



## GREENWICH POLITICAL ECONOMY RESEARCH CENTRE

# A stock-flow-fund ecological macroeconomic model

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**Abstract:** This paper develops a stock-flow-fund ecological macroeconomic model that combines the stock-flow consistent approach of Godley and Lavoie with the flow-fund model of Georgescu-Roegen. The model has the following key features. First, monetary and physical stocks and flows are explicitly formalised taking into account the accounting principles and the laws of thermodynamics. Second, Georgescu-Roegen's distinction between stock-flow and fund-service resources is adopted. Third, output is demand-determined but supply constraints might arise either due to environmental damages or due to the exhaustion of natural resources. Fourth, climate change influences directly the components of aggregate demand. Fifth, finance affects macroeconomic activity and the materialisation of investment plans that determine ecological efficiency. The model is calibrated using global data. Simulations are conducted to investigate the trajectories of key environmental, macroeconomic and financial variables under (i) different assumptions about the sensitivity of economic activity to the leverage ratio of firms and (ii) different types of green finance policies.

**Keywords:** Ecological macroeconomics, stock-flow consistent modelling, laws of thermodynamics, climate change, finance

**JEL codes:** E12, E44, Q54, Q57

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# A stock-flow-fund ecological macroeconomic model

## 1. Introduction

Ecological macroeconomics is an emerging interdisciplinary field that examines the macroeconomy as part of the ecosystem, taking explicitly into account the biophysical limits of a finite planet (Jackson, 2009; Rezai et al., 2013; Rezai and Stigl, 2016). It largely draws on the synthesis of ecological economics and post-Keynesian macroeconomics which has been identified as a fruitful avenue for the combined examination of economic and ecological issues (Mearman, 2009; Kronenberg, 2010; Fontana and Sawyer, 2013, 2016).

Recent research has contributed to the development of the building blocks of ecological macroeconomics. Victor and Rosenbluth (2007), Victor (2012) and Barker et al. (2012) have presented simulation econometric models with Keynesian features that incorporate various environmental issues. Jackson (2009), Fontana and Sawyer (2013), Rezai et al. (2013) and Taylor et al. (2016) have put forward theoretical frameworks that combine ecological with Keynesian (or post-Keynesian) insights. Berg et al. (2015), Jackson and Victor (2015), Naqvi (2015) and Fontana and Sawyer (2016) have examined environmental aspects within stock-flow consistent or monetary circuit models that include a financial sector.

However, there is still a lack of an integrated ecological macroeconomic model that combines physical variables with monetary variables in a consistent way. This paper develops such a model by combining the stock-flow consistent (SFC) approach of Godley and Lavoie (2007) with the flow-fund model of Georgescu-Roegen (1971, ch. 9; 1979; 1984). Our stock-flow-fund model has the following key features. monetary and physical stocks and flows are explicitly formalised taking into account the accounting principles and the laws of thermodynamics. Second, Georgescu-Roegen's distinction between stock-flow resources and fund-service resources is adopted. Third, output is demand-determined but supply

constraints might arise either due to environmental damages or due to the exhaustion of natural resources. Fourth, climate change influences directly the components of aggregate demand. Fifth, finance affects macroeconomic activity and the materialisation of investment plans that determine ecological efficiency. The model is calibrated using global data. Simulations are conducted to illustrate the channels through which the ecosystem, the financial system and the macroeconomy interact. Particular attention is paid to the non-neutral role of finance in the ecosystem-macroeconomy interactions.

The paper is organised as follows. Section 2 describes briefly the foundations of the model. Section 3 analyses the structure of the model. Section 4 presents our simulation analysis. Section 5 summarises and concludes.

## **2. Foundations of the model**

The key innovation of the post-Keynesian SFC approach developed by Godley and Lavoie (2007) is the integration of accounting into dynamic macro modelling. This integration permits the detailed exploration of the links between the real and the financial spheres of the macroeconomy. However, a prominent drawback of the SFC models is that they ignore the transformation of matter and energy that takes place due to economic processes and the environmental problems caused by this transformation. This feature comes in stark contrast with the fundamental propositions of ecological economists according to which the macroeconomy is part of the ecosystem and economic activity unavoidably respects the laws of thermodynamics (see Daly and Farley, 2011).

The flow-fund model of Georgescu-Roegen (1971, ch. 9; 1979; 1984) encapsulates the fundamental propositions of ecological economics. The model relies on a multi-process matrix that depicts the physical inflows and outflows that take place during the various economic processes, drawing explicitly on the First and the Second Law of Thermodynamics. The model also makes a crucial distinction between the stock-

flow resources and the fund-service resources (see also Mayumi, 2001; Kurz and Salvadori, 2003; Daly and Farley, 2011). The stock-flow resources (non-renewable energy and material resources) are transformed into what they produce (including by-products), can theoretically be used at any rate desired and can be stockpiled for future use. The fund-service resources (labour, capital and Ricardian land) are not embodied in the output produced, can be used only at specific rates and cannot be stockpiled for future use. Crucially, these types of resources are not substitutable: they are both necessary for the production process.

Our stock-flow-fund ecological macroeconomic model integrates the post-Keynesian SFC approach with Georgescu-Roegen's flow-fund model. The model that we develop relies on four matrices: 1) the physical flow matrix; 2) the physical stock-flow matrix; 3) the transactions flow matrix; 4) the balance sheet matrix. The first matrix is a simplification of the matrix that Georgescu-Roegen's used in his flow-fund model. The second matrix captures the dynamic interaction between physical stocks and flows and is a natural extension of the physical flow matrix. The third matrix and the fourth matrix describe the changes in the stocks and flows of the macroeconomic and the financial system, following the traditional formulations in the SFC literature.

In line with the post-Keynesian tradition, output in the model is determined by aggregate demand. However, supply-side constraints might arise primarily due to environmental problems. This is formalised by using a Leontief-type production function that specifies the supply-determined output drawing on Georgescu-Roegen's distinction between stock-flow and fund-service resources. It is assumed that environmental problems affect in a different way each type of resources. Depletion problems affect the stock-flow resources (i.e. non-renewable energy and material resources can be exhausted) while degradation problems, related to climate change and the accumulation of hazardous waste, damage the fund-service resources (by destroying them directly or by reducing their productivity). Climate change and its damages are modelled using standard specifications from the integrated assessment modelling literature

(see Nordhaus and Sztorc, 2013). However, a key departure from this literature is that global warming damages do not affect in our model an output determined via a neoclassical production function. Instead, they influence the fund-service resources of our Leontief-type production function and the components of aggregate demand.

### 3. Structure of the model

The model portrays the global macroeconomy without a government sector. There is one type of material good that can be used for durable consumption and (conventional and green) investment purposes. Firms produce this good by using: (i) matter which has to be extracted from the ground (non-metallic minerals and metal ores); (ii) matter that has been recycled using demolished/discarded socio-economic stock;<sup>1</sup> and (iii) energy that comes either from non-renewable sources (e.g. oil, gas and coal) or renewable sources (e.g. sun, wind).<sup>2</sup> The by-products of the production process are CO<sub>2</sub> emissions, waste and dissipated energy.<sup>3</sup>

Production can be made by using either green capital or conventional capital. Compared to conventional capital, green capital is characterised by lower energy intensity, lower material intensity and higher recycling rates. Moreover, green capital produces energy using renewable sources while conventional capital produces energy using the non-renewable sources. Hence, the use of green capital is conducive to a low-carbon economy.

Firms invest in conventional and green capital by using retained profits and loans. Banks impose credit rationing on firm loans, playing thereby a crucial role in the determination of output and the accumulation

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<sup>1</sup> The socio-economic stock includes capital goods and durable consumption goods.

<sup>2</sup> For brevity, the energy produced from (non-)renewable sources is henceforth referred to as (non-)renewable energy in the paper.

<sup>3</sup> For simplicity, the model does not incorporate energy and matter from biomass. However, the figure used for the share of renewable energy in our calibrations includes bioenergy to facilitate comparison with other studies.

of green capital. Households provide their labour services to firms. They buy durable consumption goods and accumulate wealth in the form of deposits. They do not take out loans. Commercial banks distribute all their profits to households. To avoid complications related to inflation, it is assumed that the price of consumption and investment goods is equal to unity. Using dollar (\$) as a reference currency, this means that each good values 1\$.

### 3.1 Ecosystem

Table 1 depicts the physical flow matrix of our model. This matrix captures the First and the Second Law of Thermodynamics. The First Law of Thermodynamics implies that energy and matter cannot be created or destroyed when they are transformed during the economic processes. This is reflected in the material and energy balance. The first column in Table 1 depicts the material balance in Gigatonnes (Gt).<sup>4</sup> According to this balance, the total inputs of matter into the socio-economic system over a year (extracted matter, the carbon mass of non-renewable energy and the oxygen included in CO<sub>2</sub> emissions) should be equal to the total outputs of matter over the same year (industrial CO<sub>2</sub> emissions and waste) plus the change in socio-economic stock. The second column in Table 1 depicts the energy balance in Exajoules (EJ). According to this balance, the total inputs of energy into the socio-economic system over a year should be equal to the total outputs of energy over the same year. Symbols with a plus sign denote inputs into the socio-economic system. Symbols with a minus sign denote outputs or changes in socio-economic stock. The Second Law of Thermodynamics is captured by the fact that the economic processes transform low-entropy energy (e.g. fossil fuels) into high-entropy dissipated energy (e.g. thermal energy).

<Insert Table 1 here>

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<sup>4</sup> For the use of the material balance in material flow accounting see Fischer-Kowalski et al. (2011).

Table 2 displays the physical stock-flow matrix of our model.<sup>5</sup> This matrix presents the dynamic change in those physical stocks that are considered more important for human activities. These are the material and non-renewable energy reserves, the atmospheric CO<sub>2</sub> concentration, the socio-economic stock and the stock of hazardous waste. The first row of the matrix shows the stocks of the previous year. The last row presents the stocks at the end of the current year after the additions to stocks and the reductions of stocks have taken place. Additions are denoted by a plus sign. Reductions are denoted by a minus sign.

<Insert Table 2 here>

The reserves of matter and non-renewable energy are those volumes expected to be produced economically using the existing technology. The reserves stem from the resources which are the volumes presenting technical difficulties, are costly to extract or have not yet been discovered. When resources are converted into reserves, it means that people have a higher stock of matter and energy to rely on for economic processes. Note that although this conversion is important for human activities, it does not represent a physical transformation.

Tables 1 and 2 imply that in our model the laws of thermodynamics are important for three reasons. First, the First Law of Thermodynamics allows us to incorporate explicitly the harmful by-products of energy and matter transformation (CO<sub>2</sub> emissions and hazardous material waste). As will be explained below, these by-products cause the degradation of ecosystem services with feedback effects on the economy. Second, the Second Law of Thermodynamics implies that in the very long run the economic processes cannot rely on the energy produced from fossil fuels. Since the fossil fuel resources are finite and the economic processes transform the low-entropy energy embodied in these resources into high-entropy energy, sustainability requires the reliance of economic processes on renewable energy sources (even if there was no climate change). Third, by combining the laws of thermodynamics with Georgescu-Roegen's

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<sup>5</sup> For a similar presentation of the physical stock-flow interactions see United Nations (2014).



analysis of material degradation, it turns out that recycling might not be sufficient to ensure the availability of the material resources that are necessary for the economic processes. Hence, the depletion of matter needs to be checked separately.

We proceed to describe the equations of the model that refer to the ecosystem.

### 3.1.1 Matter, recycling and waste

$$MY = \mu Y \quad (1)$$

$$M = MY - REC \quad (2)$$

$$REC = \rho DEM \quad (3)$$

$$DEM = \mu(\delta K_{-1} + \xi DC_{-1}) \quad (4)$$

$$SES = SES_{-1} + MY - DEM \quad (5)$$

$$W = M + CEN + O2 - EMIS_{IN} - \Delta SES \quad (6)$$

$$CEN = \frac{EMIS_{IN}}{car} \quad (7)$$

$$O2 = EMIS_{IN} - CEN \quad (8)$$

$$HWS = HWS_{-1} + hazW \quad (9)$$

$$hazrario = \frac{HWS}{SURF} \quad (10)$$

$$REV_M = REV_{M-1} + CON_M - M \quad (11)$$

$$CON_M = con_M RES_{M-1} \quad (12)$$

$$RES_M = RES_{M-1} - CON_M \quad (13)$$

$$dep_M = \frac{M}{REV_{M-1}} \quad (14)$$

The goods produced every year ( $Y$ ) embody a specific amount of matter,  $MY$  (Eq. 1). Material intensity ( $\mu$ ) is defined as the matter included in each output produced. Not all of the matter embodied in the produced output needs to be extracted from the ground ( $M$ ). As shown in Eqs. (2) and (3), a part of  $MY$  comes from the amount of demolished/discarded socio-economic stock that is recycled ( $REC$ );  $\rho$  denotes the recycling rate. The demolished/discarded socio-economic stock ( $DEM$ ) is equal to the material content of the depreciated capital goods and the end-of-life durable consumption goods (Eq. 4);  $\delta$  is the depreciation rate of capital goods ( $K$ ) and  $\xi$  is the proportion of durable consumption goods ( $DC$ ) discarded every year. Eq. (5) shows that the socio-economic stock ( $SES$ ) increases as a result of the production of new goods and decreases due to the demolition/discard of old material goods.

Eq. (6) reflects the material balance depicted in Table 1. The waste ( $W$ ) generated during the production process is used as a residual. Regarding non-renewable energy, only its carbon mass,  $CEN$ , has been included as input in the material balance. As shown in Eq. (7), this is estimated from the industrial emissions ( $EMIS_{IN}$ ) by using the conversion rate of Gt of carbon into Gt of  $CO_2$  ( $car$ ). Carbon exits the socio-economic system in the form of  $CO_2$  emissions. Oxygen ( $O_2$ ) is introduced as an input in the material balance because it is necessary in the fossil fuel combustion process. Eq. (8) gives the mass of the oxygen that is part of the  $CO_2$  emissions. Note that by combining Eqs. (2), (5), (6) and (8) it can be easily shown that  $W = DEM - REC$ .

Only a small proportion ( $haz$ ) of the waste produced every year is hazardous, i.e. it is harmful to human health or the environment.<sup>6</sup> This hazardous waste is added to the accumulated stock of hazardous waste,  $HWS$  (Eq. 9). Eq. (10) defines the hazardous waste accumulation ratio which expresses the accumulated stock of hazardous waste in Gt per million  $km^2$  of earth surface ( $SURF$ ).

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<sup>6</sup> Asbestos, heavy metals and fluoride compounds are examples of hazardous waste. For an analysis of hazardous waste and its impact on health and the environment see Misra and Pandey (2005).

