank**	**Government**	**Σ**
	Lower class	**Upper class**					
Money	$+H_w$	$+H_\pi$			$-H_s$		0
Deposits	$+D_w$	$+D_\pi$		$-D_s$			0
Loans	$-L_w$		$-L_f$	$+L_s$			0
Reserve requirement				$+H_s^B$	$-H_s^B$		0
Advances (or excess reserves if negative)				$-A_d$	$+A_s$		0
Conventional capital			$+K_c$				$+K_c$
Green capital			$+K_{gr}$				$+K_{gr}$
Shares		$+e_d \cdot p_e$	$-e_s \cdot p_e$				0
Government bills		$+B_d$			$+B_{cb}$	$-B_s$	0
Balance (net worth)	$-NW_w$	$-NW_\pi$	$-NW_f$	0	0	$+GDEB$	$-K_f$
Σ	0	0	0	0	0	0	0

Notes: A ‘+’ before a magnitude denotes an asset, whereas ‘–’ denotes a liability (except for Balance’s entries, where signs are reversed).

Table 2. Transactions-flow matrix

	Households		**Production firms**		**Commercial banks + Central bank**	**Government**	**Σ**
	Lower class	**Upper class**	Current	Capital			
Routine consumption	$-C_c^w$	$-C_c^{\pi}$	$+C_{c,s}$				0
Green consumption	$-C_{gr}^w$	$-C_{gr}^{\pi}$	$+C_{gr,s}$				0
Investment in conventional capital			$+I_{c,s}$	$-I_{c,d}$			0
Innovation spending:							
- Green investment			$+I_{gr,s}$	$-I_{gr,d}$			0
- Other			$+BE_{tech,s}$	$-BE_{tech,d}$			0
Gov. routine spending			$+G_{rout}$			$-G_{rout}$	0
Gov. innovative sp. (G_{mois}):							
- Green spending			$+G_{gr}$			$-G_{gr}$	0
- Other			$+G_{tech}$			$-G_{tech}$	0
Taxes on income	$-T_w$	$-T_{\pi}$	$-T_f$			$+T$	0
Taxes on consumption (VAT)	$-VAT_w$	$-VAT_{\pi}$				$+VAT$	0
Wage bill	$+WB$		$-WB$				0
Interests on loans	$-r_{l,-1} \cdot L_{w,-1}$		$-r_{l,-1} \cdot L_{f,-1}$		$+r_{l,-1} \cdot L_{s,-1}$		0
Repayments on loans	$-rep \cdot L_{w,-1}$				$+rep \cdot L_{w,-1}$		0
Interests on deposits	$+r_{d,-1} \cdot D_{w,-1}$	$+r_{d,-1} \cdot D_{\pi,-1}$			$-r_{d,-1} \cdot D_{s,-1}$		0
Return on gov. bills		$+r_{b,-1} \cdot B_{\pi,-1}$				$-r_{b,-1} \cdot B_{d,-1}$	0
Entrepreneurial profit		$+F_{fd}$	$-F_f$	$+F_{fu}$			0
Bank profit		$+F_b$			$-F_b$		0
Change in money	$-\Delta H_w$	$-\Delta H_{\pi}$			$+\Delta H_s$		0
Change in loans	$+\Delta L_w$			$+\Delta L_f$	$-\Delta L_s$		0
Change in deposits	$-\Delta D_w$	$-\Delta D_{\pi}$			$+\Delta D_s$		0
Change in shares		$-\Delta e_d \cdot p_e$		$+\Delta e_s \cdot p_e$			0
Change in gov. bills		$-\Delta B_d$			$-\Delta B_{cb}$	$+\Delta B_s$	0
Σ	0	0	0	0	0	0	0
Memo: capital gains		$-\Delta p_e \cdot e_{s,-1}$		$+\Delta p_e \cdot e_{s,-1}$			0

Notes: A '+' before a magnitude denotes a receipt or a source of funds, whereas '–' denotes a payment or a use of funds. Reserves and advances from the central bank are omitted. No interest rate on government bills held by central bank, bank reserves and advances.

Table 3. Physical stock-flow matrix (*a*) and related physical flow matrix (*b*)

(*a*)

	Material reserves	**Energy reserves**	**Atmospheric CO₂ concentration**	**Socio-economic stock**	**Hazardous waste**
Initial stock	$k_{m,-1}$	$k_{en,-1}$	$co2_{AT,-1}$	$k_{se,-1}$	hws_{-1}
Resources converted into reserves	$+conv_m$	$+conv_{en}$			
CO₂ emissions (global)			$+emis$		
Production of material goods				$+y_{mat}$	
Non-recycled hazardous waste					$+haz \cdot wa$
Extraction/use of matter/energy	$-mat$	$-en$			
Net transfer to oceans/biosphere			$+(\phi_{11} - 1) \cdot co2_{AT,-1}$ $+\phi_{21} \cdot co2_{UP,-1}$		
Demolition of socio-economic stock				$-des$	
Final stock	k_m	k_{en}	$co2_{AT}$	k_{se}	hws

(*b*)

	Material balance	**Energy balance**
Inputs		
Extracted matter	$+mat$	
Renewable energy		$+er$
Non-renewable energy	$+cen$	$+en$
Oxygen	$+o2$	
Outputs		
Industrial emissions	$-emis_{in}$	
Waste	$-wa$	
Dissipated energy		$-ed$
Change in s.e.s.	$-\Delta k_{se}$	
Σ	0	0

Notes: Matter is measured in Gt while energy is measured in EJ. In sub-table (*a*), a '+' sign denotes additions to the opening stock, whereas '–' denotes reductions; in sub-table (*b*), a '+' sign denotes inputs in the socio-economic system, whereas '–' denotes outputs.

Table 4. Impact of expansionary fiscal policies on selected variables

	Type of policy	Description of policy	Economy	Society	Financial Sector	Ecosystem
			GDP Growth	Income and wealth (in)equality	Firms' leverage ratio and households' debt burden	CO_2 emissions and atmospheric temperature
1	Tax cut for the capitalists	1% cut in the tax rate	+	–––	~	–
2	Tax cut for the workers	1% cut in the tax rate	++	++	~	––
3	Selective taxation on consumption	2% cut in the VAT rate on green consumer goods	+	~	~	–
4	Increase in routine government spending funded by issues of Treasury bills and/or money base.	1.5% increase in routine government spending growth rate	++++	~	~	––––
5	Increase in overall MOIS funded by issues of Treasury bills and/or money base	1.5% increase in MOIS growth rate	++++	~	~	––––
6	Increase in green MOIS funded by issues of Treasury bills and/or money base	1.5% increase in MOIS growth rate coupled with a change in its composition	+++	+	++	+
7	Increase in green MOIS funded by levying taxes on capitalists' income	1.5% increase in MOIS growth rate coupled with a change in its composition and a 1% increase in capitalists' income tax rate.	++	+++	++	+++
8	Increase in green MOIS funded by green taxes on consumption	1.5% increase in the VAT rate on non-green products (to fund green MOIS policies)	+++	+	++	+
9	Increase in green MOIS funded by carbon tax	30 million USD taxes on firms per 1 Gt of industrial emissions of CO_2	++	+++	++	++++

Notes: + = positive impact; – = negative impact; multiple signs highlight stronger impacts; ~ = no significant (or no univocal) impact.

Figure 1. Main interactions among the productive sector (blue shade), the financial institutions (purple shade), the ecosystem (green shade) and the society (orange shade). The policy makers (yellow shade) cannot influence one sphere (e.g., production) without affecting other spheres (e.g., matter resources).

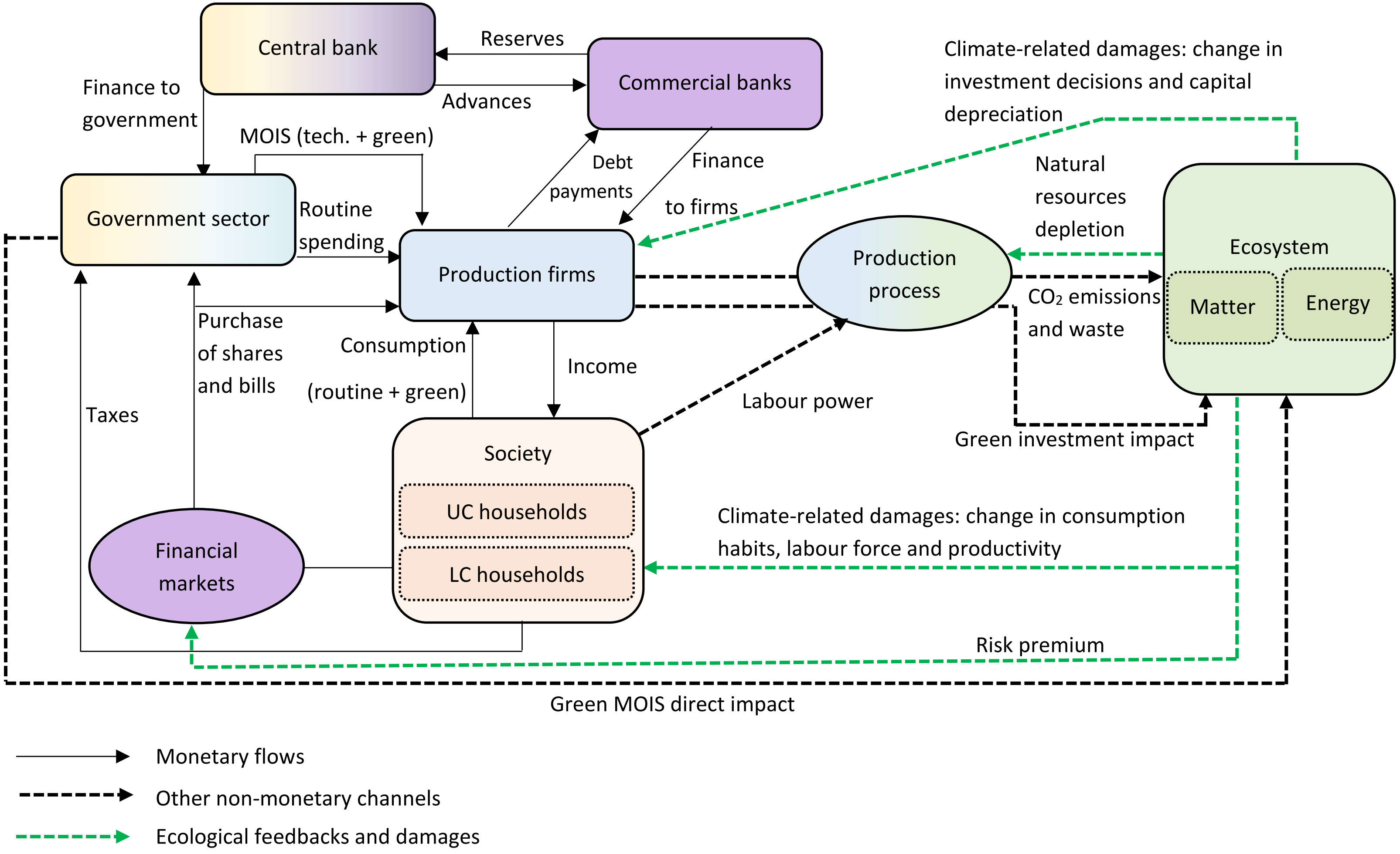


Figure 2. Selected variables under the baseline scenario (all forecasted values after 2018)

