Climate change, financial stability and monetary policy

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Abstract: Using a stock-flow-fund ecological macroeconomic model, we analyse (i) the effects of climate change on financial stability and (ii) the financial and global warming implications of a green QE programme. Emphasis is placed on the impact of climate change damages on the price of financial assets and the financial position of firms and banks. The model is calibrated using global data and simulations are conducted for the period 2015-2115. Four key results arise. First, by destroying the capital of firms and reducing their profitability, climate change is likely to increase gradually their burden of debt, leading to a higher rate of default that could harm both the financial and the non-financial corporate sector. Second, climate change damages can lead to a portfolio reallocation that can cause a gradual decline in the price of corporate bonds. Third, financial instability might adversely affect credit expansion and the investment in green capital, with adverse feedback effects on climate change. Fourth, the implementation of a green QE programme can reduce climate-induced financial instability and restrict global warming. The effectiveness of the programme is higher the higher is the responsiveness of green investment to changes in bond yields.

Keywords*:* ecological macroeconomics, stock-flow consistent modelling, climate change, financial stability, green quantitative easing

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1. Introduction

There is a growing concern that climate change is likely to have severe effects on the stability of the financial system. So far, most analyses have concentrated on the potential effects of climate change on the asset prices of fossil-fuel companies (see e.g. NEF, 2012; Carbon Tracker Initiative, 2015; McGlade and Ekins, 2015) and the performance of the insurance sector (see e.g. Bank of England, 2015). Much less attention has been paid to the impact of climate change on financial stability as a result of its economic damages.[1] This impact is non-trivial and equally important. First, the increase in temperature and the economic catastrophes caused by climate change could reduce the profitability of firms and could deteriorate their financial position. Accordingly, debt defaults could arise which would lead to systemic bank losses. Second, lower firm profitability combined with global warming-related damages can affect the confidence of investors, inducing a rise in liquidity preference and a fire sale of the financial assets issued by the corporate sector.

In this paper, we develop an ecological macroeconomic model that sheds light on these financial stability effects of climate change. The model builds on the stock-flow-fund model of Dafermos et al. (2017) which relies on a novel synthesis of the stock-flow consistent approach of Godley and Lavoie (2007) with the flow-fund model of Georgescu-Roegen (1971, ch. 9; 1979; 1984). The model is calibrated using global data and simulations are presented which illustrate the effects of climate change on the financial system.

Dietz et al. (2016) have recently investigated quantitatively certain implications of climate change for the financial sector. They use a standard Integrated Assessment model (IAM) and the climate value at risk (VAR) framework. Assuming that climate change can reduce the dividend payments of firms and, hence, the price of financial assets, they provide various estimates about the climate-induced loss in the value of financial assets. Our study moves beyond their analysis in three different ways. First, by relying on the stock-flow consistent approach, we portray explicitly the balance sheets and the financial flows in the financial sector. This allows us to model the climate-

[1] Two recent exceptions are Aglietta and Espagne (2016) and Batten et al. (2016) who discuss the channels through which climate change could harm the financial system.

induced fragility that can be caused in the financial structures of firms and banks, a feature which is absent in Dietz et al. (2016). Second, we utilise a multiple financial asset portfolio choice framework which permits an explicit analysis of the climate-induced effects on the demand of financial assets in a world of fundamental uncertainty. This allows us to capture the implications of a fire sale of certain financial assets. This is not explicitly considered in the model of Dietz et al. (2016) in which climate damages do not have diversified effects on different financial assets. Third, the financial system in our model has a non-neutral impact on economic activity: credit availability and the price of financial assets affect economic growth and employment. Accordingly, the interactions between economic performance and financial (in)stability are explicitly taken into account. This is crucial since the feedback economic effects of bank losses and asset price deflation can exacerbate climate-induced financial instability (see Batten et al., 2016). Dietz et al. (2016) utilise a neoclassical growth framework where long-run growth is independent of the financial structure of firms and banks. This leaves little room for the analysis of the macroeconomic implications of climate-induced financial problems.

Our simulation results illustrate that in a business as usual scenario climate change is likely to have important adverse effects on the default of firms, the leverage of banks and the price of financial assets. These affects are more pronounced towards the end of the 21st century and the beginning of the 22nd century. Remarkably, this climate-induced financial instability causes problems in the financing of green investment disrupting the transition to a low-carbon and more ecologically efficient economy.

An additional contribution of this paper is that it examines how monetary policy could reduce the risks imposed on the financial system by climate change. Drawing on the recent discussions about the potential use of monetary policy in tackling climate change (see e.g. Murphy and Hines, 2010; Werner, 2012; NEF, 2013; Rozenberg et al., 2013; Amin et al., 2014; Barkawi and Monnin, 2015; Campiglio, 2016), we examine the extent to which a global green quantitative easing (QE) programme could ameliorate the financial distress caused by climate change. This programme involves the purchase of green corporate bonds. The simulations presented about the effects of a green QE programme are of growing relevance since in a world of climate change central banks might not be able to safeguard financial stability without using new unconventional tools in a prudential manner.

The paper's outline is as follows. Section 2 presents the structure of the model and the key equations that capture the links between climate change, financial stability and monetary policy. Section 3 describes the calibration and the validation of the model. Section 4 analyses our simulations about the effects of climate change on the financial system. Section 5 focuses on the impact of a green QE programme. Section 6 concludes.

2. The model

Our global model consists of two big blocks: (i) the 'ecosystem' block that encapsulates the carbon cycle, the interaction between temperature and carbon, the flows/stocks of energy and matter and the evolution of ecological efficiency indicators; (ii) the 'macroeconomy and financial system' block that includes the financial transactions, the balance sheet structure and the behaviour of households, firms, banks, central banks and the government sector.

Firms produce one type of material good which is used for durable consumption and investment purposes. The matter that is necessary in the production process is either extracted from the ground or comes from recycling the demolished/discarded socio-economic stock.[2] Energy is produced by using both renewable and non-renewable sources. Production results in CO_2 emissions and waste. A distinction is made between green and conventional capital. The higher the use of green capital the lower the energy and material intensity and the higher the recycling rate and the use of renewables.

Firms invest in conventional and green capital by using retained profits, loans and bonds. Banks 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. Commercