# Dynamic Ecosystem-FINance-Economy (DEFINE) model, technical description and data, version 1.0

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## Contents

## 1. Introduction

This document presents the technical details of the DEFINE (Dynamic Ecosystem-FINance-Economy) model (version 1.0). DEFINE is a global stock-flow-fund ecological macroeconomic model that analyses the interactions between the ecosystem, the financial system and the macroeconomy. It incorporates explicitly the laws of thermodynamics, the carbon cycle, the climate change damages, the waste generation process, the endogeneity of money and the impact of finance on economic activity. DEFINE produces various scenarios for the future of the ecosystem and the global economy. It is also used to evaluate the long-run effects of various types of environmental policies and strategies, paying particular attention to the role of finance.

DEFINE combines the post-Keynesian stock-flow consistent (SFC) approach developed by Godley and Lavoie (2007) with the flow-fund model of Georgescu-Roegen (1971, ch. 9; 1979; 1984). The key innovation of the post-Keynesian SFC approach 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. The flow-fund model of Georgescu-Roegen 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 combination of the SFC approach with the flow-fund model of Georgescu-Roegen provides an integrated approach to the combined analysis of physical and monetary stocks and flows. In DEFINE this analysis 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 simplified version 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.[1] 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 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.

*Section 2* describes the matrices and the equations of the model. *Section 3* presents the key features of the baseline scenario used in this version. *Section 4* reports all the symbols of the model, the data sources and the values used for parameters and variables.

## 2. Structure of the model

DEFINE consists of two big blocks. The first block is the ecosystem block which includes equations about (i) matter, recycling and waste, (ii) energy, (iii) emissions and climate change and (iv) ecological efficiency and technology. The second block is the macroeconomy and financial system block which includes equations about (i) output determination, (ii) firms, (iii) households, (iii) banks, (iv) the government sector and (v) the central banks.

It is assumed that there is one type of material good that can be used for durable consumption and (conventional and green) investment purposes. Four matter/energy transformation processes are necessary for the production of this good and all of them require capital and labour. First, matter (non-metallic minerals and metal ores) has to be extracted from the ground and has to be transformed into a form that can be used as an input in the production.

[1] 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.

Second, useful energy has to be generated based on non-renewable sources (e.g. oil, gas and coal) or renewable sources (e.g. sun, wind).[2] Third, recycling has to take place. Every year a part of the capital stock and the durable consumption goods that have been accumulated in the socio-economic system are demolished/discarded; the material content of these accumulated capital goods and durable consumption goods is called socio-economic stock.[3] A proportion of this demolished/discarded socio-economic stock is recycled and is used as an inflow in the production of the final good. This means that not all of the matter that is necessary for the production of the good has to be extracted from the ground. Fourth, the final good needs to be produced using material and energy inflows from the other processes.

Crucially, all these four processes, in combination with the functioning of the whole socio-economic system, generate by-products. In particular, industrial $CO_2$ emissions are produced as a result of the combustion of fossil fuels. Energy is dissipated in all transformation processes; this energy cannot be used again. In addition, the demolished/discarded socio-economic stock that is not recycled becomes waste. Part of this waste is hazardous and can have adverse effects on the health of the population.

Since the model focuses on the aggregate effects of production, all the above-mentioned processes have been consolidated and are presented as part of the total production process. An unconsolidated formulation of the production process would make the model and its calibration much more complicated without changing the substance of the analysis that we pursue here. However, such an unconsolidated version would be useful for the analysis of intra-firm dynamics and could be the subject of future extensions of the model.

Although capital, labour, energy and matter are all necessary in the transformation processes, these resources do not directly determine the level of production as long as they are not scarce: in the absence of scarcity, the level of production is demand-determined, in line with the post-Keynesian tradition. However, if any of these resources is not sufficient to satisfy the demand, production is directly affected by resource scarcity. In particular, we assume that,

[2] For brevity, the energy produced from (non-)renewable sources is henceforth referred to as (non-)renewable energy. 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.

[3] This is a term used in material flow analysis (see e.g. Krausmann et al., 2015). In general, socio-economic stock also includes animal livestock and humans. However, these stocks (whose mass remains relatively stable over time) are not included in our analysis. As will be explained below, socio-economic stock is measured in Gigatonnes.

under supply-side constraints, consumption and investment demand might decline. Moreover, although all these resources are necessary for the production of goods based on our Leontief-type production function (i.e. there is imperfect substitutability), their relative use changes because of technological progress.

A crucial distinction is made between green capital and conventional capital. Compared to conventional capital, green capital is characterised by lower energy intensity, lower material intensity and higher recycling rate. 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.[4] As the proportion of green capital to conventional capital increases, the goods consumed by households are produced in a more environmentally friendly way. However, we do not make a distinction between conventional and green consumption goods. This means that households' environmental preferences do not have a direct impact on the decisions of firms about green and conventional investment.

Firms invest in conventional and green capital by using retained profits, loans and bonds. Commercial banks accumulate capital and distribute part of their profits to households. They impose credit rationing on firm loans. This means that they play an active role in the determination of output and the accumulation of green capital. Households receive labour income, buy durable consumption goods and accumulate wealth in the form of deposits, corporate bonds and government securities (there are no household loans). Corporate bonds can be either green or conventional. When the demand for green bonds increases, the price of these bonds tends to go up, leading to a lower cost of borrowing for green projects.

Central banks determine the base interest rate, provide liquidity to the commercial banks and purchase government securities and corporate bonds. Governments collect taxes, decide about the level of government expenditures and can implement bailout programmes if there are financial problems in the banking sector. Inflation has been assumed away and, for simplicity, the price of goods is equal to unity. We use US dollar ($) as a reference currency.

[4] A more realistic formulation would be to assume different 'shades of green' depending on the number of 'green' properties that each capital has. In that, case the 'greenest' capital would be that capital that can generate renewable energy and is endowed by lower energy intensity, lower material intensity and higher recycling rate compared to conventional capital. On the other hand, the least 'green' capital would be the capital that has only one of these properties. However, such a formulation would complicate the model significantly since it would require the distinction between many types of green investment and would make the calibration of the model a much more challenging exercise.

## 2.1 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).[5] 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 $CO_2$ emissions) should be equal to the total outputs of matter over the same year (industrial $CO_2$ 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).

**Table 1:** Physical flow matrix

| | Material balance | Energy balance |
|---|---|---|
| **Inputs** | | |
| Extracted matter | $+M$ | |
| Renewable energy | | $+ER$ |
| Non-renewable energy | $+CEN$ | $+EN$ |
| Oxygen used for fossil fuel combustion | $+O2$ | |
| **Outputs** | | |
| Industrial $CO_2$ emissions | $-EMIS_{IN}$ | |
| Waste | $-W$ | |
| Dissipated energy | | $-ED$ |
| **Change in socio-economic stock** | $-\Delta SES$ | |
| **Total** | 0 | 0 |

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

[5] 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.[6] 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 $CO_2$ 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.

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

| | Material reserves | Non-renewable energy reserves | Atmospheric $CO_2$ concentration | Socio-economic stock | Hazardous waste |
|---|---|---|---|---|---|
| **Opening stock** | $REV_{M-1}$ | $REV_{E-1}$ | $CO2_{AT-1}$ | $SES_{-1}$ | $HWS_{-1}$ |
| **Additions to stock** | | | | | |
| Resources converted into reserves | $+CON_M$ | $+CON_E$ | | | |
| $CO_2$ emissions | | | $+EMIS$ | | |
| Production of material goods | | | | $+MY$ | |
| Non-recycled hazardous waste | | | | | $+hazW$ |
| **Reductions of stock** | | | | | |
| Extraction/use of matter or energy | $-M$ | $-EN$ | | | |
| Net transfer of $CO_2$ to oceans/biosphere | | | $+(\phi_{11}-1)CO2_{AT-1}+\phi_{21}CO2_{UP-1}$ | | |
| Demolished/disposed socio-economic stock | | | | $-DEM$ | |
| **Closing stock** | $REV_M$ | $REV_E$ | $CO2_{AT}$ | $SES$ | $HWS$ |

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

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 ($CO_2$ 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

[6] For a similar presentation of the physical stock-flow interactions see United Nations (2014).

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 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.

*2.1.1 Matter, recycling and waste*

The goods produced every year, denoted by $Y$, embody a specific amount of matter, $MY$ (Eq. 1).[7] Material intensity ($\mu$) is defined as the matter included in each output produced. The socio-economic stock ($SES$) is the material content of the capital goods ($K$) and durable consumption goods ($DC$) that remain in the socio-economic system. Thus, $SES = \mu(K + DC)$. As shown in Eq. (2), the matter embodied in goods comes from extraction ($M$ denotes the extracted matter that is used every year in the production of goods) and the demolished/discarded socio-economic stock that is recycled ($REC$). The latter is defined in Eq. (3); $\rho$ denotes the recycling rate, which is defined as the ratio of recycled matter to the total amount of demolished/discarded socio-economic stock ($DEM$). The demolished/discarded socio-economic stock 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 and $\xi$ is the proportion of durable consumption goods discarded every year. Eq. (5) shows that 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 mass 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 ($O2$) is introduced as an input in the material balance because it is

[7] For simplicity, we have assumed away the material content of the goods related with government spending ($G$).

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 $W = DEM - REC$; in other words, the waste is equal to the demolished/discarded socio-economic stock that is not recycled.

Only a small proportion ($haz$) of the waste produced every year is hazardous, i.e. it is harmful to human health or the environment.[8] This hazardous waste is added to the accumulated stock of hazardous waste, $HWS$ (Eq. 9). Eq. (10) defines the per capital accumulated hazardous waste ($hazratio$) which is equal to the accumulated stock of hazardous waste in Gt divided by the population ($POP$).

$$MY = \mu(Y - G) \tag{1}$$

$$M = MY - REC \tag{2}$$

$$REC = \rho DEM \tag{3}$$

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

$$SES = SES_{-1} + MY - DEM \tag{5}$$

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

$$CEN = \frac{EMIS_{IN}}{car} \tag{7}$$

$$O2 = EMIS_{IN} - CEN \tag{8}$$

$$HWS = HWS_{-1} + hazW \tag{9}$$

$$hazratio = \frac{HWS}{POP} \tag{10}$$

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 (in order to be used in the production of goods) and increase when resources are converted into reserves. The annual conversion ($CON_M$) is given by Eq. (12). An exogenous conversion rate, denoted by $con_M$, 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.

[8] 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).

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

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

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

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

### 2.1.2 *Energy*

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).

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

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

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

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

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 ($dep_E$), which captures scarcity problems, shows the non-renewable energy that is extracted and is used every year, relative to the remaining reserves (Eq. 22).

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

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

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

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

### 2.1.3 *Emissions and climate change*

Our formalisation of emissions and climate change follows closely the traditional integrated assessment models (see Nordhaus and Sztorc, 2013). Every year industrial $CO_2$ emissions ($EMIS_{IN}$) are generated due to the use of the non-renewable energy sources (Eq. 23). $CO_2$ intensity ($\omega$) is defined as the industrial emissions produced per unit of non-renewable energy. Every year land-use $CO_2$ 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 $CO_2$ concentration from pre-industrial levels ($CO2_{AT-PRE}$) and $S$ is the equilibrium climate sensitivity. For simplicity, the radiative forcing due to non-$CO_2$ greenhouse gas emissions ($F_{EX}$) is determined exogenously (Eq. 30).[9] Eq. (32) shows the change in the temperature of the lower ocean ($T_{LO}$).

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

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

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

$$CO2_{AT} = EMIS + \phi_{11} CO2_{AT-1} + \phi_{21} CO2_{UP-1} \quad (26)$$

$$CO2_{UP} = \phi_{12} CO2_{AT-1} + \phi_{22} CO2_{UP-1} + \phi_{32} CO2_{LO-1} \quad (27)$$

$$CO2_{LO} = \phi_{23} CO2_{UP-1} + \phi_{33} CO2_{LO-1} \quad (28)$$

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

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

[9] For the modelling of radiative forcing as an endogenous function of some key non-$CO_2$ greenhouse gas emissions, see e.g. Anthoff and Tol (2014).

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

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

*2.1.4 Ecological efficiency and technology*

The ecological efficiency of production is considered to be higher the lower is the energy, material and $CO_2$ intensity and the higher is the recycling rate. Ecological efficiency also increases when the share of renewable energy in total energy goes up. $CO_2$ intensity changes in an exogenous way. As shown in Eqs. (33) and (34), $CO_2$ intensity is reduced with a declining rate ($g_{\omega} < 0$ and $\zeta_1 > 0$).[10] This reduction is, for example, related to use of technologies, like carbon capture and storage, and the replacement of coal with other fossil fuels that generate less carbon emissions.