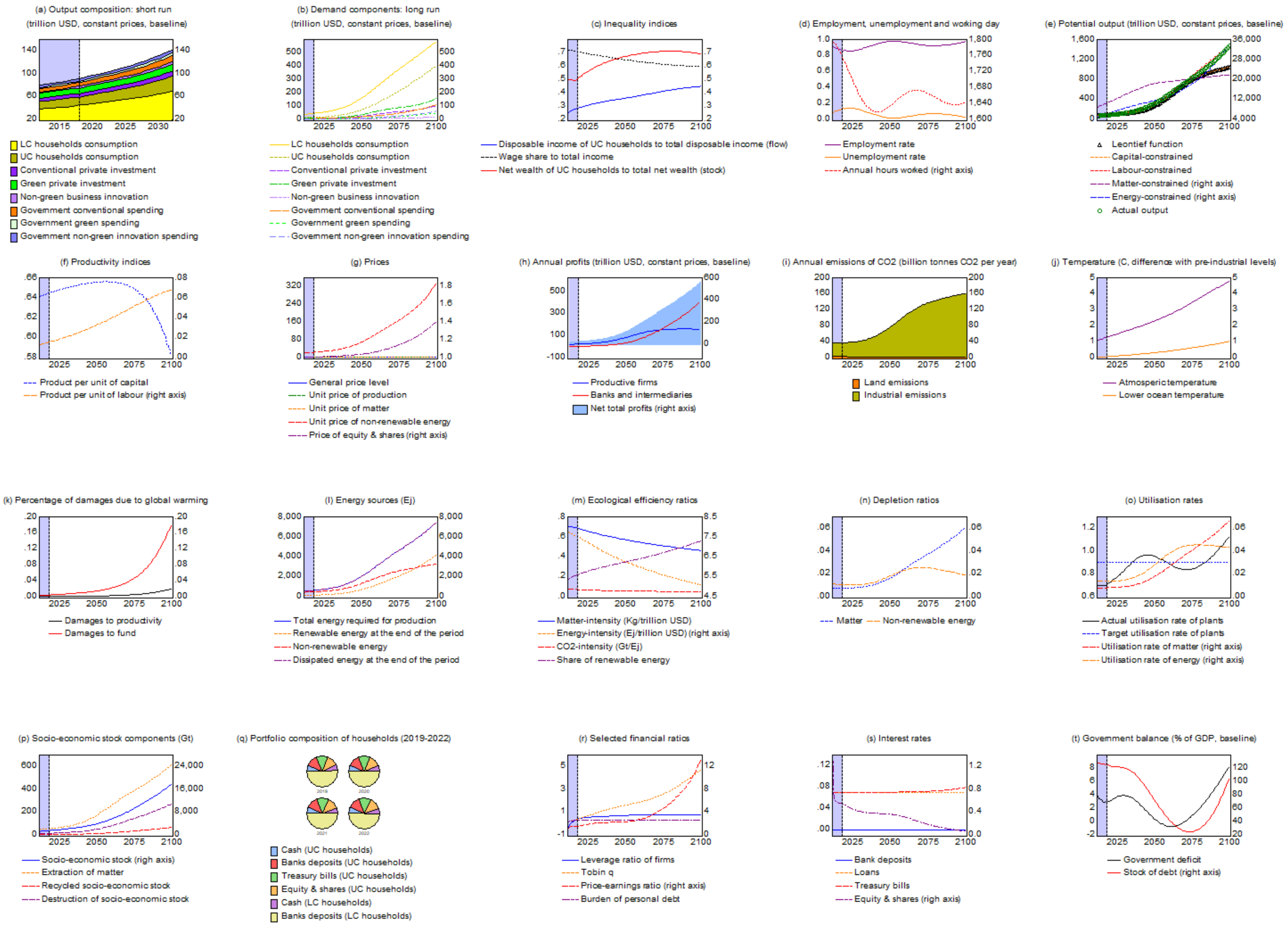


Figure 3. Impact of fiscal policies on the economy (selected variables)

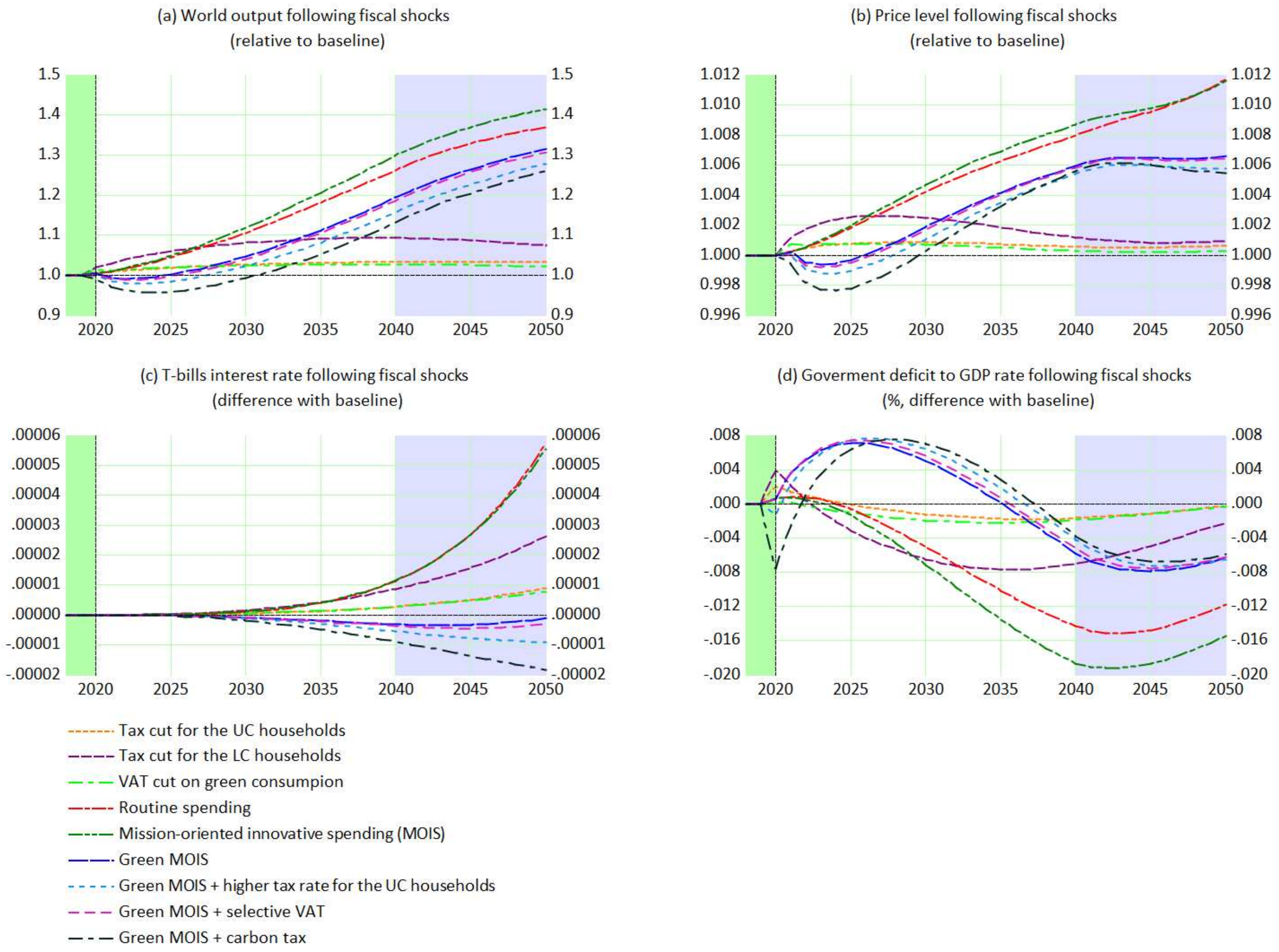


Figure 4. Impact of fiscal policies on the financial sector (selected variables)

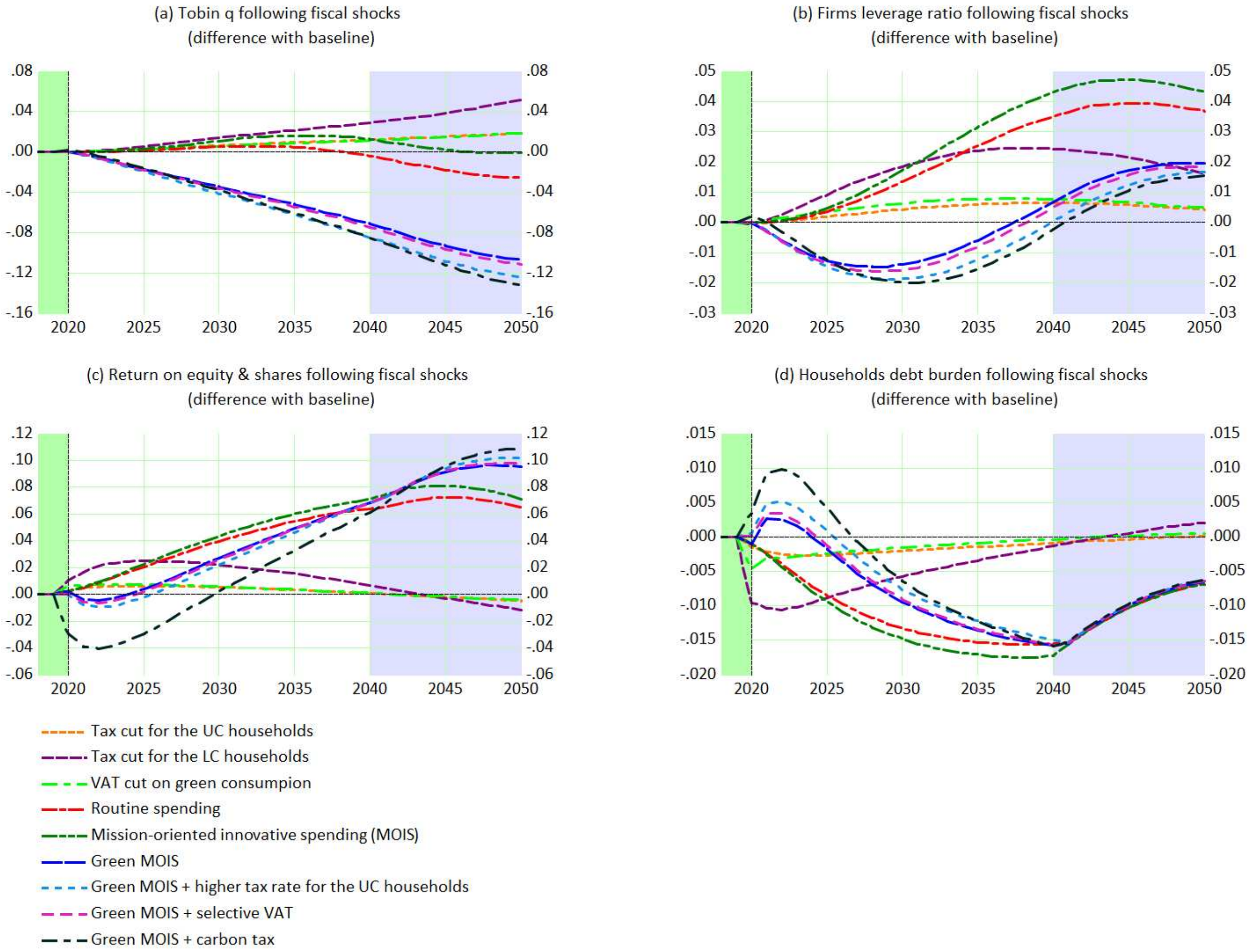


Figure 5. Impact of fiscal policies to the society (selected variables)

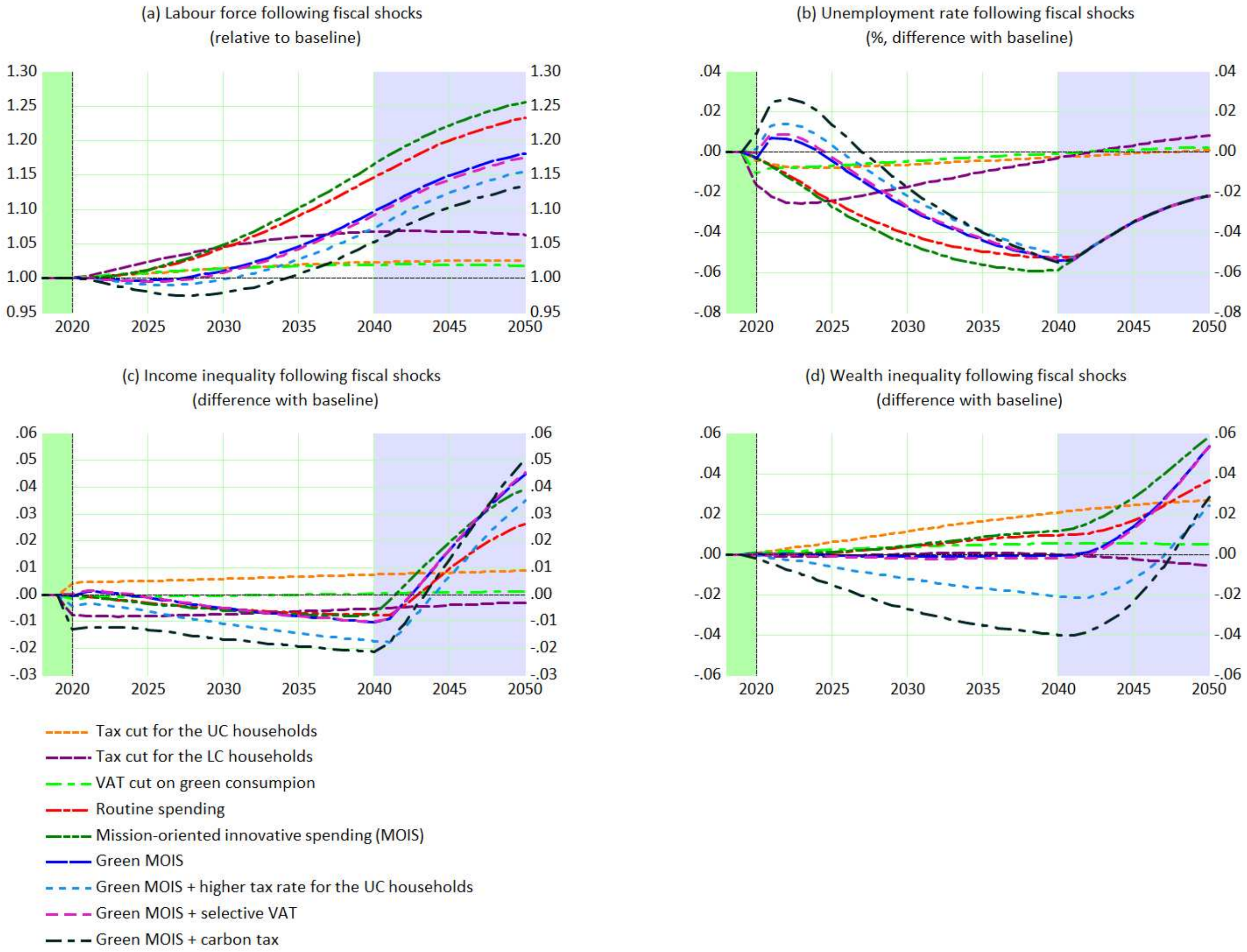
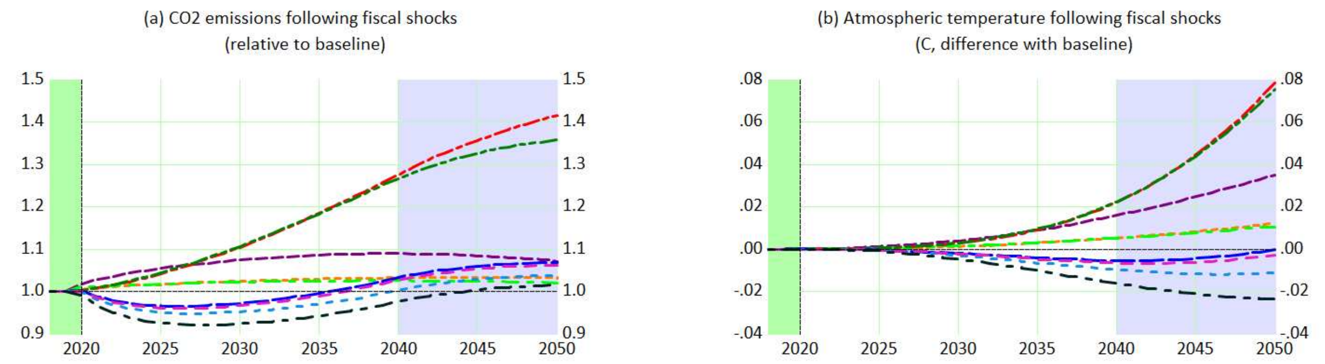
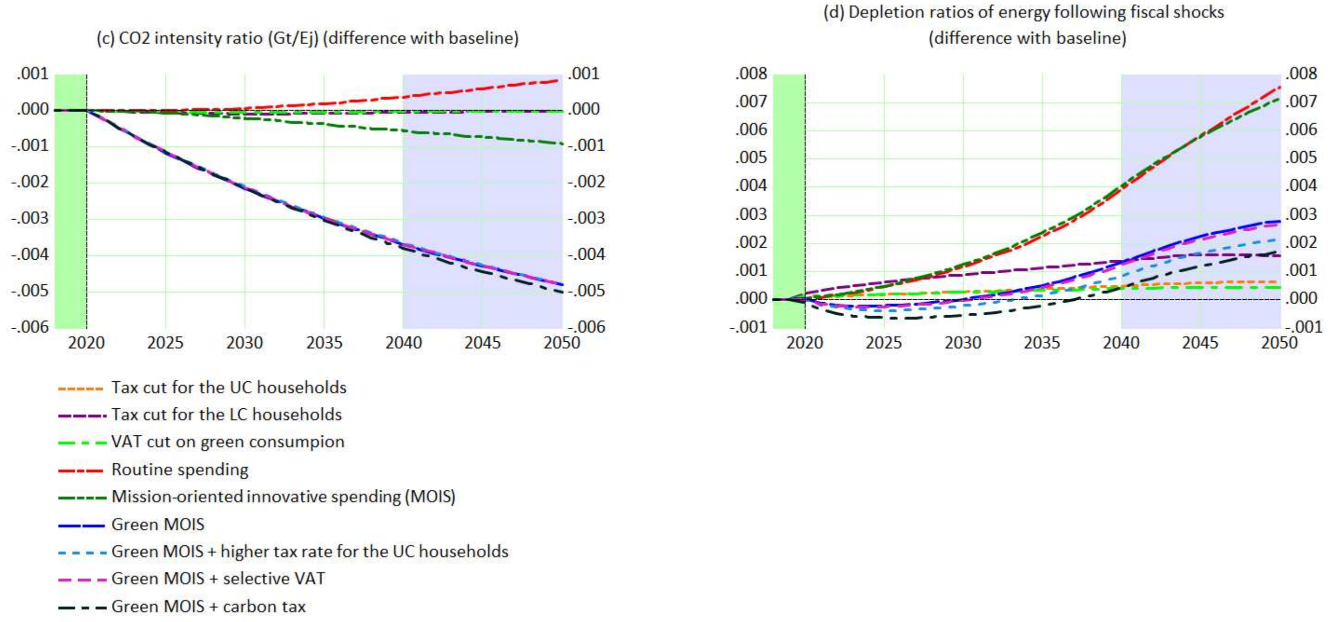


Figure 6. Impact of fiscal policies to the ecosystem (selected variables)


(a) CO2 emissions following fiscal shocks (relative to baseline)

(b) Atmospheric temperature following fiscal shocks (C, difference with baseline)

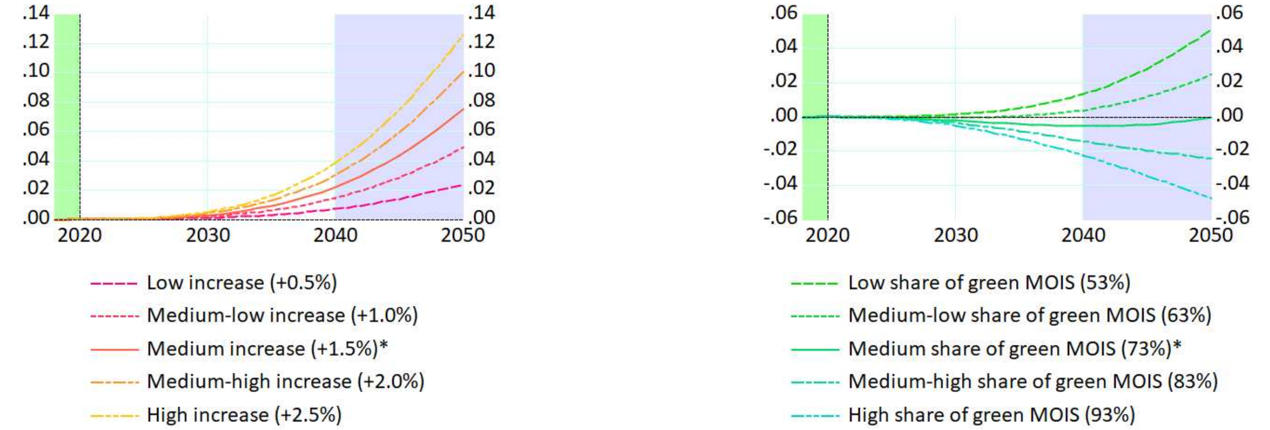

(c) CO2 intensity ratio (Gt/Ej) (difference with baseline)

(d) Depletion ratios of energy following fiscal shocks (difference with baseline)

Figure 7. Univariate sensitivity tests on green policies

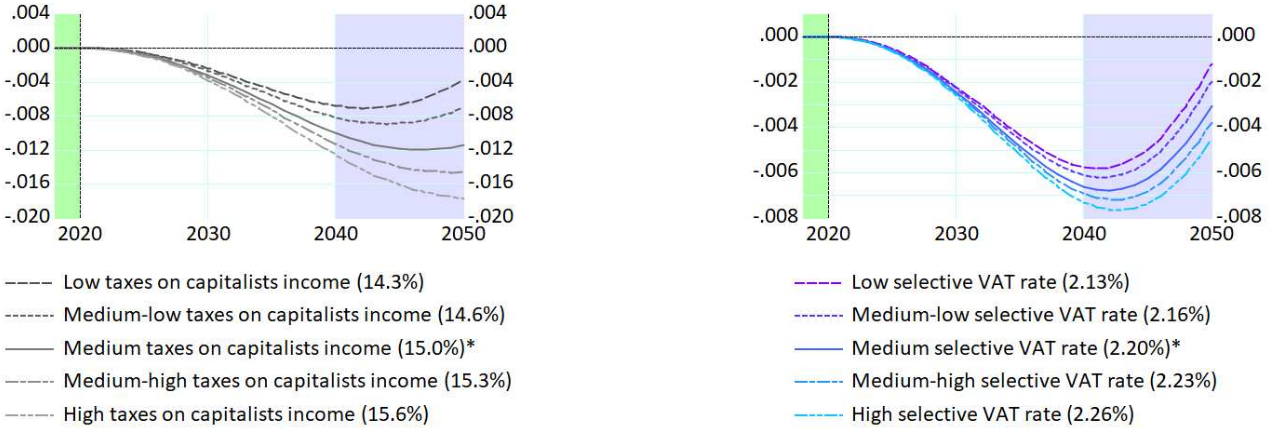
(a) Effect of MOIS on atmospheric temperature (sensitivity test, difference with baseline)

(b) Effect of green MOIS on atmospheric temperature (sensitivity test, difference with baseline)

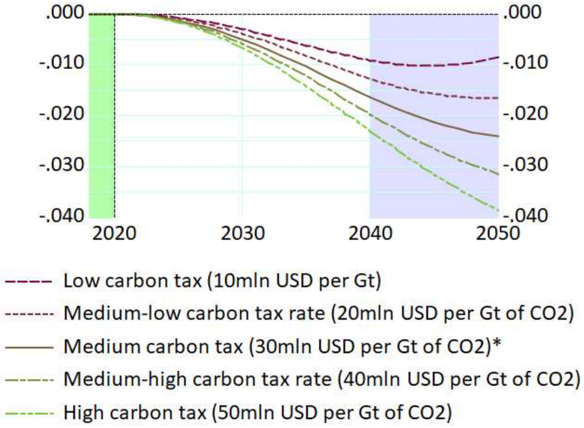


(c) Effect of green MOIS + higher income tax rate on atmospheric temperature (sensitivity test, difference with baseline)