The material stock-flow dynamics are presented in Eqs. (11)-(14). Eq. (11) shows that the material reserves ( $REV_M$ ) decline when matter is extracted and increase when resources are converted into reserves. The annual conversion ( $CON_M$ ) is given by Eq. (12). An exogenous conversion rate,  $con_M$ , has been assumed. Eq. (13) describes the change in material resources ( $RES_M$ ). To capture the scarcity of matter we define the matter depletion ratio ( $dep_M$ ), which is the ratio of matter that is extracted every year relative to the remaining material reserves (Eq. 14). The higher this ratio the greater the matter depletion problems.

### 3.1.2 Energy

$$E = \varepsilon Y \quad (15)$$

$$ER = \theta E \quad (16)$$

$$EN = E - ER \quad (17)$$

$$ED = EN + ER \quad (18)$$

$$REV_E = REV_{E-1} + CON_E - EN \quad (19)$$

$$CON_E = con_E RES_{E-1} \quad (20)$$

$$RES_E = RES_{E-1} - CON_E \quad (21)$$

$$dep_E = \frac{EN}{REV_{E-1}} \quad (22)$$

The energy required for production ( $E$ ) is a function of output (Eq. 15). When energy intensity ( $\varepsilon$ ) declines, the energy required per unit of output becomes lower. As shown in Eqs. (16) and (17), energy is generated either from renewable ( $ER$ ) or non-renewable sources ( $EN$ ). The share of renewable energy in total energy is denoted by  $\theta$ . The dissipated energy ( $ED$ ) is determined based on the energy balance (Eq. 18).

Eqs. (19)-(22) represent the stock-flow dynamics of the energy produced from non-renewables. Eq. (19) shows the change in the non-renewable energy reserves ( $REV_E$ ).  $CON_E$  denotes the amount of resources converted into reserves every year. This amount is determined by Eq. (20), where  $con_E$  is the conversion rate. The resources of non-renewable energy ( $RES_E$ ) change every year according to Eq. (21). The energy depletion ratio, which captures scarcity problems, shows the extracted energy relative to the remaining reserves (Eq. 22).

### 3.1.3 Emissions and climate change

$$EMIS_{IN} = \omega EN \quad (23)$$

$$EMIS_L = EMIS_{L-1}(1-lr) \quad (24)$$

$$EMIS = EMIS_{IN} + EMIS_L \quad (25)$$

$$CO2_{AT} = EMIS + \phi_1 CO2_{AT-1} + \phi_2 CO2_{UP-1} \quad (26)$$

$$CO2_{UP} = \phi_2 CO2_{AT-1} + \phi_2 CO2_{UP-1} + \phi_3 CO2_{LO-1} \quad (27)$$

$$CO2_{LO} = \phi_3 CO2_{UP-1} + \phi_3 CO2_{LO-1} \quad (28)$$

$$F = F_{2 \times CO2} \log_2 \frac{CO2_{AT}}{CO2_{AT-PRE}} + F_{EX} \quad (29)$$

$$F_{EX} = F_{EX-1} + fex \quad (30)$$

$$T_{AT} = T_{AT-1} + t_1 \left( F - \frac{F_{2 \times CO2}}{S} T_{AT-1} - t_2 (T_{AT-1} - T_{LO-1}) \right) \quad (31)$$

$$T_{LO} = T_{LO-1} + t_3 (T_{AT-1} - T_{LO-1}) \quad (32)$$

Our formalisation of emissions and climate change follows closely the traditional integrated assessment models (see Nordhaus and Sztorc, 2013). Every year industrial CO<sub>2</sub> emissions ( $EMIS_{IN}$ ) are generated due to the use of the non-renewable energy sources (Eq. 23). CO<sub>2</sub> intensity ( $\omega$ ) is defined as the industrial emissions produced per unit of non-renewable energy. Every year land-use CO<sub>2</sub> emissions ( $EMIS_L$ ) are

also generated because of changes in the use of land (Eq. 24). These emissions are assumed to decline exogenously at a rate  $lr$ . Eq. (25) gives the total emissions ( $EMIS$ ).

The atmospheric  $CO_2$  concentration ( $CO2_{AT}$ ) is driven by these emissions and the carbon cycle. The carbon cycle, represented by Eqs. (26)-(28), shows that every year there is exchange of carbon between the atmosphere and the upper ocean/biosphere and between the upper ocean/biosphere and the lower ocean;  $CO2_{UP}$  is the upper ocean/biosphere  $CO_2$  concentration and  $CO2_{LO}$  is the lower ocean  $CO_2$  concentration. The higher the net transfers of carbon from the atmosphere into the other two reservoirs the lower the atmospheric  $CO_2$  concentration. The accumulation of atmospheric  $CO_2$  and other greenhouse gases increases radiative forcing,  $F$  (Eq. 29), placing upward pressures on the atmospheric temperature,  $T_{AT}$  (Eq. 31).  $F_{2\times CO_2}$  is the increase in radiative forcing (since the pre-industrial period) due to doubling of  $CO_2$  concentrations from pre-industrial levels ( $CO2_{AT-PRE}$ ). For simplicity, the radiative forcing due to non- $CO_2$  greenhouse gas emissions ( $F_{EX}$ ) is determined exogenously (Eq. 30). Eq. (32) shows the change in the temperature of the lower ocean ( $T_{LO}$ ).

### 3.1.4 Ecological efficiency and technology

$$\omega = \omega_{-1}(1 + g_\omega) \quad (33)$$

$$g_\omega = g_{\omega-1}(1 - \zeta_1) \quad (34)$$

$$\mu = \kappa_{-1}\mu_G + (1 - \kappa_{-1})\mu_C \quad (35)$$

$$\mu_G = \mu_{G-1}(1 + g_{\mu G}) \quad (36)$$

$$g_{\mu G} = g_{\mu G-1}(1 - \zeta_2) \quad (37)$$

$$\rho = \kappa_{-1}\rho_G + (1 - \kappa_{-1})\rho_C \quad (38)$$

$$\rho_G = \rho_{G-1}(1 + g_{\rho G}) \quad (39)$$

$$g_{\rho G} = g_{\rho G-1}(1 - \zeta_3) \quad (40)$$

$$\varepsilon = \kappa_{-1}\varepsilon_G + (1 - \kappa_{-1})\varepsilon_C \quad (41)$$

$$\varepsilon_G = \varepsilon_{G-1}(1 + g_{\varepsilon G}) \quad (42)$$

$$g_{\varepsilon G} = g_{\varepsilon G-1}(1 - \zeta_4) \quad (43)$$

$$\theta = \left( 1 + \frac{1}{\pi(K_{G-1}/K_{C-1})} \right)^{-1} \quad (44)$$

The ecological efficiency of production is considered to be higher the lower is the energy, material and CO<sub>2</sub> intensity and the higher is the recycling rate. Ecological efficiency also increases when the share of renewable energy in total energy goes up. CO<sub>2</sub> intensity changes in an exogenous way. As shown in Eqs. (33) and (34), every year technical progress reduces CO<sub>2</sub> intensity with a declining rate ( $g_{\omega} < 0$  and  $\zeta_1 > 0$ ).<sup>7</sup> Material intensity, energy intensity and recycling rate are not affected only by exogenous technical progress. Since green capital is characterised by lower material and energy intensity and by higher recycling rate, the efficiency related to these indicators increases when the ratio,  $\kappa$ , of green capital ( $K_G$ ) to total capital ( $K$ ) rises. This is shown in Eqs. (35), (38) and (41) where  $\mu_G$ ,  $\rho_G$  and  $\varepsilon_G$  denote, respectively, the material intensity, recycling rate and energy intensity of green capital and  $\mu_C$ ,  $\rho_C$  and  $\varepsilon_C$  are the respective indicators for conventional capital. Eqs. (36), (37), (39), (40), (42) and (43) reflect the fact that exogenous technical progress improves (with a declining rate) the ecological efficiency of green capital ( $g_{\mu G} < 0$ ,  $g_{\rho G} > 0$ ,  $g_{\varepsilon G} < 0$ ,  $\zeta_2 > 0$ ,  $\zeta_3 > 0$  and  $\zeta_4 > 0$ ). The ecological efficiency of conventional capital is assumed to be constant. The share of renewable energy in total energy ( $\theta$ ) is higher the higher is the ratio of green capital stock to conventional capital stock (Eq. 44).

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<sup>7</sup> See Nordhaus and Sutorc (2013) for a similar assumption.

### ***3.2 Macroeconomy and financial system***

Table 3 and Table 4 portray the transactions flow matrix and the balance sheet matrix of our macroeconomy (these types of matrices have been presented in detail by Godley and Lavoie, 2007). The transactions flow matrix shows the transactions that take place between the various sectors of the economy (each row represents a category of transactions). For each sector inflows are denoted by a plus sign and outflows are denoted by a minus sign. The upper part of the matrix shows transactions related to the revenues and expenditures of the various sectors. The bottom part of the matrix indicates changes in financial assets and liabilities that arise from transactions. The columns represent the budget constraints of the sectors. For firms and commercial banks a distinction is made between current and capital accounts. The current accounts register payments made or received. The capital accounts show the changes in assets and liabilities as well as the funds that are used to finance investment (in the case of firms). At the aggregate level, monetary inflows are equal to monetary outflows.

<Insert Table 3 here>

Table 4 shows the assets and the liabilities of the sectors. We use a plus sign for the assets and a minus sign for the liabilities. Households and firms have non-zero net worth. Commercial banks have a zero net worth due to the assumption that they distribute all their profits. Accounting requires that at the aggregate level financial assets are equal to financial liabilities. Hence, the net worth of the economy is equal to the real assets which include the capital stock of firms and the durable consumption goods of households.

<Insert Table 4 here>

In the next subsections we present the equations for the macroeconomy and the financial system.

### 3.2.1 Output determination and damages

$$Y_M^* = \frac{REV_{M-1} + REC}{\mu} \quad (45)$$

$$Y_E^* = \frac{REV_{E-1}}{(1-\theta)\epsilon} \quad (46)$$

$$Y_K^* = vK \quad (47)$$

$$Y_N^* = \lambda hLF \quad (48)$$

$$Y^* = \min(Y_M^*, Y_E^*, Y_K^*, Y_N^*) \quad (49)$$

$$Y = C + I \quad (50)$$

$$um = \frac{Y}{Y_M^*} \quad (51)$$

$$ue = \frac{Y}{Y_E^*} \quad (52)$$

$$u = \frac{Y}{Y_K^*} \quad (53)$$

$$re = \frac{Y}{Y_N^*} \quad (54)$$

$$D_T = 1 - \frac{1}{1 + \eta_1 T_{AT} + \eta_2 T_{AT}^2 + \eta_3 T_{AT}^{6.754}} \quad (55)$$

$$D_{TP} = pD_T \quad (56)$$

$$D_{TF} = 1 - \frac{1 - D_T}{1 - D_{TP}} \quad (57)$$

We assume a Leontief-type production function that incorporates Georgescu-Roegen's distinction between stock-flow and fund-service resources. The stock-flow resources are matter and non-renewable energy. The fund-service resources are labour and capital. We define four different types of potential output. The matter-determined potential output ( $Y_M^*$ ) is defined in Eq. (45) and is higher the higher are the material reserves, the higher is the recycled matter and the lower is the material intensity. The energy-determined



potential output ( $Y_E^*$ ) is defined in Eq. (46) and is higher the higher are the non-renewable energy reserves, the lower is the energy intensity and the higher is the share of renewable energy in total energy. The capital-determined potential output ( $Y_K^*$ ) is defined in Eq. (47) and is higher the higher is the capital stock and the productivity of capital ( $v$ ). Lastly, the labour-determined potential output ( $Y_N^*$ ) is defined in Eq. (48) and is higher the higher is the labour force ( $LF$ ), the hourly labour productivity ( $\lambda$ ) and the annual working hours per employee ( $h$ ). The overall potential output ( $Y^*$ ) is the minimum of all these potential outputs (Eq. 49).

In line with the post-Keynesian tradition, actual output ( $Y$ ) is demand-determined (Eq. 50): it is equal to consumption demand ( $C$ ) plus investment demand ( $I$ ). However, as shown in Eqs. (62)-(67) below, demand is not independent of supply. When actual output approaches potential output, demand tends to decline as a result of supply-side constraints. We define four ratios which capture the extent to which potential output is utilised (Eqs. 51-54). The first two ratios are the matter utilisation rate ( $um$ ) and the energy utilisation rate ( $ue$ ), which refer to the use of stock-flow resources. When these ratios increase, the output produced approaches the potential output determined by the material and energy reserves. The last two ratios are the utilisation rate ( $u$ ) and the rate of employment ( $re$ ) which refer to the use of fund-service resources. A rise in these ratios reflects a higher scarcity of capital and labour.

Global warming causes damages to the fund-service resources (capital and labour), reducing thereby the potential output determined by them. There are two types of damages: the damages that affect directly the funds (capital stock and labour force) and the damages that affect the productivities of the funds (capital productivity and labour productivity). Capital stock is affected because climate change can destroy infrastructure by causing storms or inundations, or it can trigger the abandonment of capital in coastal areas by causing a rise in the sea level (see Dietz and Stern, 2015; Naqvi, 2015; Taylor et al., 2016). Labour force can be reduced since climate change can adversely affect morbidity, mortality, air quality and the

vector and proliferation of infectious diseases. It can also lead to storms and floods that injure and kill people (Toll, 2002). All these phenomena might reduce the population or the proportion of the population that can participate in the labour force. Capital productivity can be driven down since climate change might create a hostile environment that can reduce the ability of firms to use capital effectively (Stern, 2013; Dietz and Stern, 2015). Finally, by affecting the health of the workers, the rise in temperature might decrease their ability to perform work tasks, reducing labour productivity (Kjellstrom et al., 2009; Dell et al., 2014; Taylor et al., 2016).

Aggregate demand is affected by these damages in two ways. First, the catastrophes caused by climate change might increase the fears of entrepreneurs that their capital will be destroyed or that it will have very low returns. This reduces their desired investment.<sup>8</sup> Moreover, observing the natural disasters and the health problems, households might be induced to save more for precautionary reasons. This can lead to less consumption. Measures that restrict consumption directly might also be adopted. Second, since global warming damages tends to reduce  $Y_K^*$  and  $Y_N^*$ , they place upward pressures on  $u$  and  $re$ . As mentioned above, this rise in the scarcity of capital and labour can reduce demand.