Since, as mentioned above, green capital is characterised by lower material and energy intensity and by higher recycling rate and share of renewable in total energy, the efficiency related to these indicators increases when the ratio of green capital ($K_G$) to conventional capital ($K_C$) rises. This is shown in Eqs. (35)-(38). $\mu$, $\rho$, $\varepsilon$ and $\theta$ denote, respectively, the material intensity, recycling rate, energy intensity and the share of renewable energy in total energy. $\varepsilon^{min}$ and $\mu^{\min}$ are the minimum potential values of energy intensity and material intensity respectively. These minimum values are approached when green capital becomes sufficiently high compared to conventional capital. $\rho^{\max}$ is the maximum potential value of recycling rate which is also approached when $K_G / K_C$ becomes sufficiently high. $\varepsilon^{max}$, $\mu^{\max}$ are, respectively, the maximum potential values of energy intensity and material intensity which are approached when green capital is equal to zero.

The use of logistic functions in Eqs. (35)-(38) allows us to take into account the processes of learning-by-doing and learning-by-installing which play a key role in the diffusion of new technologies.[11] It also allows us to derive patterns about the future trajectories of energy intensity and renewable energy that are similar with those of other studies that examine the

[10] See Nordhaus and Sztorc (2013) for a similar assumption.
[11] For the importance of these processes in energy systems and renewable energy technologies, see e.g. Kahouli-Brahmi (2009) and Tang and Popp (2016).

use of energy in the next decades (see, for instance, Jones and Warner, 2016; Peters et al., 2017).

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

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

$$\mu = \mu^{max} - \frac{\mu^{max} - \mu^{min}}{1 + \pi_1 e^{-\pi_2 (K_{G-1}/K_{C-1})}} \tag{35}$$

$$\rho = \frac{\rho^{max}}{1 + \pi_3 e^{-\pi_4 (K_{G-1}/K_{C-1})}} \tag{36}$$

$$\varepsilon = \varepsilon^{max} - \frac{\varepsilon^{max} - \varepsilon^{min}}{1 + \pi_5 e^{-\pi_6 (K_{G-1}/K_{C-1})}} \tag{37}$$

$$\theta = \frac{1}{1 + \pi_7 e^{-\pi_8 (K_{G-1}/K_{C-1})}} \tag{38}$$

### 2.2 Macroeconomy and financial system

Table 3 and Table 4 portray the transactions flow matrix and the balance sheet matrix of our macroeconomy. 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 reflect the budget constraints of the sectors. For households, firms, commercial banks and central banks a distinction is made between current and capital accounts. The current accounts register payments made or received. The capital accounts show how the investment in real and financial assets is funded. At the aggregate level, monetary inflows are equal to monetary outflows.

**Table 3:** Transactions flow matrix

| | Households | | Firms | | Commercial banks | | Government sector | Central banks | | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | Current | Capital | Current | Capital | Current | Capital | | Current | Capital | |
| Consumption | | $-C$ | $+C$ | | | | | | | 0 |
| Government expenditures | | | $+G$ | | | | $-G$ | | | 0 |
| Conventional investment | | | $+I_C$ | $-I_C$ | | | | | | 0 |
| Green investment | | | $+I_G$ | $-I_G$ | | | | | | 0 |
| Household disposable income net of depreciation | $-Y_{HD}$ | $+Y_{HD}$ | | | | | | | | 0 |
| Wages | $+wN$ | | $-wN$ | | | | | | | 0 |
| Taxes | $-T_H$ | | $-T_F$ | | | | $+T$ | | | 0 |
| Firms' profits | $+DP$ | | $-TP$ | $+RP$ | | | | | | 0 |
| Commercial banks' profits | $+BP_D$ | | | | $-BP$ | $+BP_U$ | | | | 0 |
| Interest on deposits | $+int_D D_{-1}$ | | | | $-int_D D_{-1}$ | | | | | 0 |
| Depreciation of green capital | | | $-\delta K_{G-1}$ | $+\delta K_{G-1}$ | | | | | | 0 |
| Depreciation of conventional capital | | | $-\delta K_{C-1}$ | $+\delta K_{C-1}$ | | | | | | 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 |
| Interest on conventional bonds | $+coupon_C b_{CH-1}$ | | $-coupon_C b_{C-1}$ | | | | | $+coupon_C b_{CCB-1}$ | | 0 |
| Interest on green bonds | $+coupon_G b_{GH-1}$ | | $-coupon_G b_{G-1}$ | | | | | $+coupon_G b_{GCB-1}$ | | 0 |
| Interest on government securities | $+int_S SEC_{H-1}$ | | | | $+int_S SEC_{B-1}$ | | $-int_S SEC_{-1}$ | $+int_S SEC_{CB-1}$ | | 0 |
| Interest on advances | | | | | $-int_A A_{-1}$ | | | $+int_A A_{-1}$ | | 0 |
| Depreciation of durable consumption goods | $-\xi DC_{-1}$ | $+\xi DC_{-1}$ | | | | | | | | 0 |
| Central bank's profits | | | | | | | $+CBP$ | $-CBP$ | | 0 |
| Bailout of banks | | | | | | $+BAILOUT$ | $-BAILOUT$ | | | 0 |
| Δdeposits | | $-\Delta D$ | | | | $+\Delta D$ | | | | 0 |
| Δconventional loans | | | | $+\Delta L_C$ | | $-\Delta L_C$ | | | | 0 |
| Δgreen loans | | | | $+\Delta L_G$ | | $-\Delta L_G$ | | | | 0 |
| Δconventional bonds | | $-\bar{p}_C \Delta b_{CH}$ | | $+\bar{p}_C \Delta b_C$ | | | | | $-\bar{p}_C \Delta b_{CCB}$ | 0 |
| Δgreen bonds | | $-\bar{p}_G \Delta b_{GH}$ | | $+\bar{p}_G \Delta b_G$ | | | | | $-\bar{p}_G \Delta b_{GCB}$ | 0 |
| Δgovernment securities | | $-\Delta SEC_H$ | | | | $-\Delta SEC_B$ | $+\Delta SEC$ | | $-\Delta SEC_{CB}$ | 0 |
| Δadvances | | | | | | $+\Delta A$ | | | $-\Delta A$ | 0 |
| Δhigh-powered money | | | | | | $-\Delta HPM$ | | | $+\Delta HPM$ | 0 |
| Defaulted loans | | | | $+DL$ | | $-DL$ | | | | 0 |
| Total | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

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

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. 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.

**Table 4:** Balance sheet matrix

| | Households | Firms | Commercial banks | Government sector | Central 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 |
| Conventional bonds | $+p_C b_{CH}$ | $-p_C b_C$ | | | $+p_C b_{CCB}$ | 0 |
| Green bonds | $+p_G b_{GH}$ | $-p_G b_G$ | | | $+p_G b_{GCB}$ | 0 |
| Government securities | $+SEC_H$ | | $+SEC_B$ | $-SEC$ | $+SEC_{CB}$ | 0 |
| High-powered money | | | $+HPM$ | | $-HPM$ | 0 |
| Advances | | | $-A$ | | $+A$ | 0 |
| Total (net worth) | $+V_H$ | $+V_F$ | $+K_B$ | $-SEC$ | $+V_{CB}$ | $+K_C+K_G+DC$ |

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

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

### *2.2.1 Output determination and damages*

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.[12] We define four different types of potential output. The matter-determined potential output ($Y_M^*$) is defined in Eq. (39) 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. (40) 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. (41) and is higher the higher is the capital stock and the productivity of capital ($v$). Lastly, the labour-determined potential

[12] We assume away Ricardian land.

output ($Y_N^*$) is defined in Eq. (42) 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. 43).

In line with the post-Keynesian tradition, actual output ($Y$) is demand-determined (Eq. 44): it is equal to consumption demand ($C$) plus investment demand ($I$) plus government expenditures ($G$). However, demand is not independent of supply. When actual output approaches potential output, demand tends to decline as a result of supply-side constraints. This is captured by our investment and consumption functions described below. We define four ratios which capture the extent to which potential output is utilised (Eqs. 45-48). 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.[13] 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.

$$Y_M^* = \frac{REV_{M-1} + REC}{\mu} \quad (39)$$

$$Y_E^* = \frac{REV_{E-1}}{(1-\theta)\varepsilon} \quad (40)$$

$$Y_K^* = vK \quad (41)$$

$$Y_N^* = \lambda h LF \quad (42)$$

$$Y^* = min(Y_M^*, Y_E^*, Y_K^*, Y_N^*) \quad (43)$$

$$Y = C + I + G \quad (44)$$

$$um = \frac{Y - G}{Y_M^*} \quad (45)$$

$$ue = \frac{Y}{Y_E^*} \quad (46)$$

$$u = \frac{Y}{Y_K^*} \quad (47)$$

$$re = \frac{Y}{Y_N^*} \quad (48)$$

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

[13] Recall that we have assumed away the material content of the goods related with government spending.

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 because 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). The proportion of the population that participates in the labour force might decline as a result of global warming. The reason is that climate change has an adverse impact on the health of the population (see e.g. Watts et al., 2017) and poor health reduces labour force participation. 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 conditions in workplaces and the accumulation of knowledge, climate change might decrease the ability of people to perform work tasks, reducing labour productivity (Kjellstrom et al., 2009; Dell et al., 2014; Dietz and Stern, 2015; 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.[14] Moreover, experiencing or observing the natural disasters and the health problems, households might be induced to save more for precautionary reasons.[15] This can lead to less consumption. Measures that restrict consumption directly might also be adopted as climate damages become more significant. Second, since global warming damages tend 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 consumption and investment 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. Drawing on 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

[14] 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.

[15] For some empirical evidence about the impact of natural disasters on the saving behaviour of households, see Skidmore (2001).

adaptation measures and net damages are the damages that remain after the implementation of adaptation measures.[16]

Eq. (49) 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. (49) 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 $T_{AT} = 6$°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. 73, 74, 77 and 116) and (ii) the consumption and investment demand (see Eqs. 57 and 102). 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. (50) and (51).[17]

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 $0 \le ad_P, ad_K, ad_{LF} \le 1$. 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.

$$D_T = 1 - \frac{1}{1 + \eta_1 T_{AT} + \eta_2 T_{AT}^2 + \eta_3 T_{AT}^{6.754}} \tag{49}$$

$$D_{TP} = p D_T \tag{50}$$

$$D_{TF} = 1 - \frac{1 - D_T}{1 - D_{TP}} \tag{51}$$

[16] We do not include the financial cost of the adaptation measures in net damages.
[17] See also Moyer et al. (2015).

*2.2.2 Firms*

The total gross profits of firms ($TP_G$) are given by Eq. (52); $w$ 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, $coupon_C$ denotes the coupon payments on conventional bonds, $coupon_G$ denotes the coupon payments on green bonds, $L_C$ is the amount of conventional loans, $L_G$ is the amount of green loans, $b_C$ is the number of conventional bonds, $b_G$ is the number of green bonds and $\delta$ is the depreciation of capital stock (which is assumed to be the same for green capital and conventional capital). The net profits of firms ($TP$) are equal to gross profits minus the taxes on firms' profits ($T_F$) (Eq. 53). Firms' retained profits ($RP$) are a proportion ($s_F$) of their total profits (Eq. 54). The distributed profits of firms ($DP$) are determined as a residual (Eq. 55). Eq. (56) gives the rate of retained profits ($r$).

$$TP_G = Y - wN - int_C\, L_{C-1} - int_G\, L_{G-1} - \delta K_{-1} - coupon_C b_{C-1} - coupon_G b_{G-1} \quad (52)$$

$$TP = TP_G - T_F \quad (53)$$

$$RP = s_F TP_{-1} \quad (54)$$

$$DP = TP - RP \quad (55)$$

$$r = RP/K \quad (56)$$

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. (57) captures the first stage. The desired investment ($I^D$), adjusted for the damage effect, is equal to net investment plus the depreciated capital; $\alpha_{00}$, $\alpha_{01}$, $\alpha_1$, $\alpha_2$, $\alpha_{31}$, $\alpha_{41}$ and $\alpha_{51}$ are parameters.

Net investment is affected by a number of factors. First, following the Kaleckian approach (see e.g. Blecker, 2002), it depends positively on the rate of (retained) profits ($r$) and the rate of capacity utilisation ($u$). The impact of these factors is assumed to be non-linear in general line with the tradition that draws on Kaldor (1940). This means that when the profit rate and capacity utilisation are very low or very high, their effects on investment become rather small.