(d) Effect of green MOIS + higher VAT rate on atmospheric temperature (sensitivity test, difference with baseline)

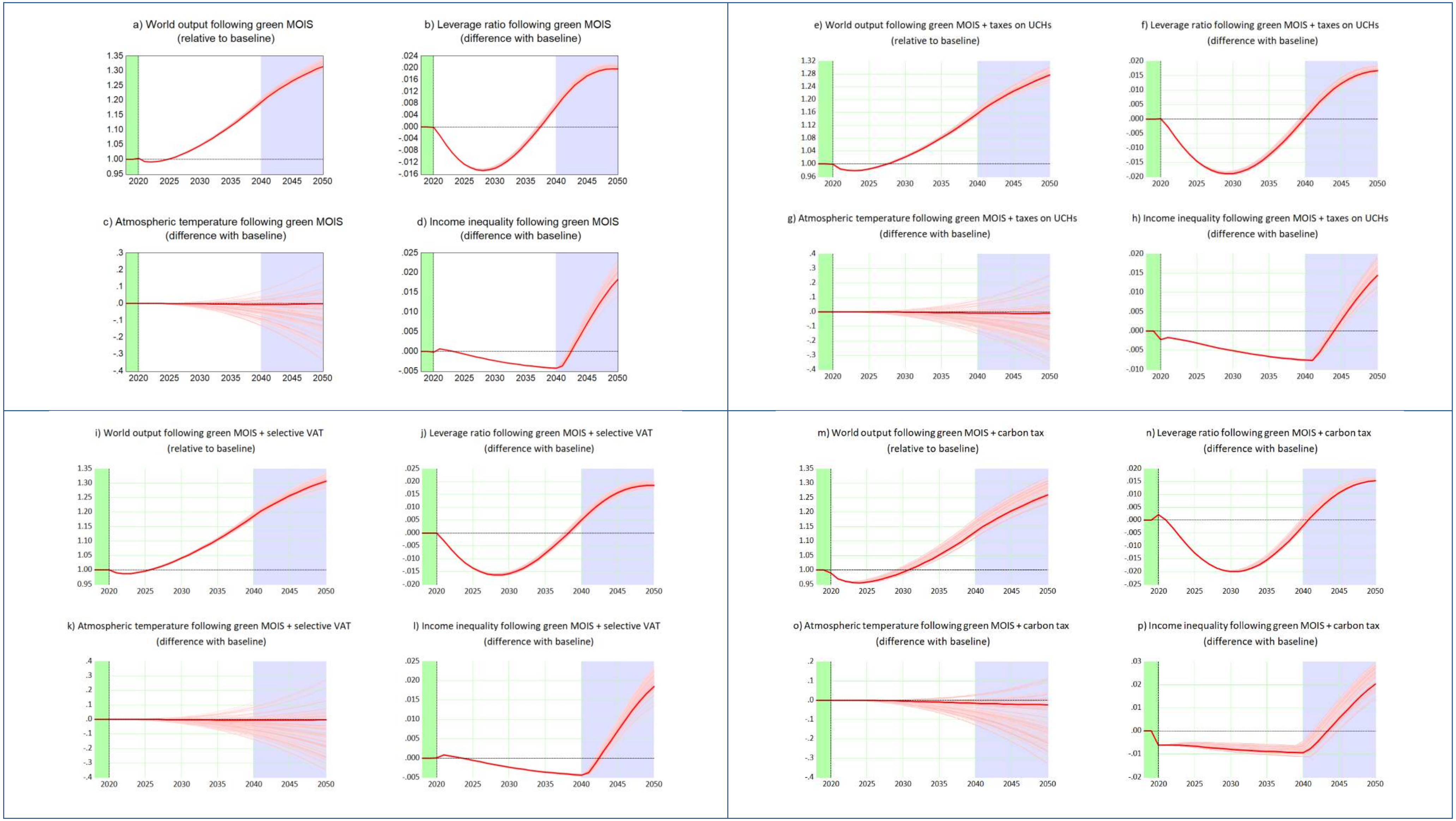


(e) Effect of green MOIS + carbon tax on atmospheric temperature (sensitivity test, difference with baseline)



Note: * scenarios considered in figures (2) to (6).

Figure 8. Multivariate sensitivity tests on green policies


a) World output following green MOIS (relative to baseline)

b) Leverage ratio following green MOIS (difference with baseline)

c) Atmospheric temperature following green MOIS (difference with baseline)

d) Income inequality following green MOIS (difference with baseline)

e) World output following green MOIS + taxes on UCHs (relative to baseline)

f) Leverage ratio following green MOIS + taxes on UCHs (difference with baseline)

g) Atmospheric temperature following green MOIS + taxes on UCHs (difference with baseline)

h) Income inequality following green MOIS + taxes on UCHs (difference with baseline)

i) World output following green MOIS + selective VAT (relative to baseline)

j) Leverage ratio following green MOIS + selective VAT (difference with baseline)

k) Atmospheric temperature following green MOIS + selective VAT (difference with baseline)

l) Income inequality following green MOIS + selective VAT (difference with baseline)

m) World output following green MOIS + carbon tax (relative to baseline)

n) Leverage ratio following green MOIS + carbon tax (difference with baseline)

o) Atmospheric temperature following green MOIS + carbon tax (difference with baseline)

p) Income inequality following green MOIS + carbon tax (difference with baseline)

Notes: 100 Monte Carlo simulations; key parameters of green consumption and investment (c_{gr}^{w}, c_{gr}^{π}, γ_2^{gr}, γ_3^{gr}, γ_4^{gr}, and γ_5^{gr}) are assigned random values in the range (0,1); red lines show original experiments.

Appendix A - Model equations

Firms Transactions and Profit

$Y_d = C + IN + G - C_{INT}$ (1) Aggregate demand (constant prices, 2010 USD)

$Y_s = Y_d$ (2) Aggregate supply (equilibrium condition)

$NY = Y_s \cdot \frac{p}{p_{[2010]}}$ (3) Nominal output (current prices)

$C_{INT} = c_0 + c_1 \cdot C_{INT,-1}$ (4) Intermediate consumption

$WB = w \cdot N \cdot H$ (5) Wage bill

$\omega = \frac{WB}{Y}$ (6) Wage share

$L_f = L_{f,-1} + I_f + BE - C_{INT} - d(e_s) \cdot p_e - F_{fu}$ (7) Loans to firms

$F_f = Y_d - WB - r_{l,-1} \cdot L_{f,-1} - TAX_f$ (8) Firms' total profit (net of taxes)

$F_{fu} = F_f \cdot \theta$ (9) Firms' retained profit

$F_{fd} = F_f - F_{fu}$ (10) Firms' distributed profit

Firms Investment Decisions

$K_c = K_{c,-1} + I_c - DA_c$ (11) Conventional capital stock

$I_f = h \cdot E(Y_d) \cdot \left(1 - d_{T,-1}\right)$ (12) Total private investment

$u = u_{-1} \cdot \frac{1+g_Y}{(1+g_K)\cdot(1+g_{Af})}$ (13) Actual utilisation rate of plants (note: $0 < u \leq 1$ and $g_{Af} = \Delta a_f / a_f$)

$h = [1 + \phi \cdot (u_{-1} - u_n)] \cdot h_{-1}$ (14) Total investment share to output

$I_c = I_f - I_{gr}$ (15) Conventional investment undertaken by firms

$DA_c = \delta_c \cdot K_{c,-1}$ (16) Depreciation allowances on conventional capital

$I_{gr} = \gamma_{gr} \cdot I_f$ (17) Green private investment

$\gamma_{gr} = \gamma_0^{gr} + \gamma_1^{gr} \cdot \gamma_{gr,-1} + \gamma_2^{gr} \cdot \frac{G_{gr,-1}}{G_{-1}} + \gamma_3^{gr} \cdot d_{T,-1} + \gamma_4^{gr} \cdot \frac{C_{gr,-1}}{C_{-1}} + \gamma_5^{gr} \cdot \tau_{f,-1}$ (18) Share of green investment to total investment

$K_{gr} = K_{gr,-1} + I_{gr} - DA_{gr}$ (19) Green capital stock

$K_f = K_c + K_{gr}$ (20) Total stock of capital at constant prices

$DA_{gr} = \delta_{gr} \cdot K_{gr,-1}$ (21) Depreciation allowances on green capital

$DA_f = DA_c + DA_{gr}$	(22) Total depreciation allowances
$BE = \gamma_0^{tech} + \gamma_1^{tech} \cdot G_{tech,-1}$	(23) Private non-green innovative spending
$IN = I_f + BE$	(24) Total spending for investment and innovation
$e_s = e_{s,-1} + \chi \cdot \frac{I_{f,-1}}{p_{e,-1}}$	(25) Quantity of new shares issued by firms as a percentage of planned investment
$g_Y = \frac{\Delta Y}{Y_{-1}}$	(26) Real output growth rate
$g_{NY} = \frac{\Delta NY}{NY_{-1}}$	(27) Nominal output growth rate
$g_K = \frac{\Delta K_f}{K_{f,-1}}$	(28) Rate of accumulation of total capital

Households Income and Wealth

$YD_w = WB + r_{d,-1} \cdot D_{w,-1} - T_w - r_{l,-1} \cdot L_{w,-1} - VAT_w$	(29) LC disposable income
$YD_\pi = F_{fd} + F_b + r_{d,-1} \cdot D_\pi + r_{b,-1} \cdot B_{d,-1} - T_\pi - VAT_\pi$	(30) UC's disposable income
$YD_\pi^{hs} = YD_\pi + CG$	(31) UC's Haig-Simons disposable income
$YD = YD_w + YD_\pi$	(32) Total disposable income
$S_w = YD_w - C_w$	(33) LC's saving
$NW_w = NW_{w,-1} + S_w$	(34) Net wealth of LC
$L_w = L_{w,-1} \cdot (1 - rep) + \psi \cdot C_w$	(35) Loans to LC
$bur = \frac{L_{w,-1} \cdot (rep + r_{l,-1})}{YD_w}$	(36) Debt burden of LC
$NW_\pi = NW_{\pi,-1} + YD_\pi^{hs} - C_\pi$	(37) Net wealth of UC
$NW = NW_w + NW_\pi$	(39) Total net wealth of households

Households Consumption Decisions

$C_w = \left[c_w \cdot YD_w \cdot \frac{E(p_w)}{p_w} + c_{aw} \cdot NW_{w,-1} \cdot \frac{E(p_w)}{p_w}\right] \cdot \left(1 - d_{T,-1}\right)$	(40) Total consumption of LC (net of climate-related damages)
$C_\pi = \left[c_\pi \cdot YD_\pi^{hs} \cdot \frac{E(p_\pi)}{p_\pi} + c_{a\pi} \cdot NW_{\pi,-1} \cdot \frac{E(p_\pi)}{p_\pi}\right] \cdot \left(1 - d_{T,-1}\right)$	(41) Total consumption of UC (net of climate-related damages)
$C_{gr}^w = c_{gr}^w \cdot C_w$	(42) Green consumption of LC

$C^{\pi}_{gr} = c^{\pi}_{gr} \cdot C^{\pi}_{w}$ (43) Green consumption of UC

$C^{w}_{c} = C_{w} - C^{w}_{gr}$ (44) Routine consumption of LC

$C^{\pi}_{c} = C_{\pi} - C^{w}_{c}$ (45) Routine consumption of UC

$c^{w}_{gr} = c^{w}_{0} + c^{w}_{1} \cdot d_{T,-1} + c^{w}_{2} \cdot \left(vat_{c} - vat_{gr}\right)$ (46) Green consumption share of LC