Importantly, societies do not react passively to the climate change-related effects on fund-service resources. They take adaptation measures that limit global warming damages. Following de Bruin et al. (2009), we thereby make a distinction between gross damages and net damages. Gross damages are the initial damages caused by climate change if there were no adaptation measures and net damages are the damages that remain after the implementation of adaptation measures.<sup>9</sup>

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<sup>8</sup> Taylor et al. (2016) have postulated a negative impact of climate change on investment demand by assuming that greenhouse gas concentration reduces the profit share.

<sup>9</sup> We do not include the financial cost of the adaptation measures in net damages.

Eq. (55) is the damage function, which shows how atmospheric temperature and damages are linked.  $D_T$  is the proportional gross damage which lies between 0 (no damage) and 1 (complete catastrophe). The form of Eq. (55) has been suggested by Weitzman (2012) who argues that the quadratic forms of damage functions used in the traditional literature of integrated assessment models do not adequately capture high-temperature damages. This issue is tackled by inserting the term  $\eta_3 T_{AT}^{6.754}$  where  $\eta_3$  and the corresponding exponent have been selected such that  $D_T = 0.5$  when  $T_{AT} = 6^\circ\text{C}$ .

In most integrated assessments models  $D_T$  affects directly the supply-determined output. On the contrary, as mentioned above, in our model  $D_T$  affects the potential output and the aggregate demand. Hence, the variable  $D_T$  enters into both (i) the determination of funds and their productivities (see Eqs. 84, 85, 88 and 96) and (ii) the consumption and investment demand (see Eqs. 62 and 93). It is also necessary to partition the gross damage between the fund ( $D_{TF}$ ) and its productivity ( $D_{TP}$ ), so as to warrant that when  $D_T = x$  the capital-determined potential output and the labour-determined potential output would be reduced by  $x\%$  if there were no adaptation measures. This is done by Eqs. (56) and (57).<sup>10</sup>

The impact of adaptation is captured by the parameters  $ad_p$ ,  $ad_K$  and  $ad_{LF}$  that represent the proportion of the gross damage (of productivity, capital stock and labour force respectively) which is eliminated due to adaptation measures. We have that  $0 \leq ad_p, ad_K, ad_{LF} \leq 1$ . This means that, for example, the proportional net damage to productivity is given by  $(1 - ad_p)D_{TP}$ . We assume that adaptation does not affect investment and consumption demand: firms and households make decisions based on gross damages.

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<sup>10</sup> See also Moyer et al. (2015).

### 3.2.2 Firms

$$TP = Y - wN - int_C L_{C-1} - int_G L_{G-1} - \delta K_{-1} \quad (58)$$

$$RP = s_F TP_{-1} \quad (59)$$

$$DP = TP - RP \quad (60)$$

$$r = RP/K \quad (61)$$

$$I^D = [(\alpha_0 + \alpha_1 r_{-1} + \alpha_2 u_{-1} - \alpha_3 g_{\varepsilon-1})K_{-1} + \delta K_{-1}](1 - D_{T-1}) \quad (62)$$

$$\alpha_0 = \alpha_{00} - \gamma_1 (um_{-1} - um_T) - \gamma_2 (ue_{-1} - ue_T) - \gamma_3 (u_{-1} - u_T) - \gamma_4 (re_{-1} - re_T) \quad (63)$$

$$\gamma_1 = \gamma_{10} \text{ iff } um_{-1} \geq um_T; \text{ otherwise } \gamma_1 = 0 \quad (64)$$

$$\gamma_2 = \gamma_{20} \text{ iff } ue_{-1} \geq ue_T; \text{ otherwise } \gamma_2 = 0 \quad (65)$$

$$\gamma_3 = \gamma_{30} \text{ iff } u_{-1} \geq u_T; \text{ otherwise } \gamma_3 = 0 \quad (66)$$

$$\gamma_4 = \gamma_{40} \text{ iff } re_{-1} \geq re_T; \text{ otherwise } \gamma_4 = 0 \quad (67)$$

$$I_G^D = \beta I^D \quad (68)$$

$$I_C^D = I^D - I_G^D \quad (69)$$

$$\beta = \beta_0 + \beta_1 - \beta_2 (int_G - int_C) + \beta_3 D_{T-1} \quad (70)$$

$$\beta_0 = \beta_{0-1} (1 + g_{\beta 0}) \quad (71)$$

$$g_{\beta 0} = g_{\beta 0-1} (1 - \zeta_5) \quad (72)$$

$$NL_G^D = I_G^D - \beta RP + rep L_{G-1} - \delta K_{G-1} \quad (73)$$

$$NL_C^D = I_C^D - (1 - \beta) RP + rep L_{C-1} - \delta K_{C-1} \quad (74)$$

$$I_G = \beta RP + (L_G - L_{G-1}) + \delta K_{G-1} \quad (75)$$

$$I_C = RP + (L_C - L_{C-1}) + (L_G - L_{G-1}) + \delta K_{-1} - I_G \quad (76)$$

$$I = I_C + I_G \quad (77)$$

$$L = L_C + L_G \quad (78)$$

$$K_G = K_{G-1} + I_G - \delta K_{G-1} \quad (79)$$

$$K_C = K_{C-1} + I_C - \delta K_{C-1} \quad (80)$$

$$K = K_C + K_G \quad (81)$$

$$\kappa = K_G / K \quad (82)$$

$$lev = L/K \quad (83)$$

$$\delta = \delta_0 + (1 - \delta_0)(1 - ad_K)D_{TF-1} \quad (84)$$

$$v = v_{-1}(1 + g_v)[1 - (1 - ad_P)D_{TP-1}] \quad (85)$$

$$g_\lambda = \sigma_0 + \sigma_1 + \sigma_2 g_{Y-1} \quad (86)$$

$$\sigma_0 = \sigma_{0-1}(1 - \zeta_6) \quad (87)$$

$$\lambda = \lambda_{-1}(1 + g_\lambda)[1 - (1 - ad_P)D_{TP-1}] \quad (88)$$

$$w = s_W \lambda h \quad (89)$$

$$N = \frac{Y}{h\lambda} \quad (90)$$

$$ur = 1 - re \quad (91)$$

The total profits of firms ( $TP$ ) are given by equation (58);  $w$  is the wage rate,  $N$  is the number of employed workers,  $int_C$  is the interest rate on conventional loans,  $int_G$  is the interest rate on green loans,  $L_C$  is the amount of conventional loans,  $L_G$  is the amount of green loans and  $\delta$  is the depreciation of capital stock (which is assumed to be the same for green capital and conventional capital). Firms' retained profits ( $RP$ ) are a proportion ( $s_F$ ) of their total profits (Eq. 59). The distributed profits of firms ( $DP$ ) are determined as a residual (Eq. 60). Eq. (61) gives the rate of retained profits ( $r$ ).

Firms' investment is formalised as a two-stage process. At a first stage, firms decide their overall desired investment in both green and conventional capital. At a second stage, they allocate their desired investment between the two types of capital. Eq. (62) captures the first stage. The desired investment ( $ID$ ), adjusted for the damage effect, is equal to net investment plus the depreciated capital. As in most Kaleckian models, net investment is a positive function of the rate of (retained) profits and the rate of capacity utilisation. We also postulate that investment depends on the growth rate of energy intensity ( $g_\varepsilon$ ) to capture the rebound

effect associated with a lower growth rate of energy intensity. The idea is that a lower energy intensity reduces the costs of production inducing firms to invest more. This increases their energy use outweighing partially the beneficial effects of a lower energy intensity.<sup>11</sup>

Eqs. (62)-(67) show that investment demand is reduced when actual output approaches potential output ( $\gamma_{10}, \gamma_{20}, \gamma_{30}, \gamma_{40} > 0$ ). In particular, when the utilisation of matter passes the  $um_T$  threshold and/or the utilisation of energy passes the  $ue_T$  threshold, investment demand is curbed because the prices of matter and energy rise significantly as a result of scarcity, leading to higher production costs. Additionally, when the rate of capacity utilisation and the rate of employment are higher than the thresholds  $u_T$  and  $re_T$  respectively, labour and capital shortages could lead to rising wages and prices that, under certain conditions, affect negatively investment demand. Labour shortages also make firms uncertain about their ability to recruit workers, deteriorating business confidence (see Ryoo and Skott, 2008; Lavoie, 2014, ch. 6).

The second stage of the investment process is reflected in Eqs. (68)-(72). At this stage firms decide about the proportion,  $\beta$ , of green investment ( $I_C^D$ ) in the overall desired investment (Eq. 68). Desired conventional investment ( $I_C^D$ ) is determined as a residual (Eq. 69). The proportion of green investment depends on three factors (Eq. 70). The first factor is captured by the term  $\beta_0 + \beta_1$  which reflects exogenous developments, such as the cost of installing and using green capital relative to conventional capital or institutional changes that promote green investment. It is assumed that  $\beta_0$  increases every year but with a declining rate (Eqs. 71-72).  $\beta_1$  is constant but can change due to exogenous institutional or technology shocks. The second factor is the divergence between the interest rate on green loans and the

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<sup>11</sup> For a description of the rebound effects see Barker et al. (2009). In our model firms' payments on energy are netted out due to the consolidation of the firm sector. Therefore, a lower energy intensity does not affect the aggregate profitability of firms. However, it is crucial to incorporate the expansionary effect of lower energy intensity into the investment function; otherwise, improvements in energy efficiency would have only beneficial effects on energy use.

interest rate on conventional loans. The interest rate differential captures the borrowing cost of investing in green capital relative to conventional capital.<sup>12</sup> The third factor is captured by the variable  $D_T$  which reflects the fact that climate change might lead to mitigation measures that promote green investment or may induce entrepreneurs to make investments that are conducive to less environmental damage.

Due to the existence of credit rationing, only a proportion of the new loans that are demanded by firms are provided by banks.<sup>13</sup> Eq. (73) gives the desired new green loans ( $NL_G^D$ ) and Eq. (74) gives the desired new conventional loans ( $NL_C^D$ ). The green, conventional and total investment goods after credit rationing are shown in Eqs. (75), (76) and (77);  $I_G$  is green investment and  $I_C$  is conventional investment. The total loans of firms ( $L$ ) are equal to conventional loans plus green loans (Eq. 78). The change in green and conventional capital stock is equal to gross investment minus the depreciation of capital (Eqs. 79 and 80). Eq. (81) shows that total capital ( $K$ ) is equal to conventional capital ( $K_C$ ) plus green capital ( $K_G$ ). The ratio of green capital to total capital is given by Eq. (82). The leverage ratio of firms ( $lev$ ) is defined in Eq. (83).

Eq. (84) shows the rate of capital depreciation. Interestingly, a higher depreciation due to climate change has two countervailing effects on economic growth. On the one hand, capital-determined potential output is reduced, placing adverse supply-side effects on economic activity (see Eq. 47). On the other hand, aggregate demand tends to increase because a higher depreciation leads to higher gross investment (see Eq. 62).

Eqs. (85)-(88) refer to capital and labour productivity. As argued above, both productivities are influenced by climate change. Capital productivity, before damages, is assumed to grow at an exogenous rate,  $g_v$ .

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<sup>12</sup> For some empirical evidence about the effects of interest rates on green investment see Eyraud et al. (2013).

<sup>13</sup> See also Dafermos (2012) and Nikolaidi (2014).

Labour productivity is affected by exogenous technology factors reflected in the term  $\sigma_0 + \sigma_1$ . These factors increase productivity growth every year but with a declining rate. Also, in line with the Kaldor-Verdoorn law (see Lavoie, 2014, ch. 6), the growth rate of labour productivity is positively affected by the growth rate of output ( $g_Y$ ). Note that, although a lower labour productivity can reduce the unemployment rate for a given level of output, it has adverse effects on the supply side by driving down the labour-determined potential output (see Eq. 48).

Eq. (89) gives the wage rate. The wage share ( $s_w$ ) is assumed to be exogenous. The number of employees is determined by Eq. (90). The unemployment rate is defined in Eq. (91).

### 3.2.3 Households

$$Y_H = wN + DP + BP + int_D D_{-1} \quad (92)$$

$$C = (c_1 Y_{H-1} + c_2 D_{-1})(1 - D_{T-1}) \quad (93)$$

$$D = D_{-1} + Y_H - C \quad (94)$$

$$DC = DC_{-1} + C - \xi DC_{-1} \quad (95)$$

$$LF = LF_{-1}(1 + g_{LF})[1 - (1 - ad_{LF})D_{TF-1}] \quad (96)$$

$$g_{LF} = lf_0 + lf_1 - lf_2 ur_{-1} - lf_3 hazratio_{-1} \quad (97)$$

$$lf_0 = lf_{0-1}(1 - \zeta_7) \quad (98)$$

Eq. (92) gives the disposable income of households ( $Y_H$ );  $BP$  denotes the profits of banks,  $int_D$  is the interest rate on deposits and  $D$  is the amount of deposits. Households' consumption, adjusted for global warming damages, depends on lagged income (which is a proxy for the expected one) and lagged deposits (Eq. 93). Recall that all consumption goods in our economy are durable (i.e. they have a life higher than



one year). Every year the stock of durable goods increases due to the production of new consumption goods and decreases due to the discard of the accumulated durable goods (Eq. 95).

As mentioned above, climate change reduces labour force (Eq. 96). However, there are three additional factors that drive the change in labour force (Eq. 97). First, in line with the population projections of United Nations (2015), there are some fundamental dynamics that influence fertility and mortality and tend to reduce the growth rate of the population (and, thus, the growth rate of the labour force). This is reflected in the term  $lf_0 + lf_1$ . Second, a higher unemployment rate places downward pressures on the growth rate of the labour force. This is because unemployment (i) adversely affects mortality/fertility and suicidal behaviour (see Clemens et al., 2011) and (ii) discourages people's participation in the labour force. Third, the accumulation of hazardous waste creates health problems (e.g. carcinogenesis, congenital anomalies) that affect labour force growth.

### 3.2.4 Banks

$$BP = int_C L_{C-1} + int_G L_{G-1} - int_D D_{-1} \quad (99)$$

$$CR_C = r_0 + r_1 lev_{-1} \quad (100)$$

$$CR_G = l_0 + l_1 lev_{-1} \quad (101)$$

$$L_C = L_{C-1} + (1 - CR_C) NL_C^D - rep L_{C-1} \quad (102)$$

$$L_G = L_{G-1} + (1 - CR_G) NL_G^D - rep L_{G-1} \quad (103)$$

$$D = L \quad (104\text{-red})$$

The profits of banks are equal to the interest on both conventional and green loans minus the interest on deposits (Eq. 99). Banks impose credit rationing based on the leverage ratio of firms (Eqs. 100 and 101). The higher the degree of credit rationing the lower the proportion of new desired loans that are provided (Eqs. 102 and 103). Due to the risky nature of green investments (see Campiglio, 2016), it is assumed that

(without government or central bank interventions) green loans are characterised by higher lending interest rates and credit rationing compared to conventional loans. Eq. (104-red) is the redundant equation of the system described in Table 3 and Table 4: it is logically implied by all the other equations of this system.