Second, following Skott and Zipperer (2012), we assume a non-linear impact of the unemployment rate ($ur$) on investment: when unemployment approaches zero, there is a scarcity of labour that discourages entrepreneurs to invest. This employment effect captures Marx's and Kalecki's insights, according to which high employment strengthens the power of workers, having an adverse impact on the business climate. Theoretically, this negative effect of employment could be put into question in the presence of immigration and labour-augmenting investment. In the presence of immigration, entrepreneurs can expect that the flow of immigrants will relax the labour shortage constraint. Thus, investment might not decline when employment approaches the full employment level. However, this does not apply in our model, since we analyse the global economy and, thus, there is no immigration effect. Regarding labour-augmenting investment, it could be argued that when entrepreneurs observe an unemployment rate close to zero, they could relax the labour shortage constraint by increasing investment that enhances labour productivity. However, the adverse impact of climate change on labour productivity, that takes place in our model, makes it more difficult for the entrepreneurs to expect that more investment in labour-augmenting technologies would relax the labour shortage constraint. Therefore, in the presence of climate change, it is less likely that firms will try to invest more in order to increase productivity and reduce the employment rate.[18]

Third, the scarcity of energy and material resources can dampen investment, for example because of a rise in resource prices; $ue$ and $um$ capture the utilisation of energy and material resources respectively. This impact, however, is highly non-linear: energy and material scarcity affects investment only once the depletion of the resources has become very severe.

Forth, in order to capture exogenous random factors that might affect desired investment, we have assumed that $I^D$ also depends on a random component, $\varepsilon_I$, that follows a stochastic AR(1) process. Overall, our investment function implies that demand declines (or stops increasing) when it approaches potential output. This allows us to take explicit into account the environmental supply-side effects on aggregate demand mentioned above.

The second stage of the investment process is reflected in Eqs. (58)-(62). At this stage firms decide about the proportion, $\beta$, of green investment ($I_G^D$) in the overall desired investment (Eq. 58). Desired conventional investment ($I_C^D$) is determined as a residual (Eq. 59). The proportion of green investment depends on two factors (Eq. 60). The first factor is captured

[18] Note, though, that our model takes into account the general role of labour-augmenting technologies by using the Kaldor-Verdoorn law in the determination of labour productivity.

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/policy changes that promote green investment (such as carbon pricing). It is assumed that $\beta_0$ increases every year but with a declining rate (Eqs. 61 and 62). $\beta_1$ is constant but can change due to exogenous institutional, technological or policy shocks. The second factor, captured by the term $\beta_2[sh_{L-1}(int_G - int_C) + (1 - sh_{L-1})(yield_{G-1} - yield_{C-1})]$, reflects the borrowing cost of investing in green capital relative to conventional capital; $yield_C$ is the yield on conventional bonds, $yield_G$ is the yield on green bonds and $sh_L$ is the share of loans in the total liabilities of firms (loans plus bonds). As the cost of borrowing of green capital (via bank lending or bonds) declines compared to conventional capital, firms tend to increase green investment.

As mentioned above, retained profits are not in general sufficient to cover the desired investment expenditures. This means that firms need external finance, which is obtained via bonds and bank loans. It is assumed that firms first issue bonds and then demand new loans from banks in order to cover the rest amount of their desired expenditures. Only a proportion of the demanded new loans is provided.[19] In other words, the model assumes that there is a quantity rationing of credit. This is in line with recent empirical evidence that shows that the quantity rationing of credit is a more important driver of macroeconomic activity than the price rationing of credit (see Jakab and Kumhof, 2015).

Eq. (63) gives the desired new green loans ($NL_G^D$) and Eq. (64) gives the desired new conventional loans ($NL_C^D$). The green, conventional and total investment goods after credit rationing are shown in Eqs. (65), (66) and (67); $I_G$ is green investment, $I_C$ is conventional investment, $\bar{p}_C$ is the par value of conventional bonds, $\bar{p}_G$ is the par value of green bonds, $DL$ is the amount of defaulted loans and $def$ is the rate of default. The total loans of firms ($L$) are equal to conventional loans plus green loans (Eq. 68). The change in green and conventional capital stock is equal to gross investment minus the depreciation of capital (Eqs. 69 and 70). Eq. (71) 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 ($\kappa$) is given by Eq. (72).

$$I^D = \left( \frac{\alpha_{00}}{1 + exp\left(\alpha_{01} - \alpha_1 u_{-1} - \alpha_2 r_{-1} + \alpha_{31} ur_{-1}^{-\alpha_{32}} + \alpha_{41}\left(1 - ue_{-1}\right)^{-\alpha_{42}} + \alpha_{51}\left(1 - um_{-1}\right)^{-\alpha_{52}}\right)} K_{-1} + \varepsilon_I K_{-1} + \delta K_{-1} \right)\left(1 - D_{T-1}\right) \quad (57)$$

[19] See also Dafermos (2012) and Nikolaidi (2014).

$$I_G^D = \beta I^D \quad (58)$$

$$I_C^D = I^D - I_G^D \quad (59)$$

$$\beta = \beta_0 + \beta_1 - \beta_2 \left[ sh_{L-1} \left( int_G - int_C \right) + \left(1 - sh_{L-1}\right)\left( yield_{G-1} - yield_{C-1} \right) \right] \quad (60)$$

$$\beta_0 = \beta_{0-1}(1 + g_{\beta 0}) \quad (61)$$

$$g_{\beta 0} = g_{\beta 0-1}(1 - \zeta_2) \quad (62)$$

$$NL_G^D = I_G^D - \beta RP + repL_{G-1} - \delta K_{G-1} - \bar{p}_G \Delta b_G \quad (63)$$

$$NL_C^D = I_C^D - (1 - \beta) RP + repL_{C-1} - \delta K_{C-1} - \bar{p}_C \Delta b_C \quad (64)$$

$$I_G = \beta RP + \Delta L_G + \delta K_{G-1} + \bar{p}_G \Delta b_G + defL_{G-1} \quad (65)$$

$$I_C = RP + \Delta L_C + \Delta L_G + \delta K_{-1} - I_G + \bar{p}_G \Delta b_G + \bar{p}_C \Delta b_C + DL \quad (66)$$

$$I = I_C + I_G \quad (67)$$

$$L = L_C + L_G \quad (68)$$

$$K_G = K_{G-1} + I_G - \delta K_{G-1} \quad (69)$$

$$K_C = K_{C-1} + I_C - \delta K_{C-1} \quad (70)$$

$$K = K_C + K_G \quad (71)$$

$$\kappa = K_G / K \quad (72)$$

Eq. (73) 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. 41); in addition, desired investment might go down because depreciation affects the profitability of firms. On the other hand, aggregate demand tends to increase because a higher depreciation leads to higher gross investment (see Eq. 57).

Eqs. (74) and (77) refer to capital and labour productivity respectively. As argued above, both productivities are influenced by climate change. Labour productivity is affected by exogenous technology factors reflected in the term $\sigma_0 + \sigma_1$ (see Eq. 75). These factors increase productivity growth ($g_\lambda$) 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. 42).

Eq. (78) gives the wage rate. The wage share ($s_W$) is assumed to be exogenous. The number of employees is determined by Eq. (79). The unemployment rate is defined in Eq. (80).

$$\delta = \delta_0 + (1-\delta_0)(1-ad_K)D_{TF-1} \quad (73)$$

$$v = v_{-1}[1-(1-ad_P)D_{TP-1}] \quad (74)$$

$$g_\lambda = \sigma_0 + \sigma_1 + \sigma_2 g_{Y-1} \quad (75)$$

$$\sigma_0 = \sigma_{0-1}(1-\zeta_3) \quad (76)$$

$$\lambda = \lambda_{-1}(1+g_\lambda)[1-(1-ad_P)D_{TP-1}] \quad (77)$$

$$w = s_W \lambda h \quad (78)$$

$$N = \frac{Y}{h\lambda} \quad (79)$$

$$ur = 1 - re \quad (80)$$

For simplicity, the bonds issued by firms are assumed to be one-year coupon bonds.[20] Once they have been issued at their par value, their market price and yield are determined according to their demand. Firms set the coupon rate of bonds based on their yield in the previous year. This means that an increase in the market price of bonds compared to their par value causes a decrease in their yield, allowing firms to issue new bonds with a lower coupon rate.

Eqs. (81) and (82) show the proportion of firms' desired investment which is funded via conventional and green bonds respectively; $x_1$ is the proportion of firms' conventional desired investment financed via bonds, $x_2$ is the proportion of firms' green desired investment funded via bonds, $\bar{p}_C$ is the par value of conventional bonds and $\bar{p}_G$ is the par value of green bonds. Eqs. (83)-(84) show that the proportion of desired investment covered by green or conventional bonds is a negative function of the bond yield. In other words, firms fund a lower proportion of their investment via bonds when the cost of borrowing increases. Eqs. (85) and (86) show that the growth rate of the proportion of firms' green desired investment funded via bonds ($g_{x20}$) increases with a declining rate ($g_{x20} > 0$ and $\zeta_4 > 0$). This reflects the fact that the green bond market is expected to expand in the next years and firms are likely to use this market more in order to fund their green investment.

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[20] This assumption, which does not change the essence of the analysis, allows us to abstract from complications that would arise from having firms that accumulate bonds with different maturities.

Eqs. (87) and (88) show the yield of conventional and green bonds, respectively. The yield of bonds is equal to the coupon payments of the bonds divided by their market price. When this yield increases, the coupon payment (for a given par value) goes up. This is captured by Eqs. (89) and (90). Note that the coupon rate is given by the coupon payment divided by the par value. Thus, when the yield increases, the coupon rate increases too. Eqs. (91) and (92) define the value of conventional bonds ($B_C$) and green bonds ($B_G$) respectively; $B_{CH}$ is the value of conventional bonds held by households, $B_{CCB}$ is the value of conventional bonds held by central banks, $B_{GH}$ is the value of green bonds held by households and $B_{GCB}$ is the value of green bonds held by central banks. We postulate a price-clearing mechanism in the bond market (see Eqs. 93 and 94). $p_C$ is the market price of conventional bonds and $p_G$ is the market price of green bonds. Eq. (95) shows the value of total bonds ($B$) that is equal to the value of conventional plus the value of green bonds.

$$b_C = b_{C-1} + \frac{x_1 I_C^D}{\bar{p}_C} \tag{81}$$

$$b_G = b_{G-1} + \frac{x_2 I_G^D}{\bar{p}_G} \tag{82}$$

$$x_1 = x_{10} - x_{11} yield_{C-1} \tag{83}$$

$$x_2 = x_{20} - x_{21} yield_{G-1} \tag{84}$$

$$x_{20} = x_{20-1}(1 + g_{x20}) \tag{85}$$

$$g_{x20} = g_{x20-1}(1 - \zeta_4) \tag{86}$$

$$yield_C = \frac{coupon_C}{p_C} \tag{87}$$

$$yield_G = \frac{coupon_G}{p_G} \tag{88}$$

$$coupon_C = yield_{C-1} \bar{p}_C \tag{89}$$

$$coupon_G = yield_{G-1} \bar{p}_G \tag{90}$$

$$B_C = B_{CH} + B_{CCB} \tag{91}$$

$$B_G = B_{GH} + B_{GCB} \tag{92}$$

$$p_C = \frac{B_C}{b_C} \tag{93}$$

$$p_G = \frac{B_G}{b_G} \tag{94}$$

$$B = B_C + B_G \tag{95}$$

Firms might default on their loans. When this happens, a part of their accumulated loans is not repaid, deteriorating the financial position of banks. The amount of defaulted loans ($DL$) is a proportion ($def$) of total loans of firms (see Eq. 96). The rate of default ($def$) is assumed to increase when firms become less liquid (see Eq. 97); $def^{max}$ is the maximum default rate and $def_0$, $def_1$ and $def_2$ are parameters.[21] This suggests that, as cash outflows increase compared to cash inflows, the ability of firms to repay their debt declines. The illiquidity of firms is captured by an illiquidity ratio, $illiq$, which expresses the cash outflows of firms relative to their cash inflows (see Eq. 98). Cash outflows include wages, interest, taxes, loan repayments and maintenance capital expenditures (which are equal to depreciation). Cash inflows comprise the revenues from sales and the funds obtained from bank loans and the issuance of bonds. $CR_C$ is the degree of credit rationing on conventional loans and $CR_G$ is the degree of credit rationing on green loans. Eq. (99) defines the debt service ratio ($dsr$), which is the ratio of debt payment commitments (interest plus principal repayments) to profits before interest. Its key difference with the illiquidity ratio is that the latter takes into account the new flow of credit.

$$DL = def L_{-1} \tag{96}$$

$$def = \frac{def^{max}}{1 + def_0 \, exp\left(def_1 - def_2 illiq_{-1}\right)} \tag{97}$$

$$illiq = \frac{\left(int_C + rep\right)L_{C-1} + \left(int_G + rep\right)L_{G-1} + coupon_C b_{C-1} + coupon_G b_{G-1} + wN + T_F + \delta K_{-1}}{Y + \left(1 - CR_C\right)NL_C^D + \left(1 - CR_G\right)NL_G^D + p_C \Delta b_C + p_G \Delta b_G} \tag{98}$$

$$dsr = \frac{\left(int_C + rep\right)L_{C-1} + \left(int_G + rep\right)L_{G-1} + coupon_C b_{C-1} + coupon_G b_{G-1}}{TP + int_C \, L_{C-1} + int_G \, L_{G-1} + coupon_C b_{C-1} + coupon_G b_{G-1}} \tag{99}$$