$c^{\pi}_{gr} = c^{\pi}_{0} + c^{\pi}_{1} \cdot d_{T,-1} + c^{\pi}_{2} \cdot \left(vat_{c} - vat_{gr}\right)$ (47) Green consumption share of UC

$C = C_{w} + C_{\pi}$ (48) Total consumption

$C_{gr} = C^{w}_{gr} + C^{\pi}_{gr}$ (49) Total green consumption

Households Portfolio Decisions

$p_{e} = E(NW_{\pi}) \cdot \left[\lambda_{10} + \lambda_{11} \cdot E(r_{e}) + \lambda_{12} \cdot \frac{E(YD_{\pi})}{E(NW_{\pi})} + \lambda_{13} \cdot E(r_{b}) + \lambda_{14} \cdot E(r_{d})\right] \cdot \frac{1}{e_{d}}$ (50) Unit price of shares

$e_{d} = e_{s}$ (51) Equilibrium condition for the stock market

$E_{d} = e_{d} \cdot p_{e}$ (52) Nominal shares held by capitalist households

$B_{d} = E(NW_{\pi}) \cdot \left[\lambda_{20} \cdot + \lambda_{21} \cdot E(r_{e}) + \lambda_{22} \cdot \frac{E(YD_{\pi})}{E(NW_{\pi})} + \lambda_{23} \cdot E(r_{b}) + \lambda_{24} \cdot E(r_{d})\right]$ (53) Nominal government bills held by capitalist households

$D_{\pi} = E(NW_{\pi}) \cdot \left[\lambda_{30} + \lambda_{31} \cdot E(r_{e}) + \lambda_{32} \cdot \frac{E(YD_{\pi})}{E(NW_{\pi})} + \lambda_{33} \cdot E(r_{b}) + \lambda_{34} \cdot E(r_{d})\right]$ (54) Deposits held by capitalist households

$H_{\pi} = NW_{\pi} - E_{d} - B_{d} - D_{\pi}$ (55) Cash held by capitalist households

$D_{w} = NW^{G}_{w} - H_{w}$ (56) Deposits held by LC

$NW^{G}_{w} = NW_{w} + L_{w}$ (57) Gross wealth of LC

$H_{w} = \lambda_{w} \cdot NW^{G}_{w}$ (58) Cash held by LC

$D_{d} = D_{w} + D_{\pi}$ (59) Total demand for bank deposits

$H_{d} = H_{w} + H_{\pi}$ (60) Total demand for cash

Commercial Banks and Central Bank

$D_{s} = D_{d}$ (61) Supply of bank deposits

$A_{d} = D_{s} - L_{s} + H^{B}_{d}$ (62) Demand for advances (+) / Excess reserves (–)

$A_{s} = A_{d}$ (63) Supply of advances (+) / Excess reserves (–)

$H^{B}_{d} = \rho_{B} \cdot D_{s,-1}$ (64) Reserve requirement (demand)

$H_s^B = H_d^B$ (65) Reserve requirement (supply)

$L_s = L_{s,-1} + d(L_d)$ (66) Supply of loans (endogenous)

$L_d = L_f + L_w$ (67) Total demand for loans

$F_b = L_{s,-1} \cdot r_{l,-1} - D_{s,-1} \cdot r_{d,-1}$ (68) Bank profit

$B_{cb} = B_s - B_d$ (69) T-bills purchased by CB (residual amount)

$H_s = B_{cb} + A_s - H_s^B$ (70) Money created by CB

$r_l = r_{cb} + \mu_l$ (71) Interest rate on bank loans

$r_d = r_{cb}$ (72) Return rate on bank deposits

Other Financial Variables and Indices

$CG = e_{s,-1} \cdot d(p_e)$ (73) Capital gains/losses on shares

$r_e = \frac{F_f}{e_{s,-1} \cdot p_{e,-1}}$ (74) Dividend yields

$q = \frac{e_s \cdot p_e + L_f}{K_f}$ (75) Tobin's q

$\ell = \frac{L_f}{e_s \cdot p_e + L_f}$ (76) Firms' leverage ratio

$per = \frac{p_e}{F_f / e_{s,-1}}$ (77) Price-earnings ratio

Government Spending and Taxation

$TAX = TAX_f + TAX_w + TAX_\pi + VAT_w + VAT_\pi$ (78) Total tax revenue

$VAT_w = C_w \cdot \frac{vat_w}{1 + vat_w}$ (79) Taxes on value added paid by LC

$VAT_\pi = C_\pi \cdot \frac{vat_\pi}{1 + vat_\pi}$ (80) Taxes on value added paid by UC

$vat_w = vat_{gr} \cdot \frac{C_{gr}^w}{C_w} + vat_c \cdot \frac{C_c^w}{C_w}$ (81) Average VAT rate for LC

$vat_\pi = vat_{gr} \cdot \frac{C_{gr}^\pi}{C_\pi} + vat_c \cdot \frac{C_c^\pi}{C_\pi}$ (82) Average VAT rate for UC

$TAX_f = \tau_f \cdot emis_{in,-1}$ (83) Taxes on firms' emissions (carbon tax)

$TAX_w = \tau_w \cdot \left(WB + r_{d,-1} \cdot D_{w,-1}\right)$	(84) Taxes on LC's income
$TAX_\pi = \tau_\pi \cdot \left(F_{fd} + F_b + r_{d,-1} \cdot D_{\pi,-1} + r_{b,-1} \cdot B_{d,-1}\right)$	(85) Taxes on UC's income (excluding capital gains)
$G = G_{rout} + G_{mois}$	(86) Total government spending (net of interest payments)
$G_{rout} = G_{rout,-1} \cdot (1 + g_G^{rout})$	(87) Routine government spending
$G_{mois} = G_{mois,-1} \cdot \left(1 + g_G^{mois}\right)$	(88) Mission-oriented innovation spending by government (MOIS)
$G_{gr} = \alpha \cdot G_{mois}$	(89) Government MOIS devoted to green conversion
$G_{tech} = (1 - \alpha) \cdot G_{mois}$	(90) Other government MOIS (e.g., new technologies)

Government Budget

$B_s = B_{s,-1} + GDEF$	(91) Nominal supply of government bills
$GDEF = G + r_{b,-1} \cdot (B_{s,-1} - B_{cb,-1}) - T$	(92) Government deficit (note: no interest payments on government bills held by CB)
$GDEB = GDEB_{-1} + GDEF$	(93) Stock of government debt
$r_b = r_{cb} + \mu_b$	(94) Return rate on government bills
$\mu_b = \eta_0 + \eta_1 \cdot d_{T,-1}$	(95) Risk premium on T-bills

The Ecosystem: Material Resources and Reserves

$y_{mat} = \mu \cdot Y_s$	(96) Production of material goods
$mat = y_{mat} - rec$	(97) Extracted matter
$rec = \rho_{rec} \cdot des$	(98) Recycled socio-economic stock
$des = \mu \cdot \left(DA_f + \zeta \cdot DC_{-1}\right)$	(99) Demolition or disposition of socio-economic stock
$DC = DC_{-1} \cdot (1 - \zeta) + C$	(100) Durable goods (lasting more than one period)
$k_{se} = k_{se,-1} + y_{mat} - des$	(101) Socio-economic stock
$wa = mat + cen + o2 - emis - \Delta k_{se} = mat - \Delta k_{se}$	(102) Waste generated by production process
$hws = hws_{-1} + haz \cdot wa$	(103) Hazardous waste level
$hratio = \frac{hws}{surf}$	(104) Hazardous waste ratio (Gt/Km^2)
$k_m = k_{m,-1} + conv_m - mat$	(105) Stock of material reserves
$conv_m = \max(\sigma_{m,-1} \cdot res_{m,-1}, mat_{-1})$	(106) Material resources converted to reserves

$res_m = res_{m,-1} - conv_m$ (107) Stock of material resources

$p_m = p_m^0 + p_m^1 \cdot \frac{mat_{-1}}{\sigma_{m,-1} \cdot res_{m,-1}}$ (108) Unit price of extracted matter

$\sigma_m = \sigma_m^0 + \sigma_m^1 \cdot E(p_m)$ (109) Actual conversion rate of matter resources

$cen = \frac{emis}{car}$ (110) Carbon mass of (non-renewable) energy

$o2 = emis - cen$ (111) Mass of oxygen (O_2)

The Ecosystem: Energy Resources and Reserves

$e = \varepsilon \cdot Y_s$ (112) Total energy required for production

$er = \eta_{en} \cdot e$ (113) Renewable energy at the end of the period

$en = e - er$ (114) Non-renewable energy

$ed = en + er$ (115) Dissipated energy at the end of the period

$k_{en} = k_{en,-1} + conv_{en} - en$ (116) Stock of energy reserves

$conv_{en} = \max(\sigma_{en,-1} \cdot res_{en,-1}, en_{-1})$ (117) Energy resources converted to reserves

$res_{en} = res_{en,-1} - conv_{en}$ (118) Stock of energy resources

$p_{en} = p_{en}^0 + p_{en}^1 \cdot \frac{en_{-1}}{\sigma_{en,-1} \cdot res_{en,-1}}$ (119) Unit price of energy

$\sigma_{en} = \sigma_{en}^0 + \sigma_{en}^1 \cdot E(p_{en})$ (120) Actual conversion rate of energy resources

Emissions and Climate Change

$emis_{in} = \beta \cdot en$ (121) Industrial emissions of CO_2

$emis_l = emis_{l,-1} \cdot (1 - g_l)$ (122) Land emissions of CO_2

$emis = emis_{in} + emis_l$ (123) Total emissions of CO_2

$co2_{AT} = emis + \psi_{11} \cdot co2_{AT,-1} + \psi_{21} \cdot co2_{UP,-1}$ (124) Atmospheric CO_2 concentration

$co2_{UP} = \psi_{12} \cdot co2_{AT,-1} + \psi_{22} \cdot co2_{UP,-1} + \psi_{32} \cdot co2_{LO,-1}$ (125) Upper ocean / biosphere CO_2 concentration

$co2_{LO} = \psi_{23} \cdot co2_{UP,-1} + \psi_{33} \cdot co2_{LO,-1}$ (126) Lower ocean CO_2 concentration

$F = F_2 \cdot \log_2\left(\frac{co2_{AT}}{co2_{AT}^{PRE}}\right) + F_{ex}$ (127) Radiative forcing over pre-industrial levels (W/m^2)

$F_{ex} = F_{ex,-1} + fex$ (128) Radiative forcing (W/m^2) due to non-CO_2 greenhouse gases

$T_{AT} = T_{AT,-1} + t_1 \cdot \left[F - \frac{F_2}{sens} \cdot T_{AT,-1} - t_2 \cdot \left(T_{AT,-1} - T_{LO,-1}\right)\right]$ (129) Atmospheric temperature (C)

$T_{LO} = T_{LO,-1} + t_3 \cdot \left(T_{AT,-1} - T_{LO,-1}\right)$ (130) Lower ocean temperature (C)

Ecological Efficiency

$\mu = \mu_{gr} \cdot \frac{K_{gr}}{K_f} + \mu_c \cdot \frac{K_c}{K_f}$ (131) Matter-intensity coefficient

$\varepsilon = \varepsilon_{gr} \cdot \frac{K_{gr}}{K_f} + \varepsilon_c \cdot \frac{K_c}{K_f}$ (132) Energy-intensity coefficient

$\beta = \beta_{gr} \cdot \frac{K_{gr}}{K_f} + \beta_c \cdot \frac{K_c}{K_f}$ (133) CO_2-intensity coefficient

$\eta_{en} = \eta_{gr} \cdot \frac{K_{gr}}{K_f} + \eta_c \cdot \frac{K_c}{K_f}$ (134) Share of renewable energy sources

$\rho_m = \frac{mat}{k_{m,-1}}$ (135) Matter depletion ratio (net of recycling)