### **3.3 Summary of the interactions between the ecosystem, the financial system and the macroeconomy**

Fig. 1 summarises the most important channels through which the ecosystem, the financial system and the macroeconomy interact in our model:

- *Degradation channel:* Higher economic activity, which is accompanied by the use of matter and non-renewable energy, leads to CO<sub>2</sub> emissions and the generation of hazardous waste. The overall result is the degradation of the ecosystem services due to the CO<sub>2</sub>-induced increase in atmospheric temperature and the harmful effects of waste accumulation.
- *Depletion channel:* The extraction of matter and non-renewable energy sources that are necessary for the production process places upward pressures on the depletion ratios. In other words, economic growth tends to deplete finite natural resources.
- *Damage channel:* The degradation of the ecosystem services damages the fund-service resources (capital and labour) either by destroying them directly or by reducing their productivities. These damages might impose supply-side constraints on economic activity. The environmental damages also affect the behaviour of households and firms, which respond to these damages by cutting consumption and investment expenditures, respectively. As a result, aggregate demand falls, reducing economic growth.
- *Natural resources constraint channel:* The depletion of natural resources reduces the availability of the stock-flow resources that are necessary in the production process (matter and non-renewable energy). This might impose supply-side constraints on economic activity.
- *Green financing channel:* The financial system finances green investment via loans, contributing to the improvement of material intensity, energy intensity and recycling rates as well as to the increase in the

use of renewable energy. Hence, the credit rationing and the interest rates determined by banks play an important role in the decoupling of economic growth from environmental problems.

- *Growth channel:* The financial system has both positive and negative effects on economic activity. The positive effects include the provision of finance that increases investment and, hence, economic growth. The negative effects are related to the potential rise in the leverage ratio of firms that, under certain conditions, can harm economic activity by reducing desired investment and credit availability.
- *Financial (in)stability channel:* The stability of the financial system is affected by macroeconomic activity. However, the links are not clear-cut. High economic growth is conducive to the expansion of the financial system, which might be associated with higher financial fragility (reflected in higher leverage ratios). Low economic activity create debt repayment difficulties that affect the stability of the financial system.

<Insert Figure 1 here>

#### **4. Simulations**

The model has been calibrated using the available global data. Parameter values have been selected in three different ways: a first set of parameters have been taken from other studies or have been calculated based on the global data; a second set of parameters have been selected such that the model generates the baseline scenario described below; a third set of parameters have been selected from a reasonable range of values. Appendix A and Appendix B report the related details.

The model is simulated for 100 years starting from 2015. The purpose of our simulation exercises is to analyse potential long-run developments that stem from the interactions between the ecosystem, the financial system and the macroeconomy. We do not pay attention to short-run fluctuations and business cycles. The baseline scenario represents a ‘business as usual’ pathway whereby the global economy

continues to expand quite smoothly and ecological efficiency improves moderately. In particular, in our baseline scenario the global economy grows at around 2.7-3% and the unemployment rate remains equal to around 6% till 2050, as it has been the case over the last two decades or so. In general line with the United Nations (2015) population projections (medium fertility variant), the labour force grows at a declining rate in the next years, increasing from 3.4bn people in 2015 to around 4.5bn people in 2050 (assuming a constant labour force-population ratio). Furthermore, the share of renewable energy is increased to about 30% by the end of the century (from about 14% which is the current level), while CO<sub>2</sub> intensity, material intensity and energy intensity are assumed to become approximately 10%, 15% and 30% lower in 2050 compared to their current levels. Finally, the recycling rate is postulated to increase by about 40% till 2050.

The simulation results are shown in Figs. 2 and 3. In the baseline scenario output increases exponentially for about 60 years (Fig. 2a). Since the share of renewable energy in total energy remains low (Fig 2b), economic growth generates an almost continuous rise in CO<sub>2</sub> emissions till the end of the 21st century (Fig. 2c). The resulting rise in CO<sub>2</sub> concentration and radiative forcing leads to severe global warming: in 2100 atmospheric temperature becomes 4°C higher than the pre-industrial levels (Fig. 2d). The rise in atmospheric temperature makes gradually the damage channel stronger. Hence, the growth rate of output declines, becoming very close to 0 at the beginning of the 22nd century. Declining economic growth leads to a gradual rise in the unemployment rate (Fig. 2e).<sup>14</sup> Low economic activity, combined with the destruction of capital due to climate change, places upward pressures on the leverage ratio of firms (Fig. 2g). The rise in the leverage ratio reinforces the recessionary effects caused by global warming (growth channel) because it reduces desired investment and increases credit rationing. Fig. 2f shows the adverse impact that the damages have on the labour force. Remarkably, these damages are not only linked to the

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<sup>14</sup> The impact of global warming on the unemployment rate depends to a great extent on the effects of the adaptation measures, which are captured by the parameters  $ad_P$  and  $ad_{LF}$ . If the adaptation measures do not limit the damages to labour productivity and labour force sufficiently, global warming might lead to a decline in the unemployment rate and might cause labour shortage problems.

effects of global warming; they are also related to the health effects from the accumulation of hazardous waste. Two additional developments are worth mentioning. First, low economic growth leads ultimately to a reduction in CO<sub>2</sub> emissions (Fig. 2c). Ironically, this cut is primarily produced by nature – which has forced the economy to slow – and not by any specific human design. Second, the expansion of the economy and the low use of renewables makes the non-renewable energy sources more scarce via the depletion channel (Fig. 2h).

A crucial question is how these baseline results are modified when key parameters change or when environmental policies are implemented. Although space limitations do not allow us to explore these issues in depth, in what follows we present a sensitivity analysis and two policy scenarios that illuminate the non-neutral impact of finance on the ecosystem-macroeconomy interactions.

The sensitivity analysis focuses on the effects of firm leverage on economic activity. A rise in the leverage ratio of firms has both contractionary and expansionary effects (see also Nikolaidi, 2014). The contractionary effects stem from the fact that a rise in leverage reduces desired investment and increases credit rationing. The expansionary effects are basically related to the fact that a rise in firm loans is always accompanied by a rise in household deposits which boosts consumption expenditures via the wealth effect. There are also some effects on the disposable income of households which are less clear-cut: a rise in firm loans increases, on the one hand, the distributed profits of banks and the interest payments of households but, on the other hand, reduces the distributed profits of firms.

<Insert Figure 2 here>

Based on the above, we have selected to modify the following parameters in the sensitivity analysis: (i) the sensitivity of the desired investment rate to profitability ( $a_1$ ); (ii) the sensitivity of credit rationing to the leverage ratio of firms ( $r_1$  and  $l_1$ ); (iii) the propensity to consume out of deposits ( $c_2$ ). In Sensitivity test I,

$a_1$ ,  $r_1$  and  $l_1$  are relatively high and  $c_2$  is relatively small. This means that the contractionary effects are strong relative to the expansionary ones. The opposite holds in Sensitivity Test II, where  $a_1$ ,  $r_1$  and  $l_1$  are relatively small and  $c_2$  is relatively high. Table 5 reports the parameter values used in the sensitivity analysis.

<Insert Table 5 here>

Fig. 2 shows the results. Under Sensitivity test I, the rise in the leverage ratio of firms caused by climate change generates stronger contractionary effects in comparison to the baseline scenario. Hence, output is lower (Fig. 2a) and unemployment rate is higher (Fig. 2e). However, there are beneficial environmental effects. Lower economic activity slows the build-up of atmospheric CO<sub>2</sub> concentration, resulting in slightly less severe global warming (Fig. 2d); it also leads to a lower use of the non-renewable energy reserves (Fig. 2h). On the contrary, under Sensitivity Test II, the adverse effects of a higher firm leverage ratio are less pronounced, allowing output to increase more than in the baseline scenario (Fig. 2a). This, of course, increases the environmental problems.

Overall, the results show that the responsiveness of economic activity to the leverage ratio affects the way that the ecosystem interacts with the macroeconomy. In the baseline scenario environmental damages reduce economic growth and destroy capital (via the damage channel), causing a rise in the financial fragility of firms (via the (in)stability channel). This, in turn, harms economic growth (via the growth channel), slowing environmental degradation and the depletion of natural resources. When the adverse impact of the leverage ratio on economic activity increases (decreases), the harmful economic effects of environmental damages are amplified (attenuated).

We now turn to analyse a set of policies linked with the financing conditions for green investment. In our model these conditions are captured by the credit rationing and the interest rate on green loans. An

improvement in the green financing conditions means that credit rationing and interest rate on green loans are reduced, leading to a higher share of green investment in total investment. This can be the result of various types of policies, such as a bank regulation policy or a central bank policy that incentivise banks to provide a higher amount of green loans (see Campiglio, 2016).

We analyse two types of green finance policies. Under green finance policy I, the credit rationing and the interest rate on green loans are reduced, while the credit rationing and the interest rate on conventional loans remain unchanged. This means that a higher share of green capital in total capital is accompanied by a higher economic growth. The latter partially offsets the beneficial environmental effects of higher green investment. Under green finance policy II, the decline in the credit rationing and the interest rate on green loans is accompanied by a rise in the credit rationing and the interest rate on conventional loans. This means that the favourable environmental effects of higher green investment are offset to a less extent by higher economic growth caused by credit expansion. Moreover, the share of green capital in total capital becomes even higher.

Figure 3 reports the results. The implementation of both policies is assumed to start in 2020. As expected, under green finance policy I, output increases more than in the baseline scenario due to the expansionary effects of higher credit availability and lower interest rates (Fig. 3a); this development is related to the growth channel. Credit expansion also has favourable effects on the unemployment rate (Fig. 3e). The increase in the share of green investment causes a rise in the use of renewable energy (Fig. 3b). Hence, CO<sub>2</sub> emissions grow less rapidly compared to the baseline scenario (Fig. 3c), leading to a slightly lower rise in atmospheric temperature. Since global warming is less severe, the damage channel is less strong and this allows the economy to expand for a slightly longer period compared to the baseline scenario (Fig. 3a).

<Insert Figure 3 here>

Green finance policy II yields better environmental results. Since the provision of finance for conventional investment is reduced, economic growth is lower compared to the Green finance policy I scenario (Fig. 3a). The combination of a lower economic activity and a higher share of green investment in total investment generates lower CO<sub>2</sub> emissions (Fig. 3c) and, thereby produces a less rapid rise in the atmospheric temperature (Fig. 3d).

Particular attention needs to be paid to the trajectory of the leverage ratio of firms (Fig. 3g). Although credit expands significantly under Green finance policy I, the leverage ratio turns out to be lower compared to the baseline scenario. The main driving force behind this development is the enhancement of green investment which reduces the damages (green financing channel), allowing output and capital stock to increase more. Furthermore, when the proportion of green credit in total credit becomes even higher (Green finance policy II), the leverage ratio decreases further despite the fact that economic growth is lower than in the Green finance policy I scenario. This has to do with the fact that global warming – and hence damages - are less severe when the proportion of green credit increases.

## **5. Conclusion**

This paper developed a stock-flow-fund ecological macroeconomic model that analyses the complex interactions between the ecosystem, the financial system and the macroeconomy. The foundations of the model lie in the post-Keynesian SFC approach and the flow-fund model of Georgescu-Roegen. We calibrated the model using global data and we performed simulations to investigate the trajectories of key environmental, macroeconomic and financial variables under (i) different assumptions about the sensitivity of economic activity to the leverage ratio of firms and (ii) different types of green finance policies. Our simulations indicated that as the contractionary effects of a higher leverage ratio become stronger, the economic damages caused by the environmental changes are reinforced. They also showed that green finance policies have favourable effects on environmental variables and the financial fragility of firms.



More importantly, these favourable effects are enhanced when the expansion of green credit is accompanied by a restriction of conventional credit.

Our analysis can be extended in various directions. First, more realistic structures can be introduced into our macroeconomy and financial system. Examples include the incorporation of the equity/bond/energy market, the government sector and the central bank. Second, additional aspects of the ecosystem can be incorporated, such as tipping points or a more sophisticated carbon cycle. Third, various simulation exercises can be conducted – using the current model or its future extensions – in order to explore how our results change when different types of environmental policies are implemented. All these extensions can contribute to a more integrated understanding of the ways through which macroeconomic and financial stability can be combined with ecological sustainability.

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## Figures and Tables

**Table 1:** Physical flow matrix

	Material balance	Energy balance
<b>Inputs</b>		
Extracted matter	$+M$	
Renewable energy		$+ER$
Non-renewable energy	$+CEN$	$+EN$
Oxygen	$+O_2$	
<b>Outputs</b>		
Industrial CO <sub>2</sub> emissions	$-EMIS_{IN}$	
Waste	$-W$	
Dissipated energy		$-ED$
<b>Change in socio-economic stock</b>	$-\Delta SES$	
<b>Total</b>	0	0

*Note: The table refers to annual global flows. Matter is measured in Gt and energy is measured in EJ.*

**Table 2:** Physical stock-flow matrix

	Material reserves	Non-renewable energy reserves	Atmospheric CO <sub>2</sub> concentration	Socio-economic stock	Hazardous waste
<b>Opening stock</b>	$REV_{M-1}$	$REV_{E-1}$	$CO2_{AT-1}$	$SES_{-1}$	$HWS_{-1}$
<b>Additions to stock</b>					
Resources converted into reserves	$+CONV_M$	$+CONV_E$			
CO <sub>2</sub> emissions			$+EMIS$		
Production of material goods				$+MY$	
Non-recycled hazardous waste					$+ba\alpha W$
<b>Reductions of stock</b>					
Extraction	$-M$	$-EN$			
Net transfer to oceans/biosphere			$+(\phi_1 - 1)CO2_{AT-1} + \phi_2 CO2_{UP-1}$		
Demolished/disposed material goods				$-DEM$	
<b>Closing stock</b>	$REV_M$	$REV_E$	$CO2_{AT}$	$SES$	$HWS$

Note: The table refers to annual global stocks. Matter is measured in Gt and energy is measured in EJ.