### *2.2.3 Households*

Eq. (100) gives the gross disposable income of households ($Y_{HG}$); $BP_D$ denotes the distributed profits of banks, $int_D$ is the interest rate on deposits, $D$ is the amount of deposits, $int_S$ is the interest rate on government securities, $SEC_H$ is the amount of government securities held by households, $b_{CH}$ is the number of conventional corporate bonds held by households and $b_{GH}$ is the number of green bonds held by households. Eq. (101) defines the net disposable income of households ($Y_H$), which is equal to the gross disposable income minus the taxes on households' gross disposable income ($T_H$). Households' consumption ($C_N$), adjusted for

[21] We use a logistic function, in similar lines with Caiani et al. (2016).

global warming damages, depends on lagged income (which is a proxy for the expected one) and lagged financial wealth (Eq. 102). However, Eq. (102) holds only when there are no supply-side constraints; in that case, $C = C_N$ . If the overall demand in the economy is higher than the supply-determined output, $Y^*$, consumption adjusts such that the overall demand in the economy is below $Y^*$; note that $pr$ is slightly lower than 1. This is shown in Eq. (103).

$$Y_{HG} = wN + DP + BP_D + int_D\, D_{-1} + int_S\, SEC_{H-1} + coupon_C b_{CH-1} + coupon_G b_{GH-1} \tag{100}$$

$$Y_H = Y_{HG} - T_H \tag{101}$$

$$C_N = (c_1 Y_{H-1} + c_2 V_{HF-1})(1 - D_{T-1}) \tag{102}$$

$$C = C_N \text{ if } C_N + I + G < Y^*\text{; otherwise } C = pr\left(Y^* - G - I\right) \tag{103}$$

Eq. (104) defines the financial wealth of households ($V_{HF}$). Households invest their expected financial wealth in four different assets: government securities ($SEC_H$), conventional corporate bonds ($B_{CH}$), green corporate bonds ($B_{GH}$) and deposits ($D$). In the portfolio choice, captured by Eqs. (105)-(108n), Godley's (1999) imperfect asset substitutability framework is adopted.[22]

Households' asset allocation is driven by three factors. The first factor is the global warming damages. We posit that damages affect households' confidence and increase the precautionary demand for more liquid and less risky assets (see also Batten et al., 2016). Since damages destroy capital and the profitability opportunities of firms, we assume that as $D_T$ increases, households reduce their holding of corporate conventional bonds and increase the proportion of their wealth held in deposits and government securities which are considered safer.[23] Second, asset allocation responds to alterations in the relative rates on return. The holding of each asset relies positively on its own rate of return and negatively on the other assets' rate of return. Third, a rise in the transactions demand for money (as a result of higher expected income) induces households to substitute deposits for other assets.[24]

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[22] The parameters in the portfolio choice equations satisfy the horizontal, vertical and symmetry constraints.

[23] It could be argued that the demand for green corporate bonds is also affected negatively by the climate change damages that harm firms' financial position. However, climate change damages might at the same time induce households to hold more green bonds in order to contribute to the restriction of global warming. Hence, the overall impact of damages on the demand of green bonds is ambiguous. For this reason, we assume that $\lambda'_{30} = 0$ in our simulations.

[24] Note that balance sheet restrictions require that Eq. (108n) must be replaced by Eq. (108) in the computer simulations.

Eqs. (109) and (110) show that the growth rate of households' portfolio choice parameter ($\lambda_{30}$) related to the autonomous demand for green bonds ($g_{\lambda 30}$) increases with a declining rate ($g_{\lambda 30} > 0$ and $\zeta_4 > 0$). This captures the fact that the preference for green bonds is expected to increase in the next years. Eq. (111) and (112) show the number of conventional and green bonds held by households.

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. 113).

$$V_{HF} = V_{HF-1} + Y_H - C + b_{CH-1}\Delta p_C + b_{GH-1}\Delta p_G \quad (104)$$

$$\frac{SEC_H}{V_{HF-1}} = \lambda_{10} + \lambda'_{10} D_{T-1} + \lambda_{11} int_S + \lambda_{12} yield_{C-1} + \lambda_{13} yield_{G-1} + \lambda_{14} int_D + \lambda_{15} \frac{Y_{H-1}}{V_{HF-1}} \quad (105)$$

$$\frac{B_{CH}}{V_{HF-1}} = \lambda_{20} + \lambda'_{20} D_{T-1} + \lambda_{21} int_S + \lambda_{22} yield_{C-1} + \lambda_{23} yield_{G-1} + \lambda_{24} int_D + \lambda_{25} \frac{Y_{H-1}}{V_{HF-1}} \quad (106)$$

$$\frac{B_{GH}}{V_{HF-1}} = \lambda_{30} + \lambda'_{30} D_{T-1} + \lambda_{31} int_S + \lambda_{32} yield_{C-1} + \lambda_{33} yield_{G-1} + \lambda_{34} int_D + \lambda_{35} \frac{Y_{H-1}}{V_{HF-1}} \quad (107)$$

$$\frac{D}{V_{HF-1}} = \lambda_{40} + \lambda'_{40} D_{T-1} + \lambda_{41} int_S + \lambda_{42} yield_{C-1} + \lambda_{43} yield_{G-1} + \lambda_{44} int_D + \lambda_{45} \frac{Y_{H-1}}{V_{HF-1}} \quad (108n)$$

$$D = D_{-1} + Y_H - C - \Delta SEC_H - \bar{p}_C \Delta b_{CH} - \bar{p}_G \Delta b_{GH} \quad (108)$$

$$\lambda_{30} = \lambda_{30-1}(1 + g_{\lambda 30}) \quad (109)$$

$$g_{\lambda 30} = g_{\lambda 30-1}(1 - \zeta_4) \quad (110)$$

$$b_{CH} = \frac{B_{CH}}{p_C} \quad (111)$$

$$b_{GH} = \frac{B_{GH}}{p_G} \quad (112)$$

$$DC = DC_{-1} + C - \xi DC_{-1} \quad (113)$$

Eqs. (114) and (115) show that the growth rate of population ($g_{POP}$) increases with a declining rate ($g_{POP} > 0$ and $\zeta_5 > 0$), reflecting the projections of United Nations (2017). As mentioned above, climate change reduces the ratio labour force to population ratio (Eq. 116). However, there are two additional factors that drive the change in labour force. First, in line with the population projections of United Nations (2017), there are some fundamental dynamics that influence fertility and mortality and tend to reduce the labour force to population ratio. This is reflected in the term $lf_1$ (see Eq. 117). Second, the accumulation of hazardous waste creates health problems (for instance, carcinogenesis and congenital anomalies) that affect the proportion of the population that is able to work ($\zeta_6 > 0$).

$$g_{POP} = g_{POP-1}(1-\zeta_5) \quad (114)$$

$$POP = POP_{-1}(1+g_{POP}) \quad (115)$$

$$LF = (lf_1 - lf_2 hazratio_{-1})(1-(1-ad_{LF})D_{TF-1})POP \quad (116)$$

$$lf_1 = lf_{1-1}(1-\zeta_6) \quad (117)$$

*2.2.4 Commercial banks*

The profits of banks ($BP$) are equal to the interest on both conventional and green loans plus the interest on government bonds minus the sum of the interest on deposits and the interest on advances (Eq. 118); $SEC_B$ stands for the government securities that banks hold, $int_A$ is the interest rate on advances and $A$ is the advances. As shown in Eq. (119), the change in the capital of banks ($K_B$) is equal to their undistributed profits ($BP_U$) minus the amount of defaulted loans plus the amount of bailout of the government ($BAILOUT$). The undistributed profits of banks are a proportion ($s_B$) of total profits of banks (see Eq. 120). The distributed profits of banks are determined as the residual (see Eq. 121). According to Eqs. (122) and (123), high-powered money ($HPM$) and the government securities held by banks are a proportion of deposits. Advances are determined as a residual from the budget constraint of banks (see Eq. 124).[25]

$$BP = int_C L_{C-1} + int_G L_{G-1} + int_S SEC_{B-1} - int_D D_{-1} - int_A A_{-1} \quad (118)$$

$$K_B = K_{B-1} + BP_U - DL + BAILOUT \quad (119)$$

$$BP_U = s_B BP_{-1} \quad (120)$$

$$BP_D = BP - BP_U \quad (121)$$

$$HPM = h_1 D \quad (122)$$

$$SEC_B = h_2 D \quad (123)$$

$$A = A_{-1} + \Delta HPM + \Delta L_G + \Delta L_C + \Delta SEC_B + DL - \Delta D - BP_U - BAILOUT \quad (124)$$

As mentioned above, banks impose credit rationing on the loans demanded by firms: they supply only a proportion of demanded loans. Following the empirical evidence presented in

[25] Note that if the amount of advances turns out to be negative, the role of residual is played by the government securities.

Lown and Morgan (2006), the degree of credit rationing both on conventional loans ($CR_C$) and green loans ($CR_G$) relies on the financial health of both firms and banks (see Eqs. 125 and 126). In particular, credit rationing increases as the debt service ratio of firms ($dsr$) increases, as the bank leverage ($lev_B$) increases relative to its maximum acceptable value ($lev_B^{max}$) and as the capital adequacy ratio ($CAR$) decreases compared to its minimum acceptable value ($CAR^{min}$). As in the case of investment, we assume that credit rationing is also dependent on a random component, $\varepsilon_{CR}$, that follows a stochastic AR(1) process; $CR^{max}$ is the maximum degree of credit rationing. Note that $r_0$, $r_1$, $r_2$, $r_3$, $r_4$, $l_0$, $l_1$, $l_2$, $l_3$ and $l_4$ are parameters.

The conventional loans and green loans are defined in Eqs. (127) and (128). Eq. (129) and (130) show the bank leverage ratio and the capital adequacy ratio of banks; $w_L$ and $w_S$ are the risk weights on loans and securities respectively. We assume that when the bank leverage ratio becomes higher than its maximum value and/or the capital adequacy ratio falls below its minimum value, the government steps in and bailouts the banking sector in order to avoid a financial collapse. The bailout takes the form of a capital transfer. This means that it has a negative impact on the fiscal balance and the government acquires no financial assets as a result of its intervention (see Popoyan et al., 2017 for a similar assumption). The bailout funds are equal to the amount that is necessary for the banking sector to restore the capital needed in order to comply with the regulatory requirements.

$$CR_C = \frac{CR^{max}}{1 + r_0\, exp\left(r_1 - r_2 dsr_{-1} - r_3\left(lev_{B-1} - lev_B^{max}\right) + r_4\left(CAR_{-1} - CAR^{min}\right)\right)} + \varepsilon_{CR} \quad (125)$$

$$CR_G = \frac{CR^{max}}{1 + l_0\, exp\left(l_1 - l_2 dsr_{-1} - l_3\left(lev_{B-1} - lev_B^{max}\right) + l_4\left(CAR_{-1} - CAR^{min}\right)\right)} + \varepsilon_{CR} \quad (126)$$

$$L_C = L_{C-1} + \left(1 - CR_C\right)NL_C^D - repL_{C-1} - defL_{C-1} \quad (127)$$

$$L_G = L_{G-1} + \left(1 - CR_G\right)NL_G^D - repL_{G-1} - defL_{G-1} \quad (128)$$

$$lev_B = \left(L_C + L_G + SEC_B + HPM\right)/K_B \quad (129)$$

$$CAR = K_B/\left[w_L\left(L_C + L_G\right) + w_S SEC_B\right] \quad (130)$$

*2.2.5 Government sector*

The government sector issues securities ($SEC$) in order to fund its deficit (Eq. 131). The government debt is therefore equal to the accumulated amount of securities. The revenues of the government are equal to taxes ($T$) plus the central bank profits ($CBP$). The total spending of the government consists of government expenditures that are used to buy goods produced by the private sector, the interest on debt and the amount of money used for the bailout of banks. Government expenditures grow at an exogenous rate ($gov$) (see Eq. 132). The taxes on households' disposable income are a proportion ($\tau_H$) of the gross disposable income (see Eq. 133) and the taxes on firms' profits are a proportion ($\tau_F$) of total gross profits (see Eq. 134). The total taxes are equal to the sum of taxes on households and the taxes on firms (see Eq. 135).

$$SEC = SEC_{-1} + G - T + ints\, SEC_{-1} - CBP + BAILOUT \quad (131)$$

$$G = gov Y_{-1} \quad (132)$$

$$T_H = \tau_H Y_{HG-1} \quad (133)$$

$$T_F = \tau_F TP_{G-1} \quad (134)$$

$$T = T_H + T_F \quad (135)$$

### *2.2.6 Central banks*

Central banks determine the base interest rate, provide liquidity to commercial banks (via advances) and buy government securities (acting as residual purchasers). Moreover, in the context of quantitative easing (QE) programmes, they buy bonds issued by the firm sector.[26] Currently, central banks do not explicitly distinguish between the holdings of conventional and green bonds. However, in order to analyse the implications of a green QE programme, we assume that central banks announce separately the amount of conventional bond and green bond purchases.