$\rho_{en} = \frac{en}{k_{en,-1}}$ (136) Non-renewable energy depletion ratio

Ecological Feedbacks and Damages

$\delta_c = \delta_c^0 + (1 - \delta_c^0) \cdot (1 - ad_K^c) \cdot d_{TF,-1}$ (137) Impact of climate change on conventional capital stock depreciation

$\delta_g = \delta_g^0 + \left(1 - \delta_g^0\right) \cdot \left(1 - ad_K^g\right) \cdot d_{TF,-1}$ (138) Impact of climate change on green capital stock depreciation

$a_f = a_{f,-1} \cdot \left(1 + g_f\right) \cdot \left[1 - (1 - ad_P) \cdot d_{TP,-1}\right]$ (139) Product per unit of (either conventional or green) capital

$g_f = g_{f0} + g_{f1} \cdot g_{BE,-1}$ (140) Growth rate of product per unit of capital

$a_n = a_{n,-1} \cdot (1 + g_n) \cdot \left[1 - (1 - ad_P) \cdot d_{TP,-1}\right]$ (141) Labour productivity

$g_n = g_{n0} + g_{n1} + g_{n2} \cdot g_{y,-1}$ (142) Growth rate of labour productivity

$g_{n0} = g_{n0,-1} \cdot (1 - g_{n3})$ (143) Deceleration rate of labour productivity

$d_T = 1 - \frac{1}{1 + dam_1 \cdot T_{AT} + dam_2 \cdot T_{AT}^2 + dam_3 \cdot T_{AT}^x}$ (144) Proportion of gross damage due to changes in at. temperature ($x = 6.6754$)

$d_{TP} = dam_P \cdot d_T$ (145) Productivity damage

$d_{TF} = 1 - \frac{1 - d_T}{1 - d_{TP}}$ (146) Fund damage

Labour force, Employment and Working Time

$LF = LF_{-1} \cdot (1 + g_{LF}) \cdot \left[1 - (1 - ad_{LF}) \cdot d_{TF,-1}\right]$ (147) Labour force level

$g_{LF} = lf_0 + lf_1 - lf_2 \cdot un_{-1} - lf_3 \cdot hratio_{-1}$ (148) Labour force growth rate

$lf_0 = lf_{0,-1} \cdot (1 - lf_4)$ (149) Autonomous component of labour force growth rate

$N = \frac{Y_S}{H \cdot a_n}$ (150) Employment level

$H = H_{-1} + h_1 \cdot (em_{-1} - h_2)$ (151) Annual working time

$em = \frac{N}{LF}$ (152) Employment rate

$un = 1 - em$ (153) Unemployment rate

Production Function and Price Level

$Y_f^* = a_f \cdot K_{f,-1}$ (154) Capital-determined potential output

$Y_n^* = a_n \cdot LF_{-1} \cdot H_{-1}$ (155) Labour-determined potential output

$Y_m^* = \frac{k_{m,-1} + rec}{\mu}$ (156) Matter-determined potential output

$Y_{en}^* = \frac{k_{en,-1}}{\varepsilon}$ (157) Energy-determined potential output

$Y_{tec}^* = \min\left(Y_f^*, Y_n^*\right)$ (158) Economically-constrained potential output

$Y_{eco}^* = \min(Y_m^*, Y_{en}^*)$ (159) Ecologically-constrained potential output

$Y^* = \min(Y_{tec}^*, Y_{eco}^*)$ (160) Potential output (Leontief function)

$p_y = \frac{w}{a_n} \cdot (1 + mk)$ (161) Unit price of production

$w = w_{-1} \cdot \left(1 + w_a \cdot \frac{d(a_n)}{a_n}\right)$ (162) Money wage rate

$mk = mk_0 + mk_1 \cdot \frac{Y_{S,-1}}{Y_{-1}^*}$ (163) Gross mark-up over labour cost

$p = \pi_1 \cdot p_y + \pi_2 \cdot p_{en} + \pi_3 \cdot p_m$ (164) General price level (output deflator)

$p_w = p \cdot (1 + vat_w)$ (165) Price paid by LC including VAT

$p_\pi = p \cdot (1 + vat_\pi)$ (166) Price paid by UC including VAT

$E(x) = x_{-1} + \psi \cdot [E(x_{-1}) - x_{-1}]$ (167) Expectation function (with: $x = p, r_b, r_d, r_e$)

Other Utilisation Rates

$u_m = \frac{Y_s}{Y_m}$ (168) Matter utilisation rate

$u_{en} = \frac{Y_s}{Y_{en}}$ (169) Energy utilisation rate

Redundant Equation

$H_s = H_d$ Cash: supply = demand

Appendix B - Additional tables and figures

Table B1. Coefficient values and initial values of lagged variables and stocks (in 2008)

Symbol	Description	Value	Remarks / Sources
a_f	Real product per unit of capital	0.64	Calibrated such that the model generates the baseline scenario presented in section 3.4
a_n	Hourly product per unit of labour input	0.012	Calibrated such that the model generates the baseline scenario presented in section 3.4
ad_K^c	Adaptation coefficient of conventional capital stock	0.75	Based on Dafermos et al. (2017)
ad_K^g	Adaptation coefficient of green capital stock	0.75	Based on Dafermos et al. (2017)
ad_{lf}	Adaptation of labour force to global warming	0.95	Based on Dafermos et al. (2017)
ad_P	Sensitivity of capital depreciation rate to sustainability gap	0.50	Based on Dafermos et al. (2017)
B_d	Demand for T-bills (and other government securities)	11.71	Calibrated such that the model generates the baseline scenario presented in section 3.4
C	Total consumption	47.70	Based on World Bank data, 2019
c_0^w	Coefficient of green consumption share of LC	0.15	Calibrated such that the model generates the baseline scenario presented in section 3.4
c_0^π	Coefficient of green consumption share of UC	0.15	Calibrated such that the model generates the baseline scenario presented in section 3.4
c_1^w	Coefficient of green consumption share of LC	0.50	Calibrated such that the model generates the baseline scenario presented in section 3.4
c_1^π	Coefficient of green consumption share of UC	0.50	Calibrated such that the model generates the baseline scenario presented in section 3.4
c_2^w	Coefficient of green consumption share of LC	0.50	Calibrated such that the model generates the baseline scenario presented in section 3.4
c_2^π	Coefficient of green consumption share of UC	0.50	Calibrated such that the model generates the baseline scenario presented in section 3.4
c_{aw}	LC's propensity to consume out of wealth	0.02	Calibrated such that the model generates the baseline scenario presented in section 3.4
$c_{a\pi}$	UC's propensity to consume out of wealth	0.0125	Calibrated such that the model generates the baseline scenario presented in section 3.4
C_{INT}	Intermediate consumption	10.68	Based on World Bank data, 2019
c_w	LC's propensity to consume out of income	0.90	Calibrated such that the model generates the baseline scenario presented in section 3.4. Note: 0.88 = average value worldwide
C_w	LC's consumption	31.95	Calibrated such that the model generates the baseline scenario presented in section 3.4
c_π	UC's propensity to consume out of income	0.60	Calibrated such that the model generates the baseline scenario presented in section 3.4. Note: 0.88 = average value worldwide
C_π	UC's consumption	15.74	Calibrated such that the model generates the baseline scenario presented in section 3.4
car	Conversion coefficient of Gt of carbon into Gt of CO_2	3.67	Based on Dafermos et al. (2017)
cen	Carbon mass of the non-renewable energy sources (Gt)	9.8	Based on Dafermos et al. (2017)
$co2_{AT}$	Initial level of atmospheric CO_2 concentration	3,120.00	Based on Dafermos et al. (2017)
$co2_{AT}^{PRE}$	Pre-industrial CO_2 concentration in atmosphere (Gt)	2,156.20	Based on Dafermos et al. (2017)
$co2_{LO}$	Lower ocean CO_2 concentration	36,706.70	Based on Dafermos et al. (2017)
$co2_{UP}$	Upper ocean/biosphere CO_2 concentration	5,628.80	Based on Dafermos et al. (2017)
d_T	Percentage of damages	0.0028	Based on Dafermos et al. (2017)
d_{TF}	Percentage of damages to fund	0.0026	Based on Dafermos et al. (2017)
d_{TP}	Percentage of damages to productivity	0.0003	Based on Dafermos et al. (2017)
D_π	Bank deposits held by UC	23.43	Calibrated such that the model generates the baseline scenario presented in section 3.4