**Table 3:** Transactions flow matrix

	Households	Firms		Commercial banks		Total
		Current	Capital	Current	Capital	
Consumption	$-C$	$+C$				0
Conventional investment		$+I_C$	$-I_C$			0
Green investment		$+I_G$	$-I_G$			0
Wages	$+mN$	$-mN$				0
Firms' profits	$+DP$	$-TP$	$+RP$			0
Commercial banks' profits	$+BP$			$-BP$		0
Interest on deposits	$+int_D D_{-1}$			$-int_D D_{-1}$		0
Capital depreciation		$-\delta K_{-1}$	$+\delta K_{-1}$			0
Interest on conventional loans		$-int_C L_{C-1}$		$+int_C L_{C-1}$		0
Interest on green loans		$-int_G L_{G-1}$		$+int_G L_{G-1}$		0
$\Delta$ deposits	$-\Delta D$				$+\Delta D$	0
$\Delta$ conventional loans			$+\Delta L_C$		$-\Delta L_C$	0
$\Delta$ green loans			$+\Delta L_G$		$-\Delta L_G$	0
Total	0	0	0	0	0	0

*Note: The table refers to annual global flows in trillion \$.*



**Table 4:** Balance sheet matrix

	Households	Firms	Commercial banks	Total
Conventional capital		$+K_C$		$+K_C$
Green capital		$+K_G$		$+K_G$
Durable consumption goods	$+DC$			$+DC$
Deposits	$+D$		$-D$	0
Conventional loans		$-L_C$	$+L_C$	0
Green loans		$-L_G$	$+L_G$	0
Total (net worth)	$+V_H$	$+V_F$	0	$+K_C +K_G +DC$

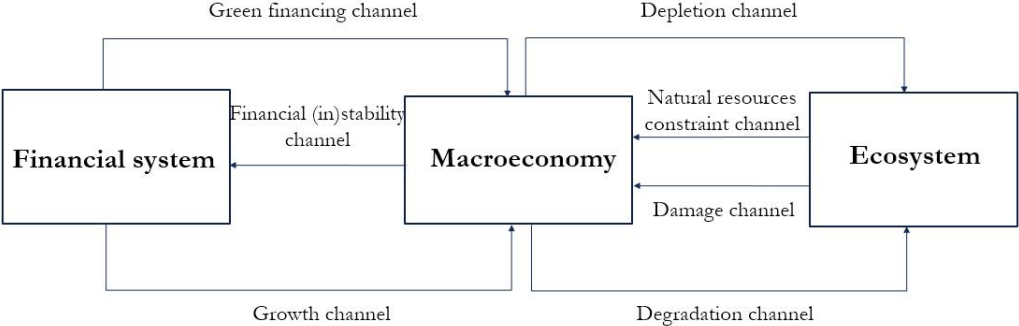
*Note: The table refers to annual global stocks in trillion \$.*

**Table 5:** Values of key parameters in the sensitivity and scenario analysis

Parameter	Baseline scenario	Sensitivity test I	Sensitivity test II	Green finance policy I	Green finance policy II
Sensitivity of desired investment rate to profitability ( $a_1$ )	0.2	0.5	0.05	0.2	0.2
Sensitivity of conventional loans' credit rationing to the leverage ratio of firms ( $r_1$ )	0.2	0.4	0.05	0.2	0.2
Sensitivity of green loans' credit rationing to the leverage ratio of firms ( $l_1$ )	0.2	0.4	0.05	0.2	0.2
Propensity to consume out of deposits ( $c_2$ )	0.075	0.05	0.1	0.075	0.075
Autonomous desired investment rate ( $a_0$ )	0.028	0.021	0.032	0.028	0.028
Propensity to consume out of disposable income ( $c_1$ )	0.88	0.92	0.85	0.88	0.88
Autonomous credit rationing on green loans ( $l_0$ )	0.37	0.33	0.39	0.27	0.27
Autonomous credit rationing on conventional loans ( $r_0$ )	0.17	0.13	0.19	0.17	0.37
Interest rate on green loans ( $int_G$ )	0.08	0.08	0.08	0.06	0.06
Interest rate on conventional loans ( $int_C$ )	0.07	0.07	0.07	0.07	0.08

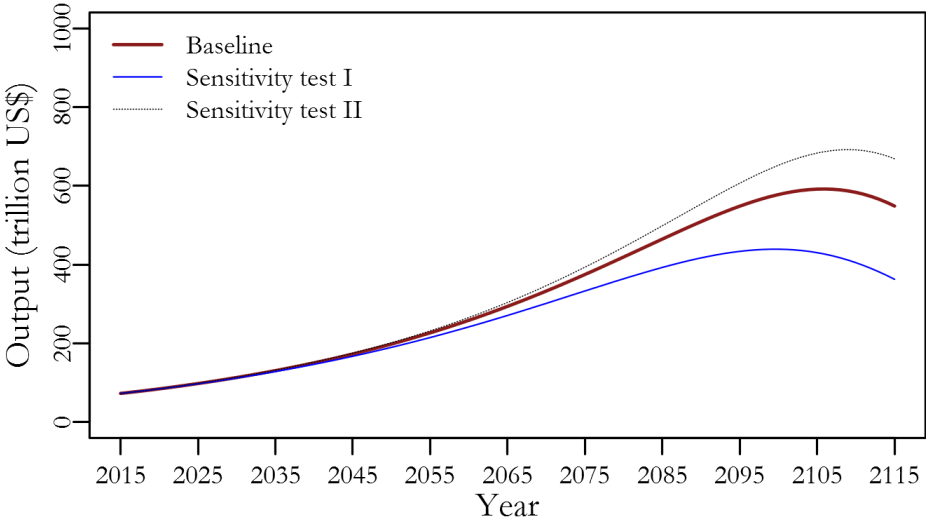
*Notes: In Sensitivity test I (Sensitivity test II) a rising leverage ratio produces stronger (weaker) contractionary effects and weaker (stronger) expansionary effects compared to the baseline scenario. In the sensitivity analysis the change in parameters  $a_1$ ,  $r_1$  and  $l_1$  and  $c_2$  is accompanied by a change in parameters  $a_0$ ,  $r_0$  and  $l_0$  and  $c_1$  so as to ensure that the initial growth rate of output remains the same. In Green finance policy I the credit rationing and the interest rate on green loans are reduced, while the credit rationing and the interest rate on conventional loans remain unchanged. In Green finance policy II the decline in the credit rationing and the interest rate on green loans is accompanied by a rise in the credit rationing and the interest rate on conventional loans. The implementation of green finance policies starts in 2020.*

**Fig. 1:** Main interactions between the ecosystem, the financial system and the macroeconomy in the model

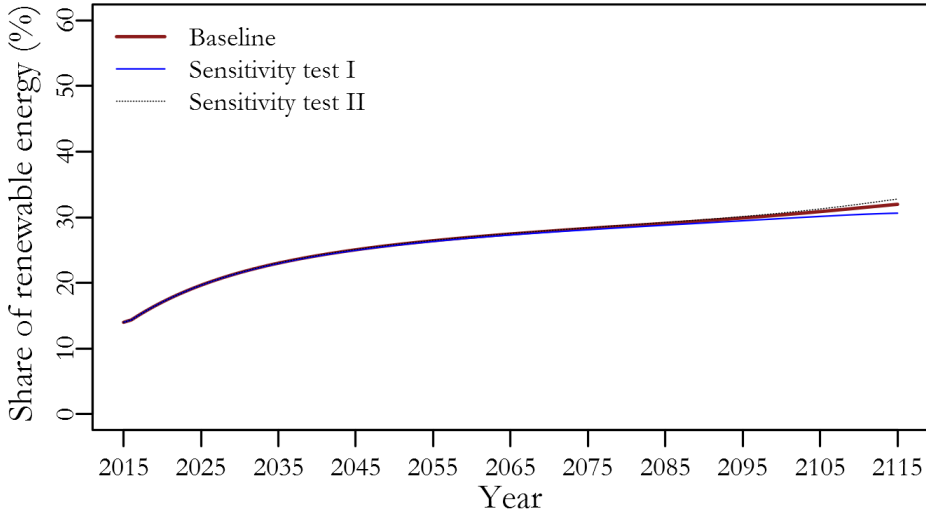


**Fig. 2:** Evolution of environmental, macroeconomic and financial variables, sensitivity analysis

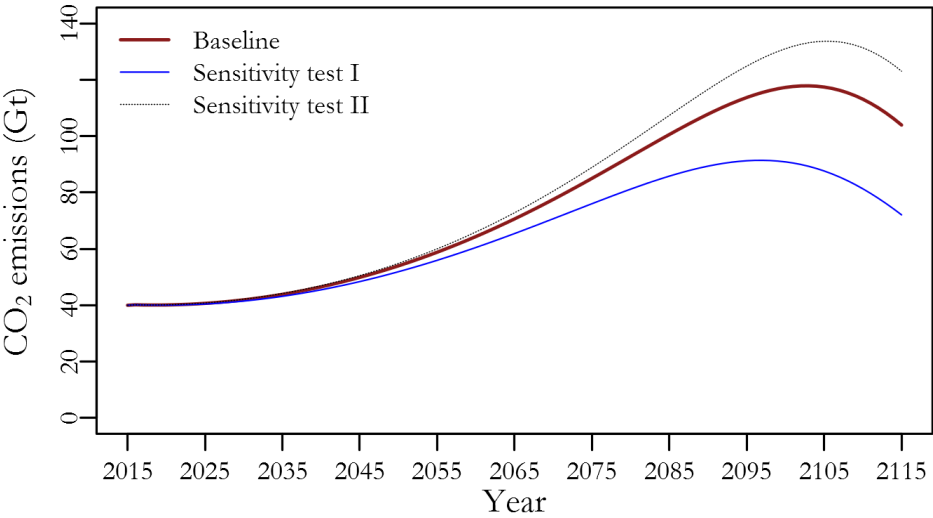
(a) Output



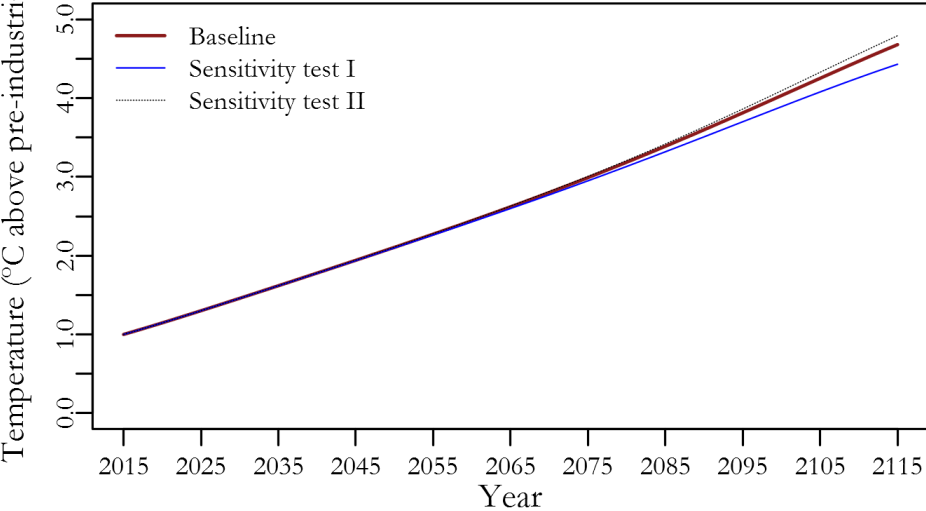
(b) Share of renewable energy in total energy



(c) CO<sub>2</sub> emissions

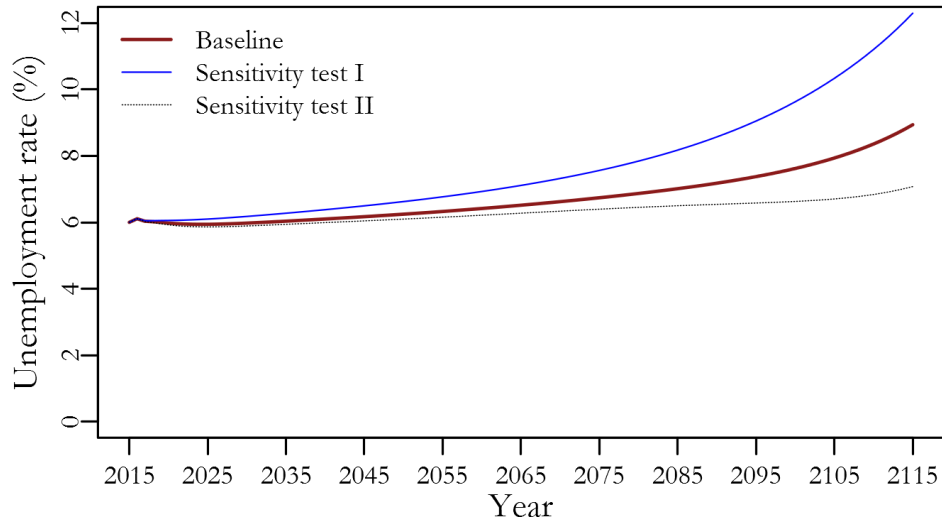


(d) Atmospheric temperature

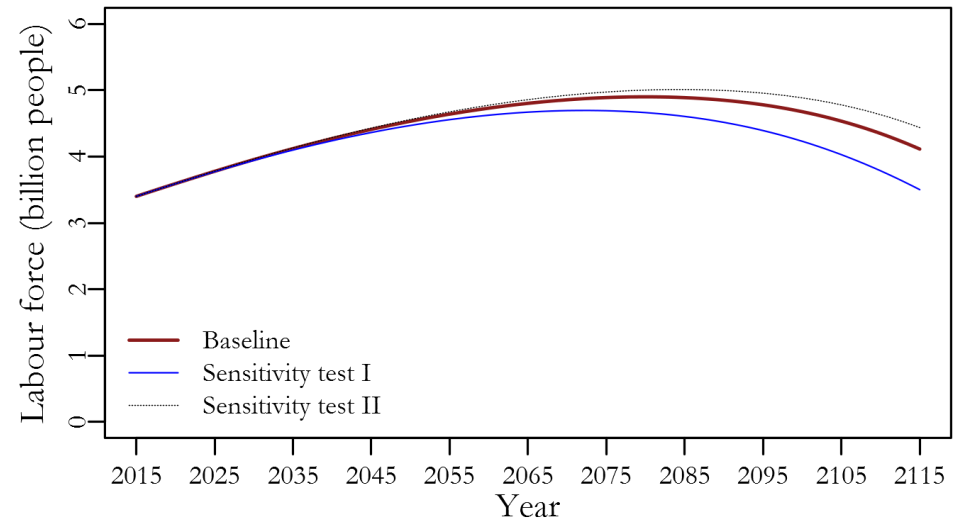


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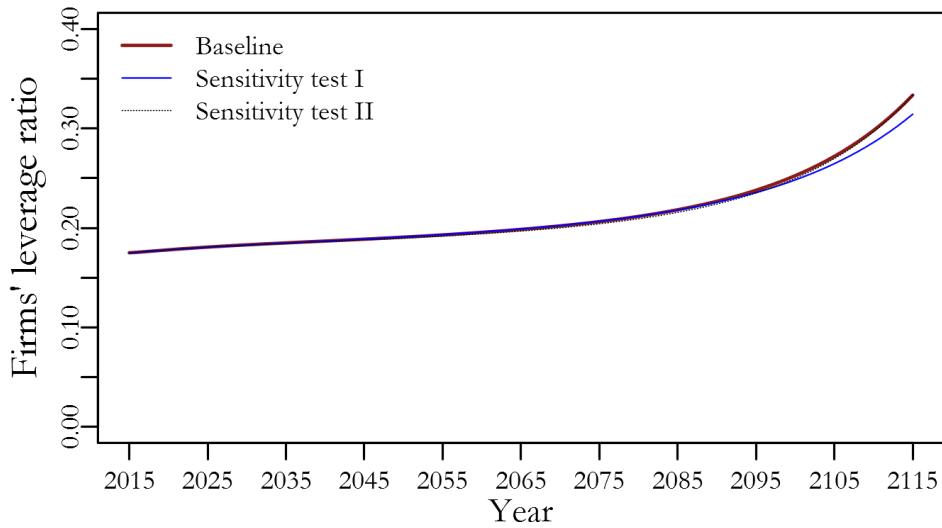
(e) Unemployment rate