Nonetheless, the implementation of a green QE programme should not be viewed as a simple extension of the current corporate sector purchase programme of central banks. The current corporate QE programmes have as an aim to improve credit conditions in order to help central banks achieve their inflation targets and they are meant to be of temporary nature. On

[26] These bonds are bought on the primary market (the essence of our analysis does not change if we also consider purchases on the secondary market). The purchase of corporate bonds by central banks leads to a temporary increase in the deposits of firms, which is matched by an increase in the excess reserves of commercial banks; the latter are used as intermediaries for the transactions between firms and the central bank. However, firms use all these deposits in order to fund their investment. This means that excess reserves do not appear on the end-of-period balance sheet of commercial banks. Moreover, an implicit assumption that is made is that the temporary increase in the excess reserves of banks does not disrupt the ability of central banks to control the base interest rate, for example because there is a corridor or a floor system in place (for the role of these systems in central bank interest rate setting, see Lavoie, 2014, ch. 4).

the contrary, a green QE would be a kind of industrial policy with a much longer-term commitment. Hence, the decision of central banks to conduct such a programme would require a re-consideration of their mandate or a different interpretation of their role in ensuring financial stability in economies that might face increasing climate-related financial risks. This is especially the case for the central banks of high-income countries, which have narrower mandates and a more strictly defined role in comparison with the central banks of low-income countries (see Campiglio et al., 2018).

The profits of the central bank are defined in Eq. (136); $b_{CCB}$ is the number of conventional corporate bonds held by central banks, $b_{GCB}$ is the number of green bonds held by central banks and $SEC_{CB}$ are the government securities held by central banks.

The value of green corporate bonds held by central banks ($B_{GCB}$) is a share ($s_G$) of total outstanding green bonds (see Eq. 137). We assume that this share is currently equal to zero since central banks do not implement green QE programmes. The value of conventional corporate bonds held by central banks ($B_{CCB}$) is a share ($s_C$) of total outstanding conventional bonds (see Eq. 138). Currently, this share is very low since the corporate bond purchases of central banks represent a very small proportion of the total bond market.

Eqs. (139) and (140) define the number of conventional corporate bonds held by central banks and the number of green bonds held by central banks respectively. Eq. (141) shows the government securities held by central banks. Eq. (142-red) reflects the capital account of banks and 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.

$$CBP = coupon_C b_{CCB-1} + coupon_G b_{GCB-1} + int_A A_{-1} + int_S SEC_{CB-1} \tag{136}$$

$$B_{GCB} = s_G B_{G-1} \tag{137}$$

$$B_{CCB} = s_C B_{C-1} \tag{138}$$

$$b_{CCB} = \frac{B_{CCB}}{p_C} \tag{139}$$

$$b_{GCB} = \frac{B_{GCB}}{p_G} \tag{140}$$

$$SEC_{CB} = SEC - SEC_H - SEC_B \tag{141}$$

$$SEC_{CB} = SEC_{CB-1} + \Delta HPM - \Delta A - \bar{p}_C \Delta b_{CCB} - \bar{p}_G \Delta b_{GGB} \tag{142-red}$$

## 3. Baseline scenario

Our baseline scenario represents a 'business as usual' pathway whereby the global economy continues to expand in broad line with recent trends, and ecological efficiency improves moderately due to the continuation of technological changes and the implementation of some policies that promote green investment. Some key features of our baseline scenario are shown in Table 5. It is assumed that the economy grows on average at a rate slightly lower than 2.7% till 2050; in other words, we postulate an economic expansion a little bit lower than the one observed over the last two decades or so.[27] The unemployment rate remains, on average, close to 6% till 2050. Drawing on the United Nations (2017) population projections (medium fertility variant), the population is assumed to grow at a declining rate, becoming equal to around 9.77bn people in 2050. Moreover, the default rate on corporate loans is assumed to remain, on average, close to its current level, which is slightly higher that 4%.

**Table 5:** Key features of the baseline scenario

| **Variable** | **Value/trend** |
|---|---|
| Economic growth till 2050 | slightly lower than 2.7% (on average) |
| Unemployment rate till 2050 | slightly lower than 6% (on average) |
| Population in 2050 | 9.77bn |
| Labour force-to-population ratio in 2050 | 0.45 |
| Default rate till 2050 | slightly higher than 4% (on average) |
| $CO_2$ intensity in 2050 as a ratio of $CO_2$ intensity in 2016 | around 0.9 |
| Share of renewable energy in total energy in 2050 | around 25% |
| Material intensity in 2050 as a ratio of material intensity in 2016 | around 0.9 |
| Energy intensity in 2050 as a ratio of energy intensity in 2016 | around 0.7 |
| Recycling rate in 2050 as a ratio of recycling rate in 2016 | around 1.4 |
| Annual green investment in the period 2016-2040 | around US$1.1tn |
| Energy use in 2040 as a ratio of energy use in 2016 | around 1.4 |
| Yield of conventional bonds | quite stable till around 2050 |
| Yield of green bonds | declines slightly in the next decade or so |

$CO_2$ intensity (which captures the industrial emissions per unit of fossil-fuel energy) declines by 10% till 2050, for example due to the continuation in the replacement of coal with gas and the use of carbon capture and storage technologies.[28] The share of renewable energy increases to about 25% till 2050 (from about 14% which is the current level), while energy intensity is assumed to become approximately 30% lower in 2050 compared to its 2016 level. Material

[27] Based on data from World Bank.

[28] For the importance of these factors in the determination of $CO_2$ intensity, see e.g. Peters et al. (2017).

intensity and recycling rate also improve. The overall improvement in ecological efficiency indicators is associated with the accumulation of green capital. In our baseline scenario the annual green investment during the period 2016-2040 is equal to around US$1.1tn.[29] The annual use of energy is 40% higher in 2040 compared to 2016.[30]

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

[29] Note that IEA (2016, p. 82) estimates that the annual investment in renewables and energy efficiency that is necessary over the period 2016-2040 in order to avoid a global warming higher that 2°C is close to US$2tn. Recall that green investment in our model does not only include investment in renewables and energy efficiency: it also includes investment that improves material intensity and the recycling rate.

[30] In the Current Policies Scenario presented in IEA (2016) the energy use in 2040 is 43% higher compared to 2016.

# 4. Symbols and values

**Table 6:** Symbols and initial values for endogenous variables (baseline scenario)

| Symbol | Description | Value | Remarks/sources |
|---|---|---|---|
| A | Advances (trillion US$) | 6.8 | Calculated from the identity $K_B=L_C+L_G+HPM+SEC_B-A-D$ using the initial values of $K_B$, $L_C$, $L_G$, $HPM$, $SEC_B$ and $D$ |
| $B$ | Value of total corporate bonds (trillion US$) | 12.0 | Based on OECD (2017, p. 21); we use the figure for the debt securities issued by non-financial corporations |
| $BAILOUT$ | Bailout funds provided to the banking system from the government sector | 0 | No bailout is assumed in 2016 since $lev_B<lev_B^{max}$ and $CAR>CAR^{min}$ |
| $B_C$ | Value of conventional corporate bonds (trillion US$) | 11.8 | Calculated from Eq. (95) using the initial values of $B$ and $B_G$ |
| $b_C$ | Number of conventional corporate bonds (trillions) | 0.118 | Calculated from Eq. (93) using the initial values of $p_C$ and $B_C$ |
| $B_{CCB}$ | Value of conventional corporate bonds held by central banks (trillion US$) | 0.1 | Based on the recent holdings of central banks as part of their corporate sector purchase programmes |
| $b_{CCB}$ | Number of conventional corporate bonds held by central banks (trillions) | 0.001 | Calculated from Eq. (139) using the initial values of $p_C$ and $B_{CCB}$ |
| $B_{CH}$ | Value of conventional corporate bonds held by households (trillion US$) | 11.7 | Calculated from Eq. (91) using the initial values of $B_{CCB}$ and $B_C$ |
| $b_{CH}$ | Number of conventional corporate bonds held by households (trillions) | 0.1 | Calculated from Eq. (111) using the initial values of $p_C$ and $B_{CH}$ |
| $B_G$ | Value of green corporate bonds (trillion US$) | 0.25 | Based on Climate Bonds Initiative (2017a); we use the value of the climate-alligned bonds that has been issued by the financial and the non-financial corporate sector |
| $b_G$ | Number of green corporate bonds (trillions) | 0.003 | Calculated from Eq. (94) using the initial values of $p_G$ and $B_G$ |
| $B_{GCB}$ | Value of green corporate bonds held by central banks (trillion US$) | 0 | There was no green QE programme in 2016 |
| $b_{GCB}$ | Number of green corporate bonds held by central banks (trillions) | 0 | Calculated from Eq. (140) using the initial values of $p_G$ and $B_{GCB}$ |
| $B_{GH}$ | Value of green corporate bonds held by households (trillion US$) | 0.25 | Calculated from Eq. (92) using the initial values of $B_G$ and $B_{GCB}$ |
| $b_{GH}$ | Number of green corporate bonds held by households (trillions) | 0.0025 | Calculated from Eq. (112) using the initial values of $p_G$ and $B_{GH}$ |
| $BP$ | Profits of banks (trillion US$) | 3.01 | Calculated from Eq. (118) using the initial values of $L_C$, $L_G$, $SEC_B$, $D$ and $A$ |
| $BP_D$ | Distributed profits of banks (trillion US$) | 0.54 | Calculated from Eq. (121) using the initial values of $BP$ and $BP_U$ |
| $BP_U$ | Retained profits of banks (trillion US$) | 2.47 | Calculated from Eq. (120) using the initial value of $BP$ |
| $C$ | Consumption (trillion US$) | 48.3 | No supply-side constraints are assumed in 2016 since $C_N+I+G<Y^*$; therefore $C=C_N$ |
| $C_N$ | Consumption when no supply-side constraints exist (trillion US$) | 48.3 | Calculated from Eq. (44) using the initial values of $Y$, $G$ and $I$ (since $C=C_N$) |
| $CAR$ | Capital adequacy ratio | 0.1 | Calculated from Eq. (130) using the initial values of $K_B$, $L_C$, $L_G$ and $SEC_B$ |
| $CBP$ | Central banks' profits (trillion US$) | 0.2 | Calculated from Eq. (136) using the initial values of $coupon_C$, $b_{CCB}$, $coupon_G$, $b_{GCB}$, $A$ and $SEC_{CB}$ |
| $CEN$ | Carbon mass of the non-renewable energy sources (Gt) | 9.9 | Calculated from Eq. (7) using the initial value of $EMIS_{IN}$ |
| $CO2_{AT}$ | Atmospheric $CO_2$ concentration ($GtCO_2$) | 3146 | Taken from NOAA/ESRL (National Oceanic & Atmospheric Administration/Earth System Research Laboratory) |
| $CO2_{LO}$ | Lower ocean $CO_2$ concentration ($GtCO_2$) | 6380.6 | Based on the DICE-2016R model (Nordhaus, 2016); GtC have been transformed into $GtCO_2$ |
| $CO2_{UP}$ | Upper ocean/biosphere $CO_2$ concentration ($GtCO_2$) | 1694.2 | Based on the DICE-2016R model (Nordhaus, 2016); GtC have been transformed into $GtCO_2$ |
| $CON_E$ | Amount of non-renewable energy resources converted into non-renewable energy reserves (EJ) | 1629.0 | Calculated from Eq. (20) using the initial value of $RES_E$ |
| $CON_M$ | Amount of material resources converted into material reserves (Gt) | 209 | Calculated from Eq. (12) using the initial value of $RES_M$ |
| $coupon_C$ | Fixed coupon paid per conventional corporate bond (US$) | 5 | Calculated from Eq. (87) using the initial values of $p_C$ and $yield_C$ |
| $coupon_G$ | Fixed coupon paid per green corporate bond (US$) | 5 | Calculated from Eq. (88) using the initial values of $p_G$ and $yield_G$ |
| $CR_C$ | Degree of credit rationing for conventional loans | 0.2 | Calculated from Eq. (125) using the initial values of $dsr$, $lev_B$ and $CAR$ |
| $CR_G$ | Degree of credit rationing for green loans | 0.3 | Calculated from Eq. (126) using the initial values of $dsr$, $lev_B$ and $CAR$ |
| $D$ | Deposits (trillion US$) | 65.0 | Based on Allianz (2017) |
| $DC$ | Stock of durable consumption goods (trillion US$) | 1456 | Calculated from Eq. (4) using the initial values of $K$, $DEM$, $\delta$ and $\mu$ |
| $def$ | Rate of default | 0.040 | Based on World Bank |
| $DEM$ | Demolished/discarded socio-economic stock (Gt) | 17.0 | Based on Haas et al. (2015) |
| $dep_E$ | Energy depletion ratio | 0.013 | Calculated from Eq. (22) using the initial values of $EN$ and $REV_E$ |
| $dep_M$ | Matter depletion ratio | 0.008 | Selected from a reasonable range of values |
| $DL$ | Amount of defaulted loans (trillion US$) | 2.2 | Calculated from Eq. (96) using the initial values of $L$ and $def$ |
| $DP$ | Distributed profits of firms (trillion US$) | 17.5 | Calculated from Eq. (55) using the initial values of $TP$ and $RP$ |
| $dsr$ | Debt service ratio | 0.42 | Calculated from Eq. (99) using the initial values of $L_C$, $L_G$, $coupon_C$, $b_C$, $coupon_G$, $b_G$ and $TP$ |
| $D_T$ | Total proportional damage caused by global warming | 0.0031 | Calculated from Eq. (49) using the initial value of $T_{AT}$ |
| $D_{TF}$ | Part of damage that affects directly the fund-service resources | 0.0028 | Calculated from Eq. (51) 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. (50) using the initial value of $D_T$ |
| $E$ | Energy used 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 $CO_2$ emissions ($GtCO_2$) | 38.8 | Calculated from Eq. (25) using the initial values of $EMIS_{IN}$ and $EMIS_L$ |
| $EMIS_{IN}$ | Industrial $CO_2$ emissions ($GtCO_2$) | 36.2 | Taken from CDIAC (Carbon Dioxide Information Analysis Center) |
| $EMIS_L$ | Land-use $CO_2$ emissions ($GtCO_2$) | 2.5 | Taken from the DICE-2016R model (Nordhaus, 2016) |
| $EN$ | 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 ($W/m^2$) | 2.52 | 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-$CO_2$ greenhouse gases ($W/m^2$) | 0.51 | Based on the DICE-2016R model (Nordhaus, 2016) |
| $G$ | Government expenditures (trillion US$) | 12.5 | Calculated from Eq. (132) using the initial value of $Y$ |
| $g_{POP}$ | Growth rate of population | 0.014 | Taken from United Nations (medium fertility variant) |
| $g_{x20}$ | Growth rate of the autonomous proportion of desired green investment funded via bonds | 0.040 | Calibrated such that the model generates the baseline scenario |