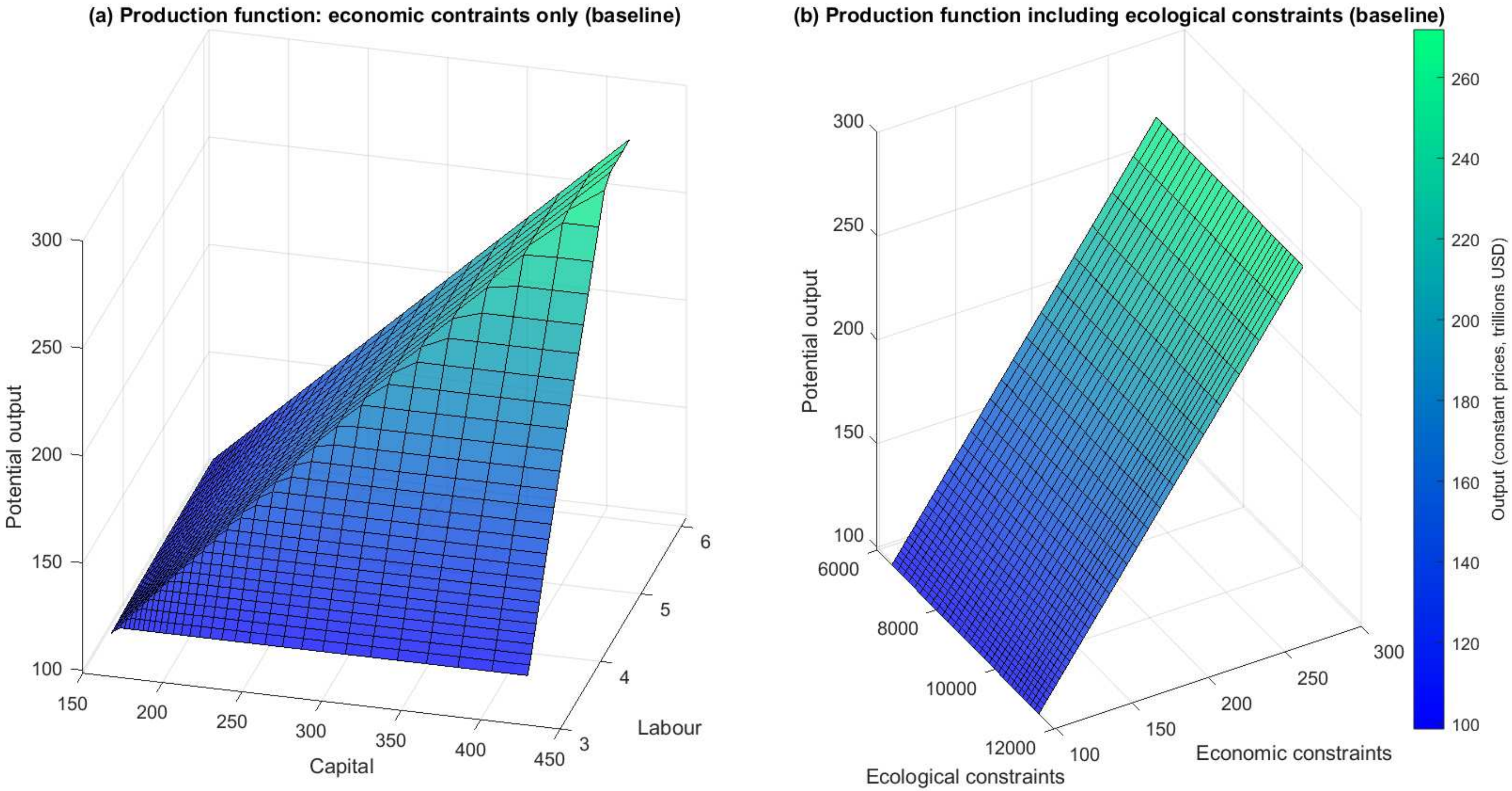
dam_1	Parameter of damage function	0	Based on Dafermos et al. (2017)
dam_2	Parameter of damage function	0.00284	Based on Dafermos et al. (2017)
dam_3	Parameter of damage function	0.000005	Based on Dafermos et al. (2017)
dam_p	Share of productivity damage in total damage due to global warming	0.1	Based on Dafermos et al. (2017)
E_d	Nominal amount of shares held by UC	11.71	Calibrated such that the model generates the baseline scenario presented in section 3.4
em	Employment rate (to total labour force)	0.95	Based on World Bank data, 2019
$emis_{in}$	Land-use CO_2 emissions (Gt)	36.00	Based on Dafermos et al. (2017)
$emis_l$	Land-use CO_2 emissions (Gt)	4.00	Based on Dafermos et al. (2017)
F	Radiative forcing over pre-industrial levels (W/m^2)	2.30	Based on Dafermos et al. (2017)
F_2	Increase in radiative forcing due to doubling of CO_2 concentraton since pre-industrial levels (W/m^2)	3.80	Based on Dafermos et al. (2017)
F_{ex}	Radiative forcing over pre-industrial levels (W/m^2) due to non-CO_2 greenhouse gases (W/m^2)	0.28	Based on Dafermos et al. (2017)
fex	Annual increase in radiative forcing due to non-CO_2 greenhouse gas emissions (W/m^2)	0.005	Based on Dafermos et al. (2017)
G	Total government spending (net of interests)	10.95	Based on World Bank data, 2019
g_{BE}	Growth rate of private innovation	0	Calibrated such that the model generates the baseline scenario presented in section 3.4
g_{f0}	Baseline value of growth rate of real product per unit of capital before global warming damages	0.001	Based on Dafermos et al. (2017)
g_{f1}	Sensitivity of growth rate of real product per unit of capital to innovative spending growth rate	0	Calibrated such that the model generates the baseline scenario presented in section 3.4
g_G^{mois}	Growth rate of mission-oriented government spending	0.04	Calibrated such that the model generates the baseline scenario presented in section 3.4
g_G^{rout}	Routine government expenditure growth rate	0.04	Calibrated such that the model generates the baseline scenario presented in section 3.4
g_l	Rate of decline of land-use CO2 emissions	0.044	Based on Dafermos et al. (2017)
g_{lf}	Labour force growth rate before global warming	0.012	Based on United Nations data, 2019
G_{mois}	Mission-oriented government spending (MOIS)	5.47	Calibrated such that the model generates the baseline scenario presented in section 3.4
g_{n0}	Autonomous growth rate of labour productivity	0.029	Based on Dafermos et al. (2017)
g_{n1}	Additional component of autonomous growth rate of labour productivity	0	Calibrated such that the model generates the baseline scenario presented in section 3.4
g_{n2}	Sensitivity of labour productivity growth rate to growth rate of output	0.6	Based on Dafermos et al. (2017)
g_{n3}	Rate of decline of autonomous (absolute) growth rate of labour productivity	0.007	Based on Dafermos et al. (2017)
G_{rout}	Routine government spending	5.47	Calibrated such that the model generates the baseline scenario presented in section 3.4
$GDEB$	Government debt (non-consolidated)	15.62	Calibrated such that the model generates the baseline scenario presented in section 3.4
h	Investment share	0.237	Based on World Bank data, 2019
H	Annual working hours per employee	1,800.00	Based on Penn World, Table 8.1
h_1	Sensitivity of working day length to output gap	100	Calibrated such that the model generates the baseline scenario presented in section 3.4
H_d^B	Reserve requirement (demand)	11.80	Calibrated such that the model generates the baseline scenario presented in section 3.4
haz	Hazardous waste ratio (Gt/million km^2)	0.03	Based on Dafermos et al. (2017)
haz	Proportion of hazardous waste to total waste	0.04	Based on Dafermos et al. (2017)
hws	Hazardous waste stock (Gt)	14.00	Based on Dafermos et al. (2017)
k_{en}	Stock of energy reserves	37,000.00	Based on Dafermos et al. (2017)
K_f	Total capital stock	124,26	Based on World Bank data, 2019

K_c	Conventional capital stock	94.78	Based on World Bank data, 2019, and Dafermos et al. (2017)
K_{gr}	Green capital stock	29.48	Based on World Bank data, 2019, and Dafermos et al. (2017)
k_m	Stock of material reserves	6,000.00	Based on Dafermos et al. (2017)
k_{se}	Socio-economic stock	1,135.60	Based on Dafermos et al. (2017)
LF	Labour force (billion people)	3.12	Based on World Bank data, 2019
lf_0	Coefficient of labour force growth rate function	0.022	Calibrated such that the model generates the baseline scenario presented in section 3.4
lf_1	Coefficient of labour force growth rate function	0.022	Calibrated such that the model generates the baseline scenario presented in section 3.4
lf_2	Coefficient of labour force growth rate function	0.2	Based on Dafermos et al. (2017)
lf_3	Coefficient of labour force growth rate function	0.001	Based on Dafermos et al. (2017)
lf_4	Deceleration rate of labour force	0.018	Based on Dafermos et al. (2017)
N	Employment (billion people)	2.96	Based on World Bank data, 2019
NW	Total net wealth	156.20	Based on World Bank data, 2019
NW_w	Total net wealth of LC	78.10	Calibrated such that the model generates the baseline scenario presented in section 3.4
NW_π	Total net wealth of UC	78.10	Calibrated such that the model generates the baseline scenario presented in section 3.4
p	Price level (GDP deflator, 2010 = 100)	0.98	Based on World Bank data, 2019
p_1	Sensitivity of price level to output gap	0.05	Calibrated such that the model generates the baseline scenario presented in section 3.4
p_2	Sensitivity of price level to price of energy	0.05	Calibrated such that the model generates the baseline scenario presented in section 3.4
p_3	Sensitivity of price level to price of matter	0.05	Calibrated such that the model generates the baseline scenario presented in section 3.4
p_e	Unit price of shares	1.00	Normalisation condition
p_{en}^0	Autonomous component of energy price	1.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
p_{en}^1	Sensitivity of energy price to demand-supply gap	0.20	Calibrated such that the model generates the baseline scenario presented in section 3.4
p_m^0	Autonomous component of matter price	1.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
p_m^1	Sensitivity of matter price to demand-supply gap	0.20	Calibrated such that the model generates the baseline scenario presented in section 3.4
r_{cb}	Interest rate set by central bank	0.015	Based on World Bank data, 2019
r_d	Interest rate on bank deposits	0.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
rep	Repayment rate of LC's loans	0.60	Calibrated such that the model generates the baseline scenario presented in section 3.4
res_{en}	Stock of non-renewable energy resources in 2010	542,000.00	Based on Dafermos et al. (2017)
res_m	Stock of material resources in 2010	388,889.00	Based on Dafermos et al. (2017)
$sens$	Equilibrium climate sensitivity	3	Based on Dafermos et al. (2017)
$surf$	Earth surface (million km^2)	510.10	Based on Google data, 2019
t_1	Speed of adjustment parameter in atmospheric temperature function	0.027	Based on Dafermos et al. (2017)
t_2	Coefficient of heat loss from the atmosphere to the lower ocean in atmospheric temperature function	0.0018	Based on Dafermos et al. (2017)
t_3	Coefficient of heat loss from the atmosphere to the lower ocean in lower ocean temperature function	0.005	Based on Dafermos et al. (2017)
T_{AT}	Atmospheric temperature over pre-industrial levels (C)	1	Based on Dafermos et al. (2017)
T_{LO}	Lower ocean temperature over pre-industrial levels (C)	0.0068	Based on Dafermos et al. (2017)
u	Actual utilisation rate of plants	0.72	Based on World Bank data, 2019

u_n	Normal utilisation rate of plants	0.90	Calibrated such that the model generates the baseline scenario presented in section 3.4
vat_c	VAT rate on brown consumption goods	0.02	Calibrated such that the model generates the baseline scenario presented in section 3.4
vat_{gr}	VAT rate on green consumption goods	0.02	Calibrated such that the model generates the baseline scenario presented in section 3.4
w	Wage rate per hour (trillion USD / annual working hours)	0.0088	Calibrated such that the model generates the baseline scenario presented in section 3.4
wa	Waste generated by production activities (Gt)	11.00	Based on Dafermos et al. (2017)
WB	Wage bill	41.82	Based on World Bank data, 2019
Y	Total output (trillion USD, constant prices)	64.35	Based on World Bank data, 2019
YD_w	Total disposable income of LC	35.79	Calibrated such that the model generates the baseline scenario presented in section 3.4
YD_π	Total disposable income of UC	28.55	Calibrated such that the model generates the baseline scenario presented in section 3.4
α	Percentage of MOIS devoted to green innovation	0.44	Calibrated such that the model generates the baseline scenario presented in section 3.4
β_c	Parameter defining CO_2 intensity coefficient of conventional capital	0.09	Calibrated such that the model generates the baseline scenario presented in section 3.4
β_{gr}	Parameter defining CO_2 intensity coefficient of green capital	0.05	Based on Dafermos et al. (2017)
γ_0^{tech}	Autonomous component of firms' innovative spending	0.0328	Based on Deloitte's 2016-2017 Global CIO Survey
γ_1^{gr}	Autoregressive component of green investment	0.20	Calibrated such that the model generates the baseline scenario presented in section 3.4
γ_1^{tech}	Private non-green innovative spending following government MOIS	0.25	Calibrated such that the model generates the baseline scenario presented in section 3.4
γ_2^{gr}	Sensitivity of green investment to government MOIS	0.35	Calibrated such that the model generates the baseline scenario presented in section 3.4
γ_3^{gr}	Sensitivity of green investment to environmental damages	0.5	Calibrated such that the model generates the baseline scenario presented in section 3.4
γ_4^{gr}	Sensitivity of green investment to green consumption	0.02	Calibrated such that the model generates the baseline scenario presented in section 3.4
δ_c	Conventional capital depreciation rate	0.11	Based on World Bank data, 2019
δ_{gr}	Green capital depreciation rate	0.11	Based on World Bank data, 2019
ϵ	Energy intensity coefficient (initial value)	7.92	Based on Dafermos et al. (2017)
ϵ_{gr}	Energy intensity coefficient on green production	6.65	Based on Dafermos et al. (2017)
ζ	Portion of durable goods discarded every year	0.015	Based on Dafermos et al. (2017)
η_0	Initial value of risk premium	0.055	Calibrated such that the model generates the baseline scenario presented in section 3.4
η_1	Sensitivity of risk premium to global warming	0.05	Calibrated such that the model generates the baseline scenario presented in section 3.4
η_{en}	Share of renewable energy (initial value)	0.14	Based on Dafermos et al. (2017)
η_{gr}	Share of renewable energy linked with green production	0.4	Based on Dafermos et al. (2017)
θ	Profit retention rate of firms	0.2	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{10}	Parameter in portfolio equation for equity and shares	0.30	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{11}	Parameter in portfolio equation for equity and shares	0.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{12}	Parameter in portfolio equation for equity and shares	0.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{13}	Parameter in portfolio equation for equity and shares	0.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{14}	Parameter in portfolio equation for equity and shares	0.00	Horizontal constraint on coefficients for rates of return
λ_{20}	Parameter in portfolio equation for T-bills	0.30	Calibrated such that the model generates the baseline scenario presented in section 3.4