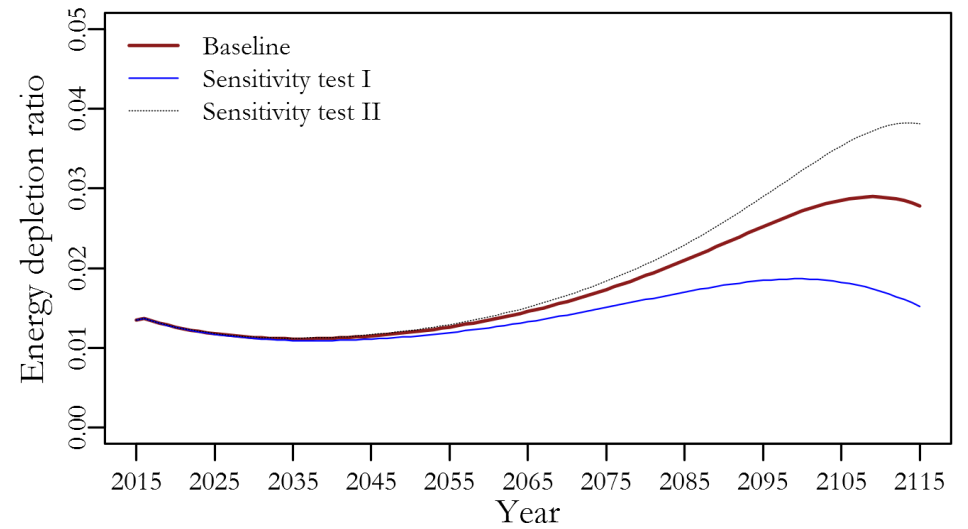
(f) Labour force



(g) Firms' leverage ratio



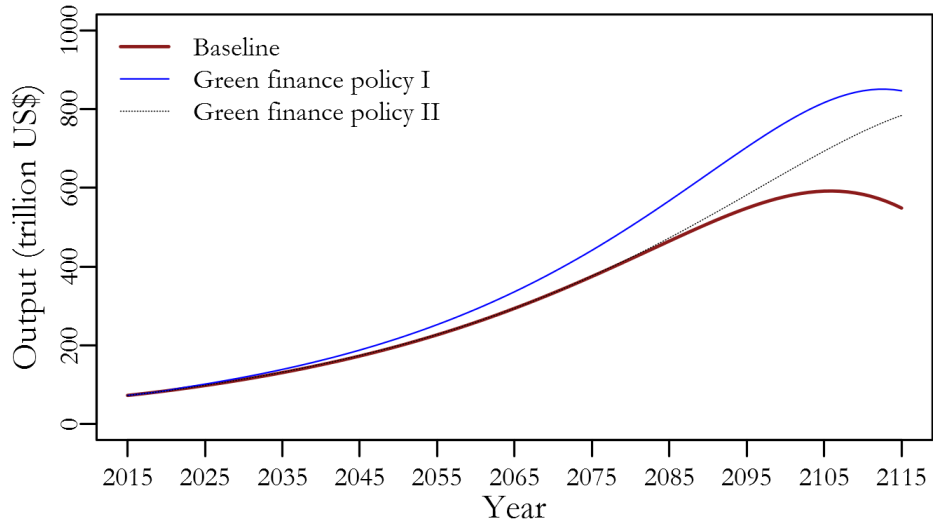
(h) Energy depletion ratio



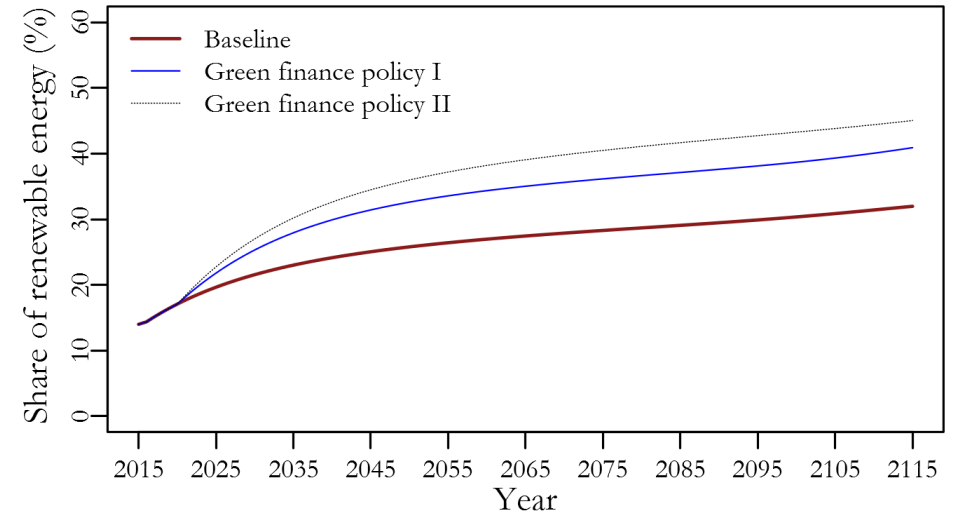
Note: The values used in the simulation analysis are reported in Appendix A, Appendix B and Table 5. In Sensitivity test I (Sensitivity test II) a rising leverage ratio produces stronger (weaker) contractionary effects and weaker (stronger) expansionary effects compared to the baseline scenario.

**Fig. 3:** Evolution of environmental, macroeconomic and financial variables, policy analysis

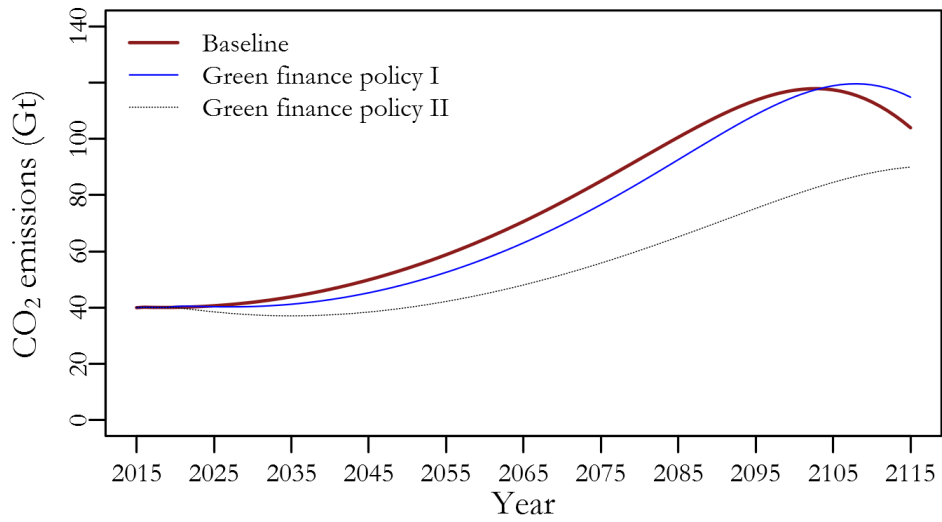
(a) Output



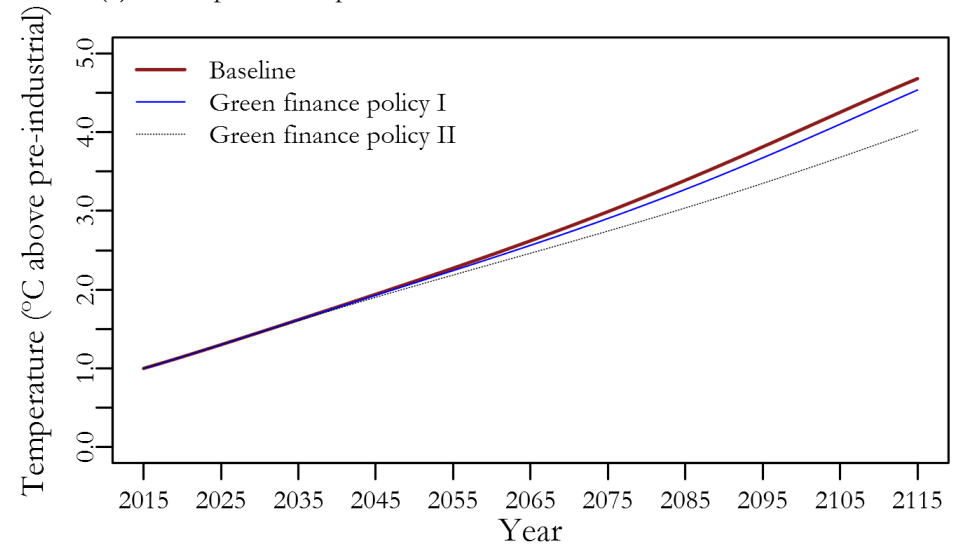
(b) Share of renewable energy in total energy



(c) CO<sub>2</sub> emissions

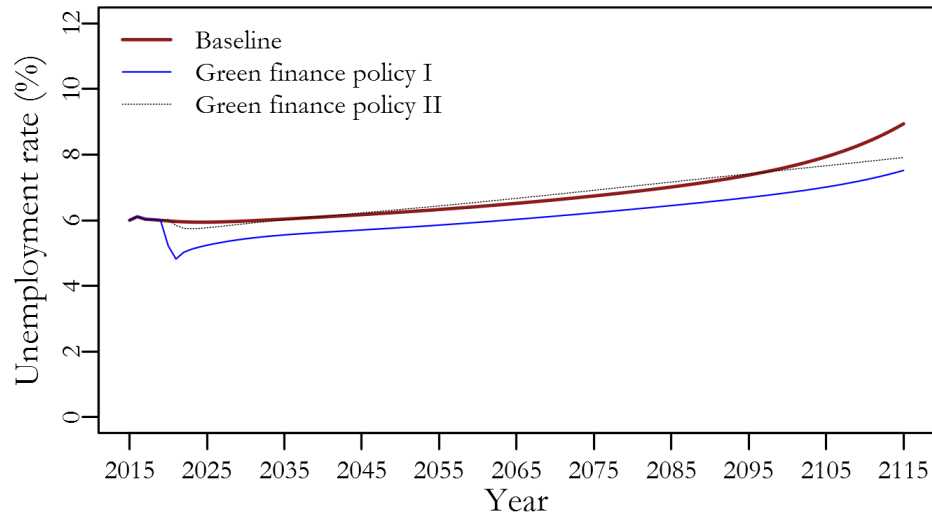


(d) Atmospheric temperature

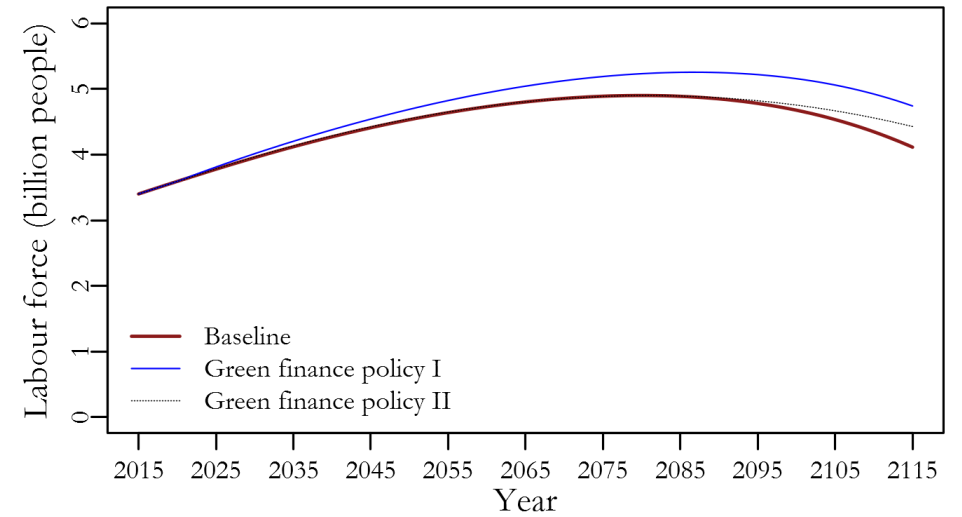


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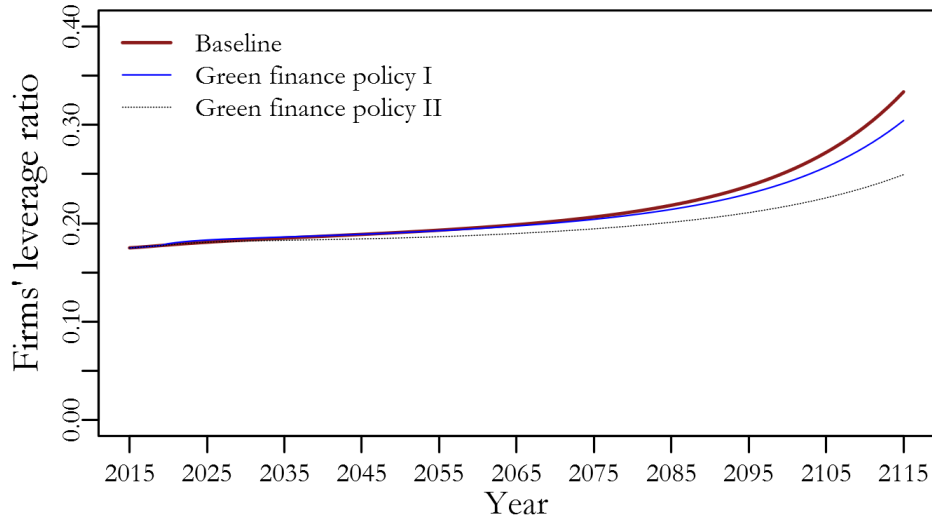
(e) Unemployment rate