(continued from the previous page)

| Symbol | Description | Value | Remarks/sources |
|---|---|---|---|
| $g_Y$ | Growth rate of output | 0.025 | Based on World Bank |
| $g_{\beta 0}$ | Growth rate of the autonomous share of green investment in total investment | 0.003 | Calibrated such that the model generates the baseline scenario |
| $g_\lambda$ | Growth rate of labour productivity | 0.012 | Calculated from Eq. (75) using the initial values of $g_Y$ and $\sigma_0$ |
| $g_{\lambda 30}$ | Growth rate of the households' portoflio choice parameter related to the autonomous demand for green bonds | 0.040 | Calibrated such that the model generates the baseline scenario |
| $g_\omega$ | Growth rate of $CO_2$ intensity | -0.003 | Calibrated such that the model generates the baseline scenario |
| *hazratio* | Hazardous waste accumulation ratio (tonnes per person) | 1.87 | Calculated from Eq. (10) using the initial values of $HWS$ and $POP$ |
| $HPM$ | High-powered money | 13.00 | Calculated from Eq. (122) using the initial value of $D$ |
| $HWS$ | Stock of hazardous waste (Gt) | 14.0 | Calculated assuming a constant ratio of hazardous waste to GDP since 1960 |
| $I$ | Total investment (trillion US$) | 15.0 | Calibrated such that the model generates the baseline scenario |
| $I_C$ | Conventional investment (trillion US$) | 14.3 | Calculated from Eq. (67) using the initial values of $I$ and $I_G$ |
| $I_C^D$ | Desired conventional investment (trillion US$) | 16.6 | Calculated from the identity $I_C^D=I^D-I_G^D$; we use the initial values of $I^D$ and $I_G^D$ |
| $I^D$ | Desired total investment (trillion US$) | 17.5 | Calibrated such that the model generates the baseline scenario |
| $I_G$ | Green investment (trillion US$) | 0.7 | Based on IEA (2016); we use a higher value than the one reported in IEA (2016) since green investment in our model is not confined to investment in energy efficiency and renewables (it also includes investment in recycling and material efficiency) |
| $I_G^D$ | Desired green investment (trillion US$) | 0.9 | Calculated such that it is reasonably higher than $I_G$ |
| *illiq* | Illiquidity ratio | 0.72 | Calculated from Eq. (98) using the initial values of $L_C$, $L_G$, $coupon_C$, $b_C$, $coupon_G$, $b_G$, $w$, $N$, $T_F$, $\delta$, $K$, $Y$, $CR_C$, $NL_C^D$, $CR_G$, $NL_G^D$, $p_C$ and $p_G$ |
| $K$ | Total capital stock of firms (trillion US$) | 227.4 | Calculated from the identity $K=(K/Y)*Y$ using the initial value of $Y$ and assuming that $K/Y=3$ (based on Penn World Table 9.0) |
| $K_B$ | Capital of banks (trillion US$) | 8.4 | Calculated from Eq. (129) using the initial values of $lev_B$, $L_C$, $L_G$, $SEC_B$ and $HPM$ |
| $K_C$ | Conventional capital stock (trillion US$) | 219.0 | Calculated from Eq. (71) using the initial values of $K$ and $K_G$ |
| $K_G$ | Green capital stock (trillion US$) | 8.4 | Calculated from Eq. (72) using the initial values of $K$ and $\varkappa$ |
| $L$ | Total loans of firms (trillion US$) | 57.7 | Calculated from the identity $L=(credit-B/Y)*Y$; *credit* is the credit to the non-financial corporations in percent of GDP taken from BIS (Bank for International Settlements); it is assumed that *credit* includes both loans and bonds |
| $L_C$ | Conventional loans (trillion US$) | 55.5 | Calculated from Eq. (68) using the initial values of $L$ and $L_G$ |
| $L_G$ | Green loans (trillion US$) | 2.1 | Calculated by assuming that $L_G/L=K_G/K=\varkappa$; we use the initial values of $\varkappa$ and $L$ |
| $lev_B$ | Banks' leverage ratio | 9.6 | Taken from World Bank |
| $LF$ | Labour force (billion people) | 3.42 | Taken from World Bank |
| $lf_1$ | Autonomous labour force-to-population ratio | 0.460 | Calculated from Eq. (116) using the initial values of $LF$, $POP$, *hazratio* and $D_{TF}$ |
| $M$ | Extraction of new matter from the ground, excluding the matter included in non-renewable energy sources (Gt) | 51.5 | Taken from UN Environment International Resource Panel Global Material Flows Database; the figure refers to non-metallic minerals plus metal ores |
| $MY$ | Output in material terms (Gt) | 56.6 | Calculated from Eq. (2) using the initial values of $M$ and $REC$ |
| $N$ | Number of employees (billion 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 US$) | 11.1 | Calculated from Eq. (64) using the initial values of $I_C^D$, $\beta$, $RP$, $L_C$, $\delta$, $K_C$ and $b_C$ |
| $NL_G^D$ | Desired new amount of green loans (trillion US$) | 0.7 | Calculated from Eq. (63) using the initial values of $I_G^D$, $\beta$, $RP$, $L_G$, $\delta$, $K_G$ and $b_G$ |
| $O2$ | Oxygen used for the combustion of fossil fuels (Gt) | 26.3 | Calculated from Eq. (8) using the initial values of $EMIS_{IN}$ and $CEN$ |
| $p_C$ | Market price of conventional corporate bonds (US$) | 100 | The price has been normalised such that it is equal to US$100 (the par value of bonds) in 2016 |
| $p_G$ | Market price of green corporate bonds (US$) | 100 | The price has been normalised such that it is equal to US$100 (the par value of bonds) in 2016 |
| $POP$ | Population (billions) | 7.47 | Taken from United Nations (medium fertility variant) |
| $r$ | Rate of retained profits | 0.009 | Calculated from Eq. (56) using the initial values of $RP$ and $K$ |
| $re$ | Rate of employment | 0.94 | Calculated from Eq. (80) using the initial value of $ur$ |
| $REC$ | Recycled socio-economic stock (Gt) | 5.1 | Calculated from Eq. (3) using the initial values of $\rho$ and $DEM$ |
| $RES_E$ | Non-renewable energy resources (EJ) | 543000 | Based on BGR (2016, p. 36) |
| $RES_M$ | Material resources (Gt) | 417245 | Calculated by assuming $RES_M/REV_M=64.8$ (based on UNEP, 2011) |
| $REV_E$ | Non-renewable energy reserves (EJ) | 38000 | Based on BGR (2016, p. 36) |
| $REV_M$ | Material reserves (Gt) | 6438 | Calculated from Eq. (14) using the initial values of $M$ and $dep_M$ |
| $RP$ | Retained profits of firms (trillion US$) | 2.0 | Calculated from Eq. (54) using the initial value of $TP$ |
| $SEC$ | Total amount of government securities | 63.4 | Calculated from the identity *general government debt-to-GDP*$=SEC/Y$ using the initial value of $Y$ and the value of the g*eneral government debt-to-GDP* ratio (taken from IMF) |
| $SEC_B$ | Government securities held by banks (trillion US$) | 9.5 | Calculated by assuming that $SEC_B/SEC=0.2$ based on Alli Abbas et al. (2014) |
| $SEC_{CB}$ | Government securities held by central banks (trillion US$) | 6.1 | Calculated from the identity $SEC_{CB}=HPM+V_{CB}-\bar{p}_C b_{CCB}-\bar{p}_G b_{GCB}-A$ using the initial values of $V_{CB}$, $b_{CCB}$, $b_{GCB}$, $A$ and $HPM$ |
| $SEC_H$ | Government securities held by households (trillion US$) | 47.7 | Calculated from Eq. (141) using the initial values of $SEC$, $SEC_{CB}$ and $SEC_B$ |
| $SES$ | Socio-economic stock (Gt) | 1506.3 | Calculated from the identity $SES=\mu(K+DC)$ using the initial values of $\mu$, $K$ and $DC$ |
| $sh_L$ | Share of loans in total firm liabilities | 0.83 | Calculated from the formula $sh_L=L/(L+B)$ using the initial values of $L$ and $B$ |
| $T$ | Total taxes (trillion US$) | 11.6 | Calculated from Eq. (135) using the initial values of $T_H$ and $T_F$ |