λ_{21}	Parameter in portfolio equation for T-bills	0.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{22}	Parameter in portfolio equation for T-bills	0.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{23}	Parameter in portfolio equation for T-bills	0.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{24}	Parameter in portfolio equation for T-bills	0.00	Horizontal constraint on coefficients for rates of return
λ_{30}	Parameter in portfolio equation for bank deposits	0.30	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{31}	Parameter in portfolio equation for bank deposits	0.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{32}	Parameter in portfolio equation for bank deposits	0.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{33}	Parameter in portfolio equation for bank deposits	0.00	Calibrated such that the model generates the baseline scenario presented in section 3.4
λ_{34}	Parameter in portfolio equation for bank deposits	0.00	Horizontal constraint on coefficients for rates of return
λ_w	Percentage of cash held by LC	010	Calibrated such that the model generates the baseline scenario presented in section 3.4
μ_b	Risk premium on T-bills	0.055	Calibrated such that the model generates the baseline scenario presented in section 3.4
μ_c	Matter intensity coefficient on conventional production	0.76	Based on Dafermos et al. (2017)
μ_{gr}	Matter intensity coefficient on green production	0.61	Based on Dafermos et al. (2017)
μ_l	Mark-up on interest rate for bank loans	0.055	Based on World Bank data, 2019
π	Adjustment coefficient of price expectations	0	Calibrated such that the model generates the baseline scenario presented in section 3.4
ρ_B	Percentage of reserve requirement	0.03	Calibrated such that the model generates the baseline scenario presented in section 3.4
ρ_{rec}	Recycling rate of discarded goods	0.24	Based on Dafermos et al. (2017)
σ_{en}^0	Autonomous component of non-renewable energy conversion rate	0.003	Based on Dafermos et al. (2017)
σ_{en}^1	Sensitivity of energy conversion rate to energy price	0.00001	Based on Dafermos et al. (2017)
σ_m^0	Autonomous component of matter conversion rate	0.0005	Based on Dafermos et al. (2017)
σ_m^1	Sensitivity of matter conversion rate to energy price	0.00001	Based on Dafermos et al. (2017)
τ_w	Average tax rate on LC's income	0.14	Based on World Bank data, 2019
τ_π	Average tax rate on UC's income	0.14	Based on World Bank data, 2019
ϕ	Sensitivity of investment share to utilisation gap	0.11	Calibrated such that the model generates the baseline scenario presented in section 3.4
ϕ_{11}	CO_2 transfer coefficient	0.9817	Based on Dafermos et al. (2017)
ϕ_{12}	CO_2 transfer coefficient	0.0183	Based on Dafermos et al. (2017)
ϕ_{21}	CO_2 transfer coefficient	0.0080	Based on Dafermos et al. (2017)
ϕ_{22}	CO_2 transfer coefficient	0.9915	Based on Dafermos et al. (2017)
ϕ_{23}	CO_2 transfer coefficient	0.0005	Based on Dafermos et al. (2017)
ϕ_{32}	CO_2 transfer coefficient	0.0001	Based on Dafermos et al. (2017)
ϕ_{33}	CO_2 transfer coefficient	0.9999	Based on Dafermos et al. (2017)
χ	Equity to capital ratio	0.001	Calibrated such that the model generates the baseline scenario presented in section 3.4
ψ	Gross percentage of new personal loans to disposable income	0.01	Calibrated such that the model generates the baseline scenario presented in section 3.4
ω	Wage share to total output	0.65	Based on World Bank data, 2019

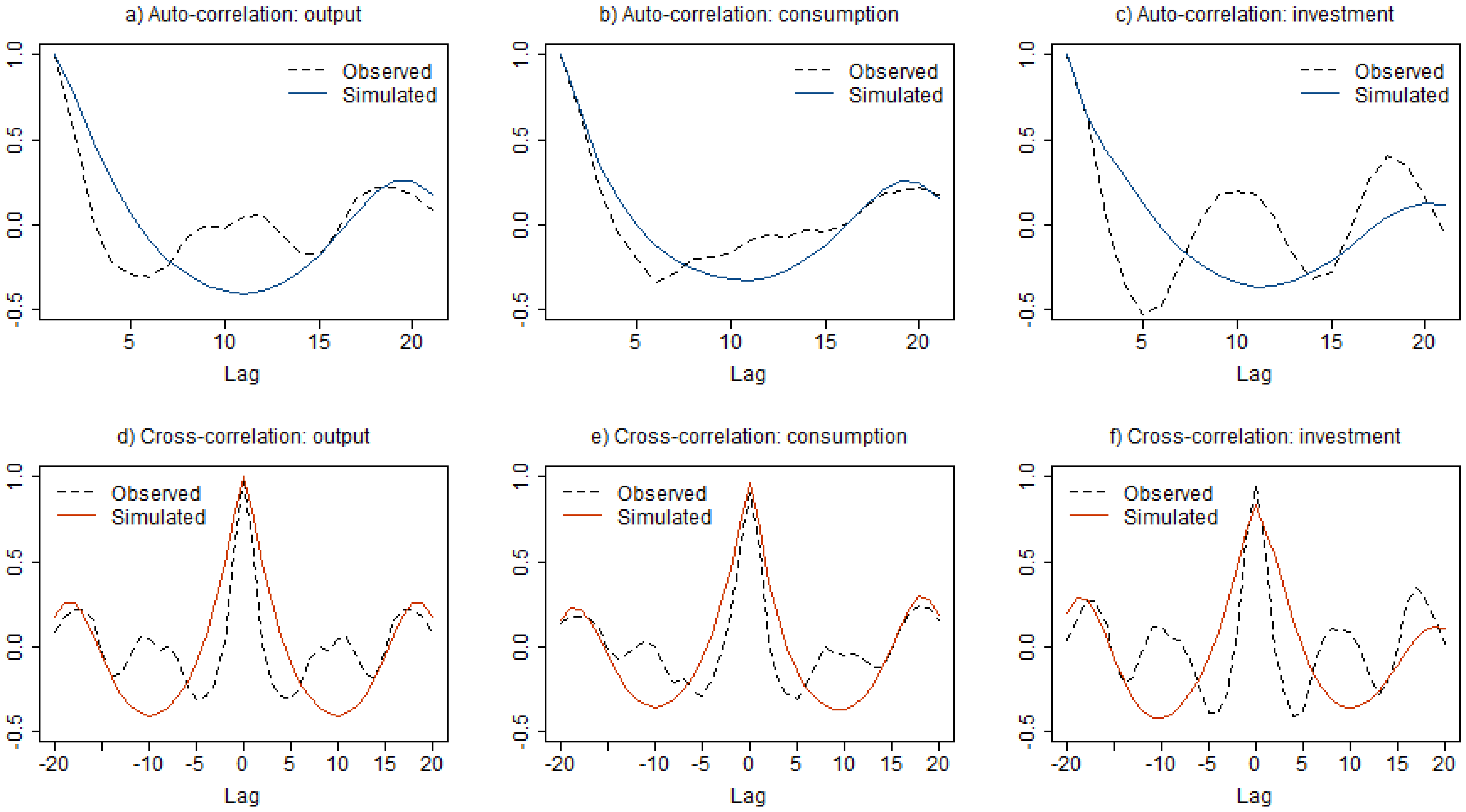
Figure B1. Potential output as determined by equations (153) to (159)


(a) Production function: economic contraints only (baseline)

(b) Production function including ecological constraints (baseline)

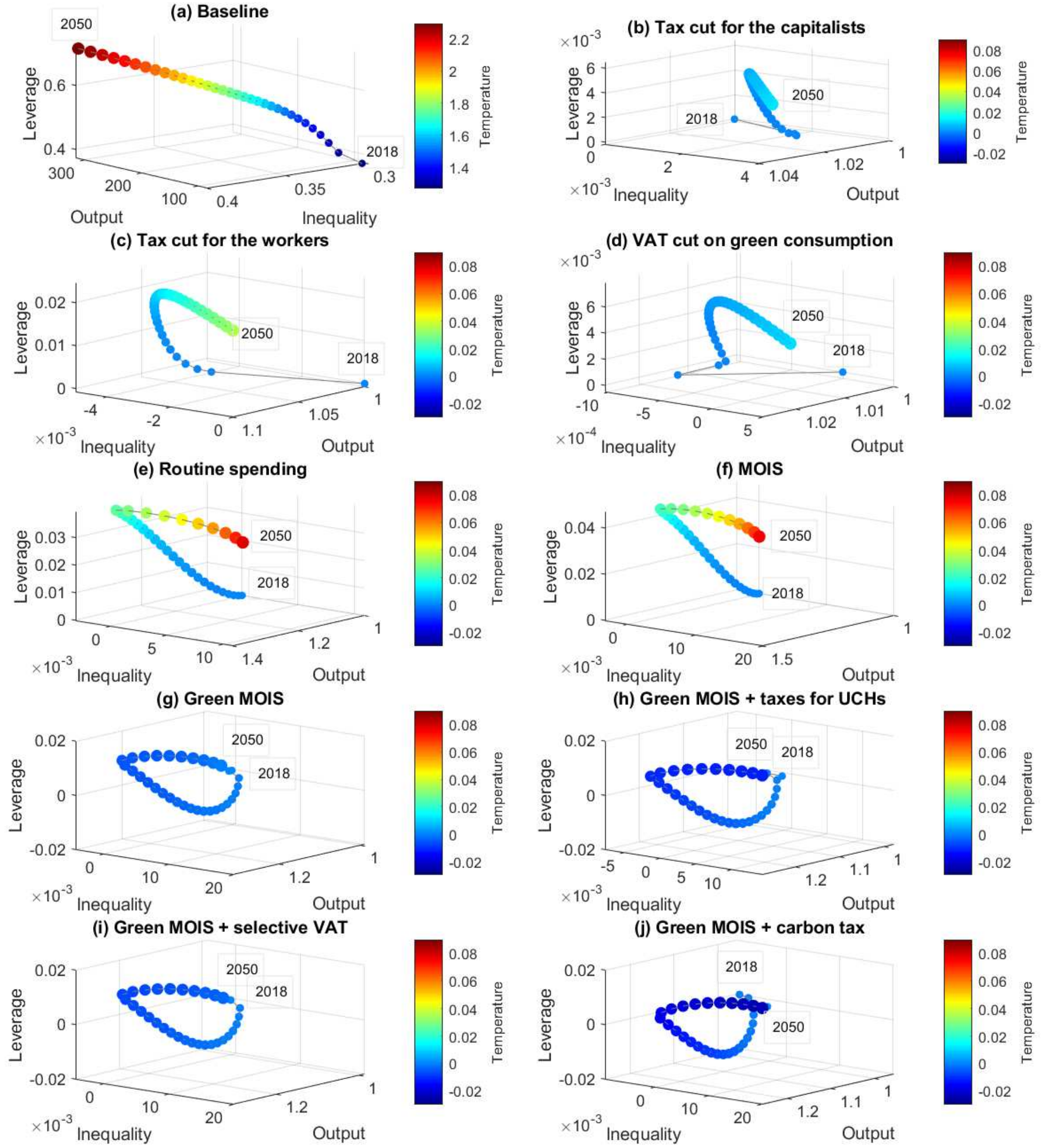
Note: ecologically-constrained output is defined by equation (158); economically-constrained output is defined by equation (157).

Figure B2. Auto- and cross-correlations of main output components: in-sample series vs. out-of-sample (predicted) series



Note: Series are all expressed in logarithms. A Hodrick-Prescott filter (with $\lambda = 100$) was used to separate the cyclical component of each series from its trend. Only the former is considered. Observed data refer to the period 1960-2018. Simulated series cover the period 2018-2050 (out-of-sample predictions).

Figure B3. Differential policy effects: a 5D comparison



Note: The five dimensions considered are: i) the economic sphere, which is expressed by real output (x axis); ii) the financial sphere, which is expressed by the leverage ratio of firms (y axis); iii) the ecosystem, which is expressed by the atmospheric temperature (colour); iv) the society, which is expressed by income inequality (z axis); v) the year of the observation (which determines the size of each marker and is sorted according to an ascending order). Variables in quadrant (a) are at their baseline values. By contrast, variables in quadrants (b) to (j) are calculated as ratios to (or differences with) baseline values.