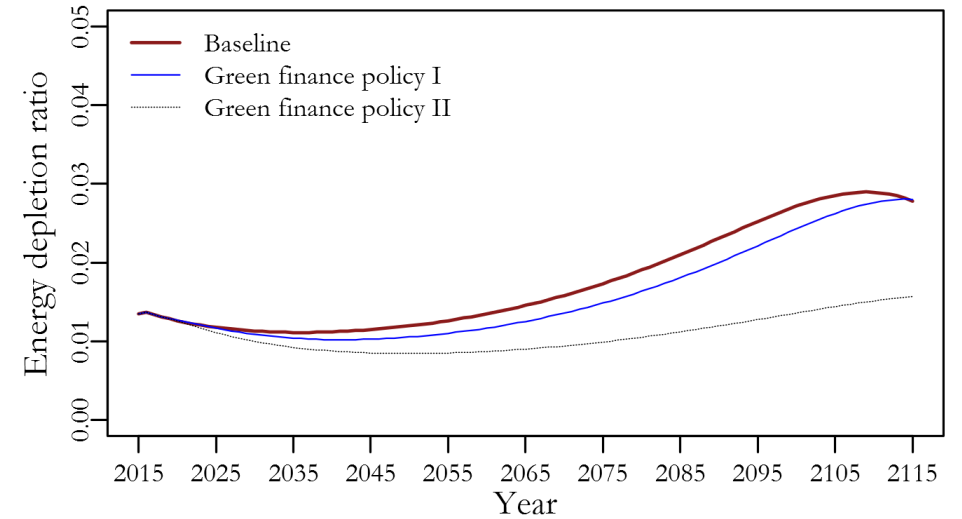
(f) Labour force



(g) Firms' leverage ratio



(h) Energy depletion ratio



Note: The values used in the simulation analysis are reported in Appendix A, Appendix B and Table 5. In Green finance policy I the credit rationing and the interest rate on green loans are reduced, while the credit rationing and the interest rate on conventional loans remain unchanged. In Green finance policy II the decline in the credit rationing and the interest rate on green loans is accompanied by a rise in the credit rationing and the interest rate on conventional loans. The implementation of green finance policies starts in 2020.

## Appendix A. Initial values for endogenous variables

Symbol	Description	Value	Remarks/sources
$BP$	Profits of banks (trillion \$)	3.7	Calculated from Eq. (99) using the initial values of $L_C$ , $L_G$ and $D$
$C$	Consumption (trillion \$)	47.1	Calculated from Eq. (93) using the initial values of $Y$ and $I$
$CEN$	Carbon mass of the non-renewable energy sources (Gt)	9.8	Calculated from Eq. (7) using the initial value of $EMIS_{IN}$
$CO2_{AT}$	Atmospheric CO <sub>2</sub> concentration (Gt)	3120	Taken from NOAA/ESRL (National Oceanic & Atmospheric Administration/Earth System Research Laboratory)
$CO2_{UP}$	Upper ocean/biosphere CO <sub>2</sub> concentration (Gt)	5628.8	Based on Nordhaus and Sutorz (2013); Gt of carbon have been transformed into Gt of CO <sub>2</sub>
$CO2_{LO}$	Lower ocean CO <sub>2</sub> concentration (Gt)	36706.7	Based on Nordhaus and Sutorz (2013); Gt of carbon have been transformed into Gt of CO <sub>2</sub>
$CON_E$	Conversion of non-renewable energy resources into non-renewable energy reserves (EJ)	1626.0	Calculated from Eq. (20) using the initial value of $RES_E$
$CON_M$	Conversion of material resources into material reserves (Gt)	194	Calculated from Eq. (12) using the initial value of $RES_M$
$CR_C$	Degree of credit rationing for conventional loans	0.2	Calculated from Eq. (100) using the initial value of $lev$
$CR_G$	Degree of credit rationing for green loans	0.4	Calculated from Eq. (101) using the initial value of $lev$
$D$	Deposits (trillion \$)	66.6	Calculated from Eq. (104) using the initial value of $L$
$DC$	Stock of durable consumption goods (trillion \$)	1185	Calculated from Eq. (4) using the initial value of $K$ , $\delta$ and $\mu$
$DEM$	Demolished/discarded socioeconomic stock (Gt)	17.0	Based on Haas et al. (2015)
$d\phi_E$	Energy depletion ratio	0.013	Calculated from Eq. (22) using the initial values of $EN$ and $REV_E$
$d\phi_M$	Matter depletion ratio	0.008	Selected from a reasonable range of values
$DP$	Distributed profits of firms (trillion \$)	6.4	Calculated from Eq. (60) using the initial values of $TP$ and $RP$
$D_T$	Total proportional damage caused by global warming	0.0028	Calculated from Eq. (55) using the initial value of $T_{AT}$
$D_{TF}$	Part of damage that affects directly the fund-service resources	0.0026	Calculated from Eq. (57) using the initial values of $D_T$ and $D_{TP}$
$D_{TP}$	Part of damage that reduces the productivities of fund-service resources	0.0003	Calculated from Eq. (56) using the initial value of $D_T$
$E$	Energy necessary for the production of output (EJ)	580.0	Based on IEA (International Energy Agency); total primary energy supply is used
$ED$	Dissipated energy (EJ)	580.0	Calculated from Eq. (18) using the initial values of $EN$ and $ER$
$EMIS$	Total CO <sub>2</sub> emissions (Gt)	40.0	Calculated from Eq. (25) using the initial values of $EMIS_{IN}$ and $EMIS_L$
$EMIS_{IN}$	Industrial CO <sub>2</sub> emissions (Gt)	36.0	Based on CDIAC (Carbon Dioxide Information Analysis Center)
$EMIS_L$	Land-use CO <sub>2</sub> emissions (Gt)	4.0	Based on CDIAC (Carbon Dioxide Information Analysis Center)
$EN$	Energy produced from non-renewable sources (EJ)	498.8	Calculated from Eq. (17) using the initial values of $E$ and $ER$
$ER$	Energy produced from renewable sources (EJ)	81.2	Calculated from Eq. (16) using the initial values of $\theta$ and $E$
$F$	Radiative forcing over pre-industrial levels (W/m <sup>2</sup> )	2.30	Calculated from Eq. (29) using the initial values of $CO2_{AT}$ and $F_{EX}$
$F_{EX}$	Radiative forcing, over pre-industrial levels, due to non-CO <sub>2</sub> greenhouse gases (W/m <sup>2</sup> )	0.28	Based on Nordhaus and Sutorz (2013)
$g_{LF}$	Growth rate of labour force before global warming damages	0.012	Based on United Nations (2015)
$g_Y$	Growth rate of output	0.030	Calibrated such that the model generates the baseline scenario described in Section 4
$g_{\theta}$	Growth rate of the autonomous share of green investment in total investment	0.001	Calibrated such that the model generates the baseline scenario described in Section 4
$g_{EG}$	Growth rate of green energy intensity	-0.050	Calibrated such that the model generates the baseline scenario described in Section 4
$g_{\lambda}$	Growth rate of labour productivity	0.018	Calculated from Eq. (86) using the initial values of $g_Y$ and $\sigma_{\theta}$
$g_{\mu G}$	Growth rate of green material intensity	-0.013	Calibrated such that the model generates the baseline scenario described in Section 4
$g_{\rho G}$	Growth rate of green recycling rate	0.01	Calibrated such that the model generates the baseline scenario described in Section 4
$g_{\omega}$	Growth rate of CO <sub>2</sub> intensity	-0.005	Calibrated such that the model generates the baseline scenario described in Section 4
$hazratio$	Hazardous waste accumulation ratio (Gt/million km <sup>2</sup> )	0.03	Calculated from Eq. (10) using the initial value of $HWS$
$HWS$	Stock of hazardous waste (Gt)	14.0	Calculated assuming a constant ratio of hazardous waste to GDP since 1960
$I$	Total investment (trillion \$)	26.1	Selected such that the model generates the baseline scenario described in Section 4
$I_C$	Conventional investment (trillion \$)	15.7	Calculated from Eq. (77) using the initial values of $I$ and $I_G$
$I_C^D$	Desired conventional investment (trillion \$)	17.5	Calculated from Eq. (69) using the initial values of $I^D$ and $I_G^D$
$I^D$	Desired total investment (trillion \$)	31.3	Selected such that it is reasonably higher than $I$
$I_G$	Green investment (trillion \$)	10.4	Calculated by assuming that $I_C/I$ is slightly lower than $\beta$ ; the initial values of $\beta$ and $I$ are used
$I_G^D$	Desired green investment (trillion \$)	13.8	Calculated from Eq. (68) using the initial values of $\beta$ and $I^D$
$K$	Total capital stock (trillion \$)	380.6	Calculated from the identity $K=(K/Y)*Y$ by using the initial value of $Y$ and assuming that $K/Y=5.2$ (this value has been selected such that the model generates the baseline scenario described in Section 4)
$K_C$	Conventional capital stock (trillion \$)	290.3	Calculated from Eq. (81) using the initial values of $K$ and $K_G$
$K_G$	Green capital stock (trillion \$)	90.4	Calculated from Eq. (82) using the initial values of $K$ and $\kappa$
$L$	Total loans of firms (trillion \$)	66.6	Calculated from Eq. (83) using the initial values of $lev$ and $K$
$L_C$	Conventional loans (trillion \$)	50.8	Calculated from Eq. (78) using the initial values of $L$ and $L_G$
$L_G$	Green loans (trillion \$)	15.8	Calculated by assuming that $L_C/L=K_G/K=\kappa$ ; we use the initial values of $\kappa$ and $L$
$lev$	Firms' leverage ratio	0.18	Calculated from the identity $lev=(L/Y)/(K/Y)$ ; $L/Y$ is taken from BIS (Bank for International Settlements); the credit to the non-financial corporations in percent of GDP is used; $K/Y$ is assumed to be equal to 5.2 (this value has been selected such that the model generates the baseline scenario described in Section 4).



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Symbol	Description	Value	Remarks/sources
$LF$	Labour force (millions)	3.4	Based on World Bank
$lf_0$	Autonomous growth rate of the labour force	0.012	Calibrated such that initial growth rate of the labour force is equal to the current one
$M$	Extraction of new matter from the ground, excluding the matter included in non-renewable energy sources (Gt)	48.0	Based on the data provided by www.materialflows.net; the figure includes industrial and construction minerals plus ores
$MY$	Output in material terms (Gt)	53.1	Calculated from Eq. (2) using the initial values of $M$ and $REC$
$N$	Number of employees (billions of people)	3.2	Calculated from the definition of the rate of employment ( $re=N/LF$ ) using the initial values of $re$ and $LF$
$NL_C^D$	Desired new amount of conventional loans (trillion \$)	6.0	Calculated from Eq. (74) using the initial values of $I_C^D, \beta, RP, L_C, \delta$ and $K_C$
$NL_G^D$	Desired new amount of green loans (trillion \$)	7.8	Calculated from Eq. (73) using the initial values of $I_G^D, \beta, RP, L_G, \delta$ and $K_C$
$O2$	Oxygen used for the combustion of fossil fuels (Gt)	26.2	Calculated from Eq. (8) using the initial value of $EMIS_{IN}$ and $CEN$
$r$	Rate of retained profits (trillion \$)	0.024	Calculated from Eq. (61) using the initial values of $RP$ and $K$
$re$	Rate of employment	0.94	Calculated from Eq. (91) using the initial value of $ur$
$REC$	Recycled socio-economic stock (Gt)	5.1	Calculated from Eq. (3) using the initial values of $\varrho$ and $DEM$
$RES_E$	Non-renewable energy resources (EJ)	542000	Based on BGR (2015, p. 33)
$RES_M$	Material resources (Gt)	388889	Calculated by assuming $RES_M/REV_M=64.8$ (based on UNEP, 2011)
$REV_E$	Non-renewable energy reserves (EJ)	37000	Based on BGR (2015, p. 33)
$REV_M$	Material reserves (Gt)	6000	Calculated from Eq. (14) using the initial values of $M$ and $dep_M$
$RP$	Retained profits of firms (trillion \$)	9.0	Calculated from Eq. (59) using the initial value of $TP$
$SES$	Socioeconomic stock (Gt)	1135.6	Calculated from the identity $SES=\mu(K+DC)$ using the initial values of $\mu, K$ and $DC$
$T_{AT}$	Atmospheric temperature over pre-industrial levels ( $^{\circ}C$ )	1.0	Based on Met Office
$T_{LO}$	Lower ocean temperature over pre-industrial levels ( $^{\circ}C$ )	0.0068	Taken from Nordhaus and Sztorz (2013)
$TP$	Total profits of firms (trillion \$)	15.4	Calculated from Eq. (58) using the initial values of $w, N, L_C, L_G, \delta$ and $K$
$u$	Rate of capacity utilisation	0.72	Based on World Bank, Enterprise Surveys
$ue$	Rate of energy utilisation	0.01	Calculated from Eq. (52) using the initial values of $Y$ and $Y_E^*$
$um$	Rate of matter utilisation	0.01	Calculated from Eq. (51) using the initial values of $Y$ and $Y_M^*$
$ur$	Unemployment rate	0.06	Based on World Bank
$v$	Capital productivity	0.27	Calculated from Eqs. (47) and (53) using the initial values of $Y, u$ and $K$
$w$	Annual wage rate (trillion \$/billions of employees)	11.91	Calculated from Eq. (89) using the initial value of $\lambda$
$W$	Waste (Gt)	11.90	Calculated from the identity $W=DEM-REC$ using the initial values of $DEM$ and $REC$
$Y$	Output (trillion \$)	73.2	Taken from IMF, World Economic Outlook (current prices)
$Y^*$	Potential output (trillion \$)	77.9	Calculated from Eq. (49) using the initial values of $Y_M^*, Y_E^*, Y_K^*$ and $Y_N^*$
$Y_E^*$	Energy-determined potential output (trillion \$)	5429.8	Calculated from Eq. (46) using the initial values of $REV_E, \theta$ and $\varepsilon$
$Y_H$	Disposable income of households (trillion \$)	49.2	Calculated from Eq. (92) using the initial values of $w, N, DP, BP$ and $D$
$Y_K^*$	Capital-determined potential output (trillion \$)	101.7	Calculated from Eq. (47) using the initial values of $v$ and $K$
$Y_M^*$	Matter-determined potential output (trillion \$)	8278.2	Calculated from Eq. (45) using the initial values of $REV_M, REC$ and $\mu$
$Y_N^*$	Labour-determined potential output (trillion \$)	77.9	Calculated from Eq. (48) using the initial values of $\lambda$ and $LF$
$a_0$	Autonomous desired investment rate	0.028	Since there are no supply-side constraints, this is equal to $a_{00}$
$\beta$	Share of green investment in total investment	0.44	Selected such that the model generates the baseline scenario described in Section 4
$\beta_0$	Autonomous share of green investment in total investment	0.46	Selected such that the model generates the baseline scenario described in Section 4
$\gamma_1$	Sensitivity of the desired investment rate to the difference between $um$ and $um_T$	0	Since $um < um_T$ , there are no matter-related supply-side constraints
$\gamma_2$	Sensitivity of the desired investment rate to the difference between $ue$ and $ue_T$	0	Since $ue < ue_T$ , there are no energy-related supply-side constraints
$\gamma_3$	Sensitivity of the desired investment rate to the difference between $u$ and $u_T$	0	Since $u < u_T$ , there are no capital-related supply-side constraints
$\gamma_4$	Sensitivity of the desired investment rate to the difference between $re$ and $re_T$	0	Since $re < re_T$ , there are no labour-related supply-side constraints
$\delta$	Depreciation rate of capital stock	0.04	Calculated from Eq. (84) using the initial value $D_{TF}$
$\varepsilon$	Total energy intensity (EJ/trillion \$)	7.92	Calculated from the definition of energy intensity ( $\varepsilon=E/Y$ ) using the initial values of $E$ and $Y$
$\varepsilon_G$	Energy intensity of green capital (EJ/trillion \$)	6.65	Selected such that it is reasonably lower than $\varepsilon_C$
$\theta$	Share of renewable energy in total energy	0.14	Based on IEA (International Energy Agency); total primary energy supply is used
$\varkappa$	Ratio of green capital to total capital	0.24	Calculated from Eqs. (44) and (82) using the initial value of $\theta$
$\lambda$	Hourly labour productivity (trillion \$/(billions of employees*annual hours worked per employee))	0.01	Calculated from Eq. (90) using the initial values of $Y$ and $N$
$\mu$	Material intensity (kg/\$)	0.73	Calculated from the definition of material intensity ( $\mu=MY/Y$ ) using the initial values of $MY$ and $Y$
$\mu_G$	Material intensity of green capital (kg/\$)	0.61	Selected such that it is reasonably lower than $\mu$
$\varrho$	Recycling rate	0.30	Based on Haas et al. (2015)
$\varrho_G$	Recycling rate of green capital	0.48	Selected such that it is reasonably higher than $\varrho$
$\sigma_0$	Autonomous growth rate of labour productivity	-0.03	Calibrated such that the model generates the baseline scenario described in Section 4
$\omega$	CO <sub>2</sub> intensity (Gt/EJ)	0.07	Calculated from Eq. (23) using the initial values of $EMIS_{IN}$ and $EN$