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| Symbol | Description | Value | Remarks/sources |
|---|---|---|---|
| $T_{AT}$ | Atmospheric temperature over pre-industrial levels (°C) | 1.04 | Based on Met Office |
| $T_F$ | Taxes on firms' profits (trillion US$) | 3.3 | Calculated from Eq. (134) using the initial value of $TP_G$ |
| $T_H$ | Taxes on households' disposable income | 8.2 | Calculated from Eq. (133) using the initial value $Y_{HG}$ |
| $T_{LO}$ | Lower ocean temperature over pre-industrial levels (°C) | 0.0112 | Based on the DICE-2016R model (Nordhaus, 2016) |
| $TP$ | Total profits of firms (trillion US$) | 19.5 | Calculated from Eq. (53) using the initial values of $TP_G$ and $T_F$ |
| $TP_G$ | Total gross profits of firms (trillion US$) | 22.9 | Calculated from Eq. (52) using the initial values of $Y$, $w$, $N$, $L_C$, $L_G$, $\delta$, $K$, $coupon_C$, $b_C$, $coupon_G$ and $b_G$ |
| $u$ | Rate of capacity utilisation | 0.72 | Based on World Bank, Enterprise Surveys |
| $ue$ | Rate of energy utilisation | 0.01 | Calculated from Eq. (46) using the initial values of $Y$ and $Y_E^*$ |
| $um$ | Rate of matter utilisation | 0.01 | Calculated from Eq. (45) using the initial values of $Y$, $G$ and $Y_M^*$ |
| $ur$ | Unemployment rate | 0.06 | Based on World Bank |
| $v$ | Capital productivity | 0.46 | Calculated from Eqs. (41) and (47) using the initial values of $Y$, $u$ and $K$ |
| $V_{CB}$ | Wealth of central banks (trillion US$) | 0 | It is assumed that there are no accumulated capital gains for the central banks |
| $V_H$ | Wealth of households (trillion US$) | 1580.6 | Calculated from the identity $V_H=DC+D+p_C b_{CH}+p_G b_{GH}+SEC_H$ using the initial values of $SEC_H$, $p_C$, $b_{CH}$, $p_G$, $b_{GH}$, $DC$ and $D$ |
| $V_{HF}$ | Financial wealth of households (trillion US$) | 124.6 | Calculated from the identity $V_{HF}=D+p_C b_{CH}+p_G b_{GH}+SEC_H$ using the initial values of $SEC_H$, $p_C$, $b_{CH}$, $p_G$, $b_{GH}$ and $D$ |
| $w$ | Annual wage rate (trillion US$/billions of employees) | 12.26 | Calculated from Eq. (78) 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 $REC$ |
| $x_1$ | Proportion of desired conventional investment funded via bonds | 0.02 | Calibrated such that the model generates the baseline scenario |
| $x_2$ | Proportion of desired green investment funded via bonds | 0.01 | Calibrated such that the model generates the baseline scenario |
| $x_{20}$ | Autonomous proportion of desired green investment funded via bonds | 0.01 | Calculated from Eq. (84) using the initial values of $yield_G$ and $x_{20}$ |
| $Y$ | Output (trillion US$) | 75.8 | Taken from World Bank (current prices) |
| $Y^*$ | Potential output (trillion US$) | 80.6 | Calculated from Eq. (43) using the initial values of $Y_M^*$, $Y_E^*$, $Y_K^*$ and $Y_N^*$ |
| $Y_E^*$ | Energy-determined potential output (trillion US$) | 5774.7 | Calculated from Eq. (40) using the initial values of $REV_E$, $\theta$ and $\varepsilon$ |
| $Y_H$ | Disposable income of households (trillion US$) | 51.5 | Calculated from Eq. (101) using the initial values of $Y_{HG}$ and $T_H$ |
| $Y_{HD}$ | Household disposable income net of depreciation (trillion US$) | 57.9 | Calculated from the identity $Y_{HD}=Y_H-\xi DC_{-1}$ using the initial values of $Y_H$ and $DC$ |
| $Y_{HG}$ | Gross disposable income of households (trillion US$) | 59.7 | Calculated from Eq. (100) using the initial values of $w$, $N$, $DP$, $BP_D$, $D$, $SEC_H$, $coupon_C$, $b_{CH}$, $coupon_G$ and $b_{GH}$ |
| $yield_C$ | Yield on conventional corporate bonds | 0.05 | Based on FTSE Russell (2016) |
| $yield_G$ | Yield on green corporate bonds | 0.05 | Based on FTSE Russell (2016) |
| $Y_K^*$ | Capital-determined potential output (trillion US$) | 105.3 | Calculated from Eq. (41) using the initial values of $v$ and $K$ |
| $Y_M^*$ | Matter-determined potential output (trillion US$) | 7199.9 | Calculated from Eq. (39) using the initial values of $REV_M$, $REC$ and $\mu$ |
| $Y_N^*$ | Labour-determined potential output (trillion US$) | 80.6 | Calculated from Eq. (42) using the initial values of $\lambda$ and $LF$ |
| $\beta$ | Share of desired green investment in total investment | 0.05 | Calculated from Eq. (58) using the initial values of $I_G^D$ and $I^D$ |
| $\beta_0$ | Autonomous share of desired green investment in total investment | 0.04 | Calculated from Eq. (60) using the initial values of $\beta$, $sb_L$, $yield_G$ and $yield_C$ |
| $\delta$ | Depreciation rate of capital stock | 0.04 | Calculated from Eq. (73) using the initial value $D_{TF}$ |
| $\varepsilon$ | Energy intensity (EJ/trillion US$) | 7.65 | Calculated from Eq. (15) using the initial values of $E$ and $Y$ |
| $\theta$ | 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 | 0.04 | Selected such that it is reasonably lower than $I_G/I$ |
| $\lambda$ | Hourly labour productivity (trillion US$/(billions of employees*annual hours worked per employee)) | 0.01 | Calculated from Eq. (79) using the initial values of $Y$ and $N$ |
| $\lambda_{30}$ | Households' portfolio choice parameter related to the autonomous demand for green bonds | 0.01 | Calculated from Eq. (107) using the initial values of $B_{GH}$, $V_{HF}$, $D_T$, $yield_C$, $yield_G$ and $Y_H$ |
| $\mu$ | Material intensity (kg/$) | 0.89 | Calculated from Eq. (1) using the initial values of $MY$, $G$ and $Y$ |
| $\rho$ | Recycling rate | 0.30 | Based on Haas et al. (2015) |
| $\sigma_0$ | Autonomous growth rate of labour productivity | -0.02 | Calibrated such that the model generates the baseline scenario |
| $\omega$ | $CO_2$ intensity of non-renewable energy ($GtCO_2$/EJ) | 0.07 | Calculated from Eq. (23) using the initial values of $EMIS_{IN}$ and $EN$ |

**Table 7:** Symbols and 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 | 0.80 | Selected from a reasonable range of values |
| $ad_{LF}$ | Fraction of gross damages to labour force avoided through adaptation | 0.70 | Selected from a reasonable range of values |
| $ad_P$ | Fraction of gross damages to productivity avoided through adaptation | 0.70 | Selected from a reasonable range of values |
| $c_1$ | Propensity to consume out of disposable income | 0.65 | Calibrated such that the model generates the baseline scenario |
| $c_2$ | Propensity to consume out of financial wealth | 0.13 | Empirically estimated using data for a panel of countries over the period 1995-2016 (the econometric estimations are available upon request) |
| $car$ | Coefficient for the conversion of GtC into $GtCO_2$ | 3.67 | Taken from CDIAC (Carbon Dioxide Information Analysis Center) |
| $CAR^{min}$ | Minimum capital adequacy ratio | 0.08 | Based on the Basel III regulatory framework |
| $CO2_{AT\text{-}PRE}$ | Pre-industrial $CO_2$ concentration in atmosphere ($GtCO_2$) | 2156.2 | Taken from DICE-2016R model (Nordhaus, 2016); GtC have been transformed into $GtCO_2$ |
| $CO2_{LO\text{-}PRE}$ | Pre-industrial $CO_2$ concentration in upper ocean/biosphere ($GtCO_2$) | 6307.2 | Taken from DICE-2016R model (Nordhaus, 2016); GtC have been transformed into $GtCO_2$ |
| $CO2_{UP\text{-}PRE}$ | Pre-industrial $CO_2$ concentration in lower ocean ($GtCO_2$) | 1320.1 | Taken from DICE-2016R model (Nordhaus, 2016); GtC have been transformed into $GtCO_2$ |
| $con_E$ | Conversion rate of non-renewable energy resources into reserves | 0.003 | Selected from a reasonable range of values |
| $con_M$ | Conversion rate of material resources into reserves | 0.0005 | Selected from a reasonable range of values |
| $CR^{max}$ | Maximum degree of credit rationing | 0.5 | Selected from a reasonable range of values |
| $def^{max}$ | Maximum default rate of loans | 0.2 | Selected from a reasonable range of values |
| $def_0$ | Parameter of the default rate function | 4.00 | Calculated from Eq. (97) using the initial value of $illiq$ |
| $def_1$ | Parameter of the default rate function | 5.65 | Calibrated such that the model generates the baseline scenario |
| $def_2$ | Parameter of the default rate function (related to the sensitivity of the default rate to the illiquidity ratio of firms) | 7.81 | Selected from a reasonable range of values |
| $F_{2xCO2}$ | Increase in radiative forcing (since the pre-industrial period) due to doubling of $CO_2$ concentration from pre-industrial levels ($W/m^2$) | 3.7 | Taken from the DICE-2016R model (Nordhaus, 2016) |
| $fex$ | Annual increase in radiative forcing (since the pre-industrial period) due to non-$CO_2$ agents ($W/m^2$) | 0.006 | Based on the DICE-2016R model (Nordhaus, 2016) |
| $gov$ | Share of government expenditures in output | 0.17 | Based on World Bank; the figure includes only the consumption government expenditures |
| $h$ | Annual working hours per employee | 1850 | Based on Penn World Table 9.0 |
| $h_1$ | Banks' reserve ratio | 0.2 | Based on World Bank |
| $h_2$ | Banks' government securities-to-deposits ratio | 0.15 | Calculated from Eq. (123) using the initial values of $SEC_B$ and $D$ |
| $haz$ | Proportion of hazardous waste in total waste | 0.04 | EEA (2012, p. 22) reports a figure equal to 3.7% for EU-27 |
| $int_A$ | Interest rate on advances | 0.02 | Based on Global Interest Rate Monitor |
| $int_C$ | 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 |
| $int_S$ | Interest rate on government securities | 0.015 | Based on FTSE Russell (2016) |
| $l_0$ | Parameter of the function of credit rationing on green loans | 0.67 | Calculated from Eq. (126) using the initial values of $dsr$, $CAR$ and $lev_B$ |
| $l_1$ | Parameter of the function of credit rationing on green loans | -0.25 | Calibrated such that the model generates the baseline scenario |
| $l_2$ | Parameter of the function of credit rationing on green loans (related to the sensitivity of credit rationing to the default rate) | 2.08 | Selected from a reasonable range of values |
| $l_3$ | Parameter of the function of credit rationing on green loans (related to the sensitivity of credit rationing to the leverage ratio of banks) | 0.04 | Selected from a reasonable range of values |
| $l_4$ | Parameter of the function of credit rationing on green loans (related to the sensitivity of credit rationing to the capital adequacy ratio of banks) | 2.08 | Selected from a reasonable range of values |
| $lev_B{}^{max}$ | Maximum leverage ratio | 33.33 | Based on the Basel III regulatory framework (the Basel III bank leverage can be proxied by the capital-to-assets ratio and its minimum value is 3%; since in our model the bank leverage is defined as the assets-to-capital ratio, the maximum value used is equal to 1/0.03) |
| $lf_2$ | Sensitivity of the labour force-to-population ratio to hazardous waste | 0.001 | Selected from a reasonable range of values |
| $lr$ | Rate of decline of land-use $CO_2$ emissions | 0.024 | Taken from the DICE-2016R model (Nordhaus, 2016); 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 |
| $\bar{p}_C$ | Par value of conventional corporate bonds (US$) | 100 | The par value of bonds is assumed to be always equal to US$100 |
| $\bar{p}_G$ | Par value of green corporate bonds (US$) | 100 | The par value of bonds is assumed to be always equal to US$100 |
| $pr$ | Ratio of demand-determined output to supply-determined output under the existence of supply-side constraints | 0.99 | Selected such that it is reasonably close to 1 |
| $r_0$ | Parameter of the function of credit rationing on conventional loans | 1.50 | Calculated from Eq. (125) using the initial values of $dsr$, $CAR$ and $lev_B$ |
| $r_1$ | Parameter of the function of credit rationing on conventional loans | -0.25 | Calibrated such that the model generates the baseline scenario |
| $r_2$ | Parameter of the function of credit rationing on conventional loans (related to the sensitivity of credit rationing to the default rate) | 2.08 | Selected from a reasonable range of values |
| $r_3$ | Parameter of the function of credit rationing on conventional loans (related to the sensitivity of credit rationing to the leverage ratio of banks) | 0.04 | Selected from a reasonable range of values |
| $r_4$ | Parameter of the function of credit rationing on conventional loans (related to the sensitivity of credit rationing to the capital adequacy ratio of banks) | 2.08 | 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 $CO_2$ concentration from pre-industrial levels ($^oC$) | 3.1 | Taken from then DICE-2016R model (Nordhaus, 2016) |

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| Symbol | Description | Value | Remarks/sources |
|---|---|---|---|
| $s_B$ | Banks' retention rate | 0.84 | Calibrated such that the model generates the baseline scenario |
| $s_C$ | Share of conventional corporate bonds held by central banks (trillion US$) | 0.01 | Calculated from Eq. (138) using the initial values of $B_{CCB}$ and $B_C$ |
| $s_F$ | Firms' retention rate | 0.11 | Calibrated such that the model generates the baseline scenario |
| $s_G$ | Share of green corporate bonds held by central banks (trillion US$) | 0.00 | Calculated from Eq. (137) using the initial values of $B_{GCB}$ and $B_G$ |
| $s_W$ | Wage income share | 0.52 | Based on Penn World Table 9.0 |
| $t_1$ | Speed of adjustment parameter in the atmospheric temperature equation | 0.020 | Taken from the DICE-2016R model (Nordhaus, 2016); has been adjusted to reflect a 1-year time step |
| $t_2$ | Coefficient of heat loss from the atmosphere to the lower ocean (atmospheric temperature equation) | 0.018 | Taken from the DICE-2016R model (Nordhaus, 2016); 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 the DICE-2016R model (Nordhaus, 2016); has been adjusted to reflect a 1-year time step |
| $w_L$ | Risk weight on loans | 1.0 | Based on BCBS (2006) |
| $w_S$ | Risk weight on government securities | 0.0 | Based on BCBS (2006) |
| $x_{10}$ | Autonomous proportion of desired conventional investment funded via bonds | 0.02 | Calculated from Eq. (83) using the initial values of $yield_C$ and $x_1$ |
| $x_{11}$ | Sensitivity of the proportion of desired conventional investment funded via bonds to the conventional bond yield | 0.10 | Selected from a reasonable range of values |
| $x_{21}$ | Sensitivity of the proportion of desired green investment funded via bonds to the green bond yield | 0.10 | Selected from a reasonable range of values |
| $a_{00}$ | Parameter of the desired investment function | 0.16 | Calibrated such that the model generates the baseline scenario |
| $a_{01}$ | Parameter of the desired investment function | 1.18 | Calibrated such that the model generates the baseline scenario |
| $a_1$ | Parameter of the desired investment function (related to the sensitivity of investment to the capacity utilisation) | 2.00 | Based on econometric estimations for a panel of countries over the period 1950-2014 (available upon request) |
| $a_2$ | Parameter of the desired investment function (related to the sensitivity of investment to the rate of profit) | 1.66 | Based on econometric estimations for a panel of countries over the period 1950-2014 (available upon request) |
| $a_{31}$ | Parameter in the investment function (related to the sensitivity of investment to the unemployment rate) | 0.02 | Based on econometric estimations for a panel of countries over the period 1950-2014 (available upon request) |
| $a_{32}$ | Parameter in the investment function (related to the sensitivity of investment to the unemployment rate) | 0.5 | Selected from a reasonable range of values |
| $a_{41}$ | Parameter in the investment function (related to the sensitivity of investment to the energy utilisation rate) | 0.1 | Selected from a reasonable range of values |
| $a_{42}$ | Parameter in the investment function (related to the sensitivity of investment to the energy utilisation rate) | 0.99 | Selected from a reasonable range of values |
| $a_{51}$ | Parameter in the investment function (related to the sensitivity of investment to the matter utilisation rate) | 0.1 | Selected from a reasonable range of values |
| $a_{52}$ | Parameter in the investment function (related to the sensitivity of investment to the matter utilisation rate) | 0.99 | Selected from a reasonable range of values |
| $\beta_1$ | Autonomous share of desired green investment in total investment | 0.02 | Calibrated such that the model generates the baseline scenario |
| $\beta_2$ | Sensitivity of the desired green investment share to the interest rate differential between green loans/bonds and conventional loans/bonds | 1 | 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 9.0 |
| $\varepsilon^{max}$ | Maximum potential value of energy intensity (EJ/trillion US$) | 12 | Selected such that it is reasonably higher than initial $\varepsilon$ |
| $\varepsilon^{min}$ | Minimum potential value of energy intensity (EJ/trillion US$) | 2 | Selected such that it is reasonably higher than 0 |
| $\zeta_1$ | Rate of decline of the (absolute) growth rate of $CO_2$ intensity | 0.0005 | Calibrated such that the model generates the baseline scenario |
| $\zeta_2$ | Rate of decline of the growth rate of $\beta_0$ | 0.005 | Calibrated such that the model generates the baseline scenario |
| $\zeta_3$ | Rate of decline of the autonomous (absolute) growth rate of labour productivity | 0.02 | Calibrated such that the model generates the baseline scenario |
| $\zeta_4$ | Rate of decline of the growth rates of $x_{20}$ and $\lambda_{30}$ | 0.20 | Calibrated such that the model generates the baseline scenario |
| $\zeta_5$ | Rate of decline of the growth rate of population | 0.04 | Calibrated such that the model generates the baseline scenario |
| $\zeta_6$ | Rate of decline of the autonomous labour force-to-population ratio | 0.0006 | Calibrated such that the model generates the baseline scenario |
| $\eta_1$ | Parameter of damage function | 0 | Based on Weitzmann (2012); $D_T$=50% when $T_{AT}$=6$^o$C |
| $\eta_2$ | Parameter of damage function | 0.00284 | Based on Weitzmann (2012); $D_T$=50% when $T_{AT}$=6$^o$C |
| $\eta_3$ | Parameter of damage function | 0.000005 | Based on Weitzmann (2012); $D_T$=50% when $T_{AT}$=6$^o$C |
| $\lambda_{10}$ | Parameter of households' portfolio choice | 0.40 | Calculated from Eq. (105) using the initial values of $SEC_H$, $V_{HF}$, $D_T$, $yield_C$, $yield_G$ and $Y_H$ |
| $\lambda_{10}'$ | Parameter of households' portfolio choice | 0.10 | Selected from a reasonable range of values |
| $\lambda_{11}$ | Parameter of households' portfolio choice | 0.03 | Calculated from the constraint $\lambda_{11}$=-$\lambda_{21}$-$\lambda_{31}$-$\lambda_{41}$ |
| $\lambda_{12}$ | Parameter of households' portfolio choice | -0.01 | Selected from a reasonable range of values |
| $\lambda_{13}$ | Parameter of households' portfolio choice | -0.01 | Selected from a reasonable range of values |
| $\lambda_{14}$ | Parameter of households' portfolio choice | -0.01 | Selected from a reasonable range of values |
| $\lambda_{15}$ | Parameter of households' portfolio choice | -0.01 | Selected from a reasonable range of values |
| $\lambda_{20}$ | Parameter of households' portfolio choice | 0.10 | Calculated from Eq. (106) using the initial values of $B_{CH}$, $V_{HF}$, $D_T$, $yield_C$, $yield_G$ and $Y_H$ |
| $\lambda_{20}'$ | Parameter of households' portfolio choice | -0.20 | Selected from a reasonable range of values |
| $\lambda_{21}$ | Parameter of households' portfolio choice | -0.01 | Calculated from the constraint $\lambda_{21}$=$\lambda_{12}$ |
| $\lambda_{22}$ | Parameter of households' portfolio choice | 0.03 | Calculated from the constraint $\lambda_{22}$=-$\lambda_{12}$-$\lambda_{32}$-$\lambda_{42}$ |
| $\lambda_{23}$ | Parameter of households' portfolio choice | -0.01 | Selected from a reasonable range of values |
| $\lambda_{24}$ | Parameter of households' portfolio choice | -0.01 | Selected from a reasonable range of values |
| $\lambda_{25}$ | Parameter of households' portfolio choice | -0.01 | Selected from a reasonable range of values |

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| Symbol | Description | Value | Remarks/sources |
|---|---|---|---|
| $\lambda_{30}{}'$ | Parameter of households' portfolio choice | 0.00 | Global warming damages are assumed to have no impact on the holdings of green bonds |
| $\lambda_{31}$ | Parameter of households' portfolio choice | -0.01 | Calculated from the constraint $\lambda_{31}=\lambda_{13}$ |
| $\lambda_{32}$ | Parameter of households' portfolio choice | -0.01 | Calculated from the constraint $\lambda_{32}=\lambda_{23}$ |
| $\lambda_{33}$ | Parameter of households' portfolio choice | 0.03 | Calculated from the constraint $\lambda_{33}=-\lambda_{13}-\lambda_{23}-\lambda_{43}$ |
| $\lambda_{34}$ | Parameter of households' portfolio choice | -0.01 | Selected from a reasonable range of values |
| $\lambda_{35}$ | Parameter of households' portfolio choice | -0.01 | Selected from a reasonable range of values |
| $\lambda_{40}$ | Parameter of households' portfolio choice | 0.50 | Calculated from the constraint $\lambda_{40}=1-\lambda_{10}-\lambda_{20}-\lambda_{30}$ |
| $\lambda_{40}{}'$ | Parameter of households' portfolio choice | 0.10 | Calculated from the constraint $\lambda_{40}{}'=-\lambda_{10}{}'-\lambda_{20}{}'-\lambda_{30}{}'$ |
| $\lambda_{41}$ | Parameter of households' portfolio choice | -0.01 | Calculated from the constraint $\lambda_{41}=\lambda_{14}$ |
| $\lambda_{42}$ | Parameter of households' portfolio choice | -0.01 | Calculated from the constraint $\lambda_{42}=\lambda_{24}$ |
| $\lambda_{43}$ | Parameter of households' portfolio choice | -0.01 | Calculated from the constraint $\lambda_{43}=\lambda_{34}$ |
| $\lambda_{44}$ | Parameter of households' portfolio choice | 0.03 | Calculated from the constraint $\lambda_{44}=-\lambda_{14}-\lambda_{24}-\lambda_{34}$ |
| $\lambda_{45}$ | Parameter of households' portfolio choice | 0.03 | Calculated from the constraint $\lambda_{45}=-\lambda_{15}-\lambda_{25}-\lambda_{35}$ |
| $\mu^{max}$ | Maximum potential value of material intensity (kg/US$) | 1.5 | Selected such that it is reasonably higher than initial $\mu$ |
| $\mu^{min}$ | Minimum potential value of material intensity (kg/US$) | 0.3 | Selected such that it is reasonably higher than 0 |
| $\xi$ | Proportion of durable consumption goods discarded every year | 0.007 | Selected such that the initial growth of $DC$ is equal to the growth rate of output |
| $\pi_1$ | Parameter linking the green capital-conventional capital ratio with material intensity | 2.08 | Calibrated such that initial $\mu$ corresponds to initial $\varkappa$ and $\mu(2050)=0.9\mu(2015)$ in line with the baseline scenario |
| $\pi_2$ | Parameter linking the green capital-conventional capital ratio with material intensity | 19.98 | Calibrated such that initial $\mu$ corresponds to initial $\varkappa$ and $\mu(2050)=0.9\mu(2015)$ in line with the baseline scenario |
| $\pi_3$ | Parameter linking the green capital-conventional capital ratio with recycling rate | 7.61 | Calibrated such that initial $\varrho$ corresponds to initial $\varkappa$ and $\varrho(2050)=1.4\varrho(2015)$ in line with the baseline scenario |
| $\pi_4$ | Parameter linking the green capital-conventional capital ratio with recycling rate | 40.55 | Calibrated such that initial $\varrho$ corresponds to initial $\varkappa$ and $\varrho(2050)=1.4\varrho(2015)$ in line with the baseline scenario |
| $\pi_5$ | Parameter linking the green capital-conventional capital ratio with energy intensity | 13.63 | Calibrated such that initial $\varepsilon$ corresponds to initial $\varkappa$ and $\varepsilon(2050)=0.7\varepsilon(2015)$ in line with the baseline scenario |
| $\pi_6$ | Parameter linking the green capital-conventional capital ratio with energy intensity | 62.74 | Calibrated such that initial $\varepsilon$ corresponds to initial $\varkappa$ and $\varepsilon(2050)=0.7\varepsilon(2015)$ in line with the baseline scenario |
| $\pi_7$ | Parameter linking the green capital-conventional capital ratio with the share of renewable energy | 36.50 | Calibrated such that initial $\theta$ corresponds to initial $\varkappa$ and $\theta(2050)=0.25$ in line with the baseline scenario |
| $\pi_8$ | Parameter linking the green capital-conventional capital ratio with the share of renewable energy | 47.58 | Calibrated such that initial $\theta$ corresponds to initial $\varkappa$ and $\theta(2050)=0.25$ in line with the baseline scenario |
| $\varrho^{max}$ | Maximum potential value of recycling rate | 0.8 | Selected such that it is reasonably lower than 1 |
| $\sigma_1$ | Autonomous growth rate of labour productivity | 0.0108 | Calibrated such that the model generates the baseline scenario |
| $\sigma_2$ | Sensitivity of labour productivity growth to the growth rate of output | 0.92 | Empirically estimated using data for a panel of countries over the period 1991-2016 (the econometric estimations are available upon request) |
| $\tau_F$ | Firms' tax rate | 0.15 | Selected from a reasonable range of values |
| $\tau_H$ | Households' tax rate | 0.14 | Calibrated such that the model generates the baseline scenario |
| $\varphi_{11}$ | Transfer coefficient for carbon from the atmosphere to the atmosphere | 0.9760 | Calculated from the formula $\varphi_{11}=1-\varphi_{12}$ (see the DICE-2016R model, Nordhaus, 2016) |
| $\varphi_{12}$ | Transfer coefficient for carbon from the atmosphere to the upper ocean/biosphere | 0.0240 | Taken from the DICE-2016R model (Nordhaus, 2016); has been adjusted to reflect a 1-year time step |
| $\varphi_{21}$ | Transfer coefficient for carbon from the upper ocean/biosphere to the atmosphere | 0.0392 | Calculated from the formula $\varphi_{21}=\varphi_{12}(CO2_{AT\text{-}PRE}/CO2_{UP\text{-}PRE})$ (see the DICE-2016R model, Nordhaus, 2016) |
| $\varphi_{22}$ | Transfer coefficient for carbon from the upper ocean/biosphere to the upper ocean/biosphere | 0.9595 | Calculated from the formula $\varphi_{22}=1-\varphi_{21}-\varphi_{23}$ (see the DICE-2016R model, Nordhaus, 2016) |
| $\varphi_{23}$ | Transfer coefficient for carbon from the upper ocean/biosphere to the lower ocean | 0.0013 | Taken from the DICE-2016R model (Nordhaus, 2016); 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 | 0.0003 | Calculated from the formula $\varphi_{32}=\varphi_{23}(CO2_{UP\text{-}PRE}/CO2_{LO\text{-}PRE})$ (see the DICE-2016R model, Nordhaus, 2016) |
| $\varphi_{33}$ | Transfer coefficient for carbon from the lower ocean to the lower ocean | 0.9997 | Calculated from the formula $\varphi_{33}=1-\varphi_{32}$ (see the DICE-2016R model, Nordhaus, 2016) |

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