## Appendix B. Values for parameters and exogenous variables (baseline scenario)

Symbol	Description	Value	Remarks/sources
$ad_K$	Fraction of gross damages to capital stock avoided through adaptation	0.75	Selected from a reasonable range of values
$ad_{LF}$	Fraction of gross damages to labour force avoided through adaptation	0.95	Selected from a reasonable range of values
$ad_P$	Fraction of gross damages to productivity avoided through adaptation	0.50	Selected from a reasonable range of values
$c_1$	Propensity to consume out of disposable income	0.88	Calibrated such that the model generates the baseline scenario described in Section 4
$c_2$	Propensity to consume out of deposits	0.075	Selected from a reasonable range of values
$car$	Coefficient for the conversion of Gt of carbon into Gt of CO <sub>2</sub>	3.67	Taken from CDIAC (Carbon Dioxide Information Analysis Center)
$CO2_{AT-PRE}$	Pre-industrial CO <sub>2</sub> concentration in atmosphere (Gt)	2156.2	Taken from Nordhaus and Sztorz (2013); Gt of carbon have been transformed into Gt of CO <sub>2</sub>
$CO2_{LO-PRE}$	Pre-industrial CO <sub>2</sub> concentration in upper ocean/biosphere (Gt)	36670.0	Taken from Nordhaus and Sztorz (2013); Gt of carbon have been transformed into Gt of CO <sub>2</sub>
$CO2_{UP-PRE}$	Pre-industrial CO <sub>2</sub> concentration in lower ocean (Gt)	4950.5	Taken from Nordhaus and Sztorz (2013); Gt of carbon have been transformed into Gt of CO <sub>2</sub>
$con_M$	Conversion rate of material resources into reserves	0.0005	Selected from a reasonable range of values
$con_E$	Conversion rate of non-renewable energy resources into reserves	0.003	Selected from a reasonable range of values
$F_{2xCO2}$	Increase in radiative forcing (since the pre-industrial period) due to doubling of CO <sub>2</sub> concentrations from pre-industrial levels (W/m <sup>2</sup> )	3.8	Taken from Nordhaus and Sztorz (2013)
$f_{ex}$	Annual increase in radiative forcing (since the pre-industrial period) due to non-CO <sub>2</sub> agents (W/m <sup>2</sup> )	0.005	Based on Nordhaus and Sztorz (2013)
$g_p$	Growth rate of capital productivity before global warming damages	0.001	Calibrated such that the model generates the baseline scenario described in Section 4
$b$	Annual working hours per employee	1800	Based on Penn World Table 8.1
$haz_{\xi}$	Proportion of hazardous waste in total waste	0.04	EEA (2012) reports a figure equal to 3.7% for EU-27
$int_C$	Interest rate on conventional loans	0.07	Based on World Bank
$int_D$	Interest rate on deposits	0.015	Based on World Bank
$int_G$	Interest rate on green loans	0.08	Based on World Bank; it is assumed that $int_G - int_C = 0.01$
$l_0$	Autonomous credit rationing on green loans	0.37	Selected from a reasonable range of values
$l_1$	Sensitivity of green loans' credit rationing to the leverage ratio of firms	0.2	Selected from a reasonable range of values
$lf_1$	Autonomous growth rate of labour force	0.012	Calibrated such that the model generates the baseline scenario described in Section 4
$lf_2$	Sensitivity of the growth rate of labour force to the unemployment rate	0.2	Calibrated such that the model generates the baseline scenario described in Section 4
$lf_3$	Sensitivity of the growth rate of labour force to the hazardous waste accumulation ratio	0.001	Calibrated such that the model generates the baseline scenario described in Section 4
$lr$	Rate of decline of land-use CO <sub>2</sub> emissions	0.044	Taken from Nordhaus and Sztorz (2013); has been adjusted to reflect a 1-year time step
$p$	Share of productivity damage in total damage caused by global warming	0.1	Selected from a reasonable range of values
$r_0$	Autonomous credit rationing on conventional loans	0.17	Selected from a reasonable range of values
$r_1$	Sensitivity of conventional loans' credit rationing to the leverage ratio of firms	0.2	Selected from a reasonable range of values
$re_T$	Threshold rate of employment above which supply-side constraints arise	0.96	Selected from a reasonable range of values
$rep$	Loan repayment ratio	0.1	Selected from a reasonable range of values
$S$	Equilibrium climate sensitivity, i.e. increase in equilibrium temperature due to doubling of CO <sub>2</sub> concentrations from pre-industrial levels (°C)	3	Taken from Dietz and Stern (2015)
$SURF$	Earth surface (million km <sup>2</sup> )	510.1	Taken from the World Factbook
$s_F$	Firms' retention rate	0.6	Selected from a reasonable range of values
$s_W$	Wage income share	0.52	Based on Penn World Table 8.1
$t_1$	Speed of adjustment parameter in the atmospheric temperature equation	0.027	Calculated using the formula in Cael et al. (2015, p. 132); effective heat capacity is assumed to be equal to 1.2 GJm <sup>-2</sup> K <sup>-1</sup>
$t_2$	Coefficient of heat loss from the atmosphere to the lower ocean (atmospheric temperature equation)	0.018	Taken from Nordhaus and Sztorz (2013); has been adjusted to reflect a 1-year time step
$t_3$	Coefficient of heat loss from the atmosphere to the lower ocean (lower ocean temperature equation)	0.005	Taken from Nordhaus and Sztorz (2013); has been adjusted to reflect a 1-year time step
$u_T$	Threshold rate of capacity utilisation above which supply-side constraints arise	0.85	Selected from a reasonable range of values
$ue_T$	Threshold rate of energy utilisation above which supply-side constraints arise	0.05	Selected from a reasonable range of values
$um_T$	Threshold rate of matter utilisation above which supply-side constraints arise	0.05	Selected from a reasonable range of values
$\alpha_{00}$	Autonomous desired investment rate	0.028	Calibrated such that the model generates the baseline scenario described in Section 4
$a_1$	Sensitivity of desired investment rate to the rate of retained profits	0.2	Selected from a reasonable range of values
$a_2$	Sensitivity of desired investment rate to the rate of capacity utilisation	0.01	Selected from a reasonable range of values

(continued from the previous page)

Symbol	Description	Value	Remarks/sources
$a_3$	Sensitivity of desired investment rate to the growth rate of energy intensity	0.1	Selected from a reasonable range of values
$\beta_1$	Autonomous share of green investment in total investment	0.02	Calibrated such that the model generates the baseline scenario described in Section 4
$\beta_2$	Sensitivity of the green investment share to the green loan-conventional loan interest rate differential	4	Selected from a reasonable range of values
$\beta_3$	Sensitivity of the green investment share to global warming damages	0.5	Selected from a reasonable range of values
$\gamma_{10}$	Sensitivity of the desired investment rate to the matter-related supply-side constraints	0.5	Selected from a reasonable range of values
$\gamma_{20}$	Sensitivity of the desired investment rate to the energy-related supply-side constraints	0.5	Selected from a reasonable range of values
$\gamma_{30}$	Sensitivity of the desired investment rate to the capital-related supply-side constraints	0.5	Selected from a reasonable range of values
$\gamma_{40}$	Sensitivity of the desired investment rate to the labour-related supply-side constraints	0.5	Selected from a reasonable range of values
$\delta_0$	Depreciation rate of capital stock when there are no global warming damages	0.04	Based on Penn World Table 8.1
$\varepsilon_C$	Energy intensity of conventional capital (EJ/trillion \$)	8.32	Selected such that it is reasonably lower than $\varepsilon$
$\zeta_1$	Rate of decline of the (absolute) growth rate of CO <sub>2</sub> intensity	0.03	Calibrated such that the model generates the baseline scenario described in Section 4
$\zeta_2$	Rate of decline of the (absolute) growth rate of green capital material intensity	0.001	Calibrated such that the model generates the baseline scenario described in Section 4
$\zeta_3$	Rate of decline of the growth rate of green capital recycling rate	0.02	Calibrated such that the model generates the baseline scenario described in Section 4
$\zeta_4$	Rate of decline of the (absolute) growth rate of green capital energy intensity	0.005	Calibrated such that the model generates the baseline scenario described in Section 4
$\zeta_5$	Rate of decline of the growth rate of $\beta_0$	0.015	Calibrated such that the model generates the baseline scenario described in Section 4
$\zeta_6$	Rate of decline of the autonomous (absolute) growth rate of labour productivity	0.007	Calibrated such that the model generates the baseline scenario described in Section 4
$\zeta_7$	Rate of decline of the autonomous growth rate of labour force	0.018	Calibrated such that the model generates the baseline scenario described in Section 4
$\eta_1$	Parameter of damage function	0	Based on Weitzmann (2012); $D_T=50\%$ when $T_{AT}=6^\circ\text{C}$
$\eta_2$	Parameter of damage function	0.00284	Based on Weitzmann (2012); $D_T=50\%$ when $T_{AT}=6^\circ\text{C}$
$\eta_3$	Parameter of damage function	0.000005	Based on Weitzmann (2012); $D_T=50\%$ when $T_{AT}=6^\circ\text{C}$
$\mu_C$	Material intensity of conventional capital	0.76	Selected such that it is reasonably higher than $\mu$
$\xi$	Proportion of durable consumption goods discarded every year	0.007	Selected such that the initial growth of $DC$ is equal to 3%
$\pi$	Parameter linking the green capital-conventional capital ratio with the share of renewable energy	0.54	Calculated from Eq. (44) by assuming that $\theta=0.35$ when $K_G=K_C$
$\varrho_C$	Recycling rate of conventional capital	0.24	Selected such that it is reasonably lower than $\varrho$
$\sigma_1$	Autonomous growth rate of labour productivity	0.029	Calibrated such that the model generates the baseline scenario described in Section 4
$\sigma_2$	Sensitivity of labour productivity growth to the growth rate of output	0.6	Calibrated such that the model generates the baseline scenario described in Section 4
$\varphi_{11}$	Transfer coefficient for carbon from the atmosphere to the atmosphere	0.9817	Calculated from the formula $\varphi_{11}=1-\varphi_{12}$ (see Nordhaus and Sutorz, 2013)
$\varphi_{12}$	Transfer coefficient for carbon from the atmosphere to the upper ocean/biosphere	0.0183	Taken from Nordhaus and Sutorz (2013); has been adjusted to reflect a 1-year time step
$\varphi_{21}$	Transfer coefficient for carbon from the upper ocean/biosphere to the atmosphere	0.0080	Calculated from the formula $\varphi_{21}=\varphi_{12}(CO2_{AT-PRE}/CO2_{UP-PRE})$ (see Nordhaus and Sutorz, 2013)
$\varphi_{22}$	Transfer coefficient for carbon from the upper ocean/biosphere to the upper ocean/biosphere	0.9915	Calculated from the formula $\varphi_{22}=1-\varphi_{21}-\varphi_{23}$ (see Nordhaus and Sutorz, 2013)
$\varphi_{23}$	Transfer coefficient for carbon from the upper ocean/biosphere to the lower ocean	0.0005	Taken from Nordhaus and Sutorz (2013); has been adjusted to reflect a 1-year time step
$\varphi_{32}$	Transfer coefficient for carbon from the lower ocean to the upper ocean/biosphere	0.0001	Calculated from the formula $\varphi_{32}=\varphi_{23}(CO2_{UP-PRE}/CO2_{LO-PRE})$ (see Nordhaus and Sutorz, 2013)
$\varphi_{33}$	Transfer coefficient for carbon from the lower ocean to the lower ocean	0.9999	Calculated from the formula $\varphi_{33}=1-\varphi_{32}$ (see Nordhaus and Sutorz, 2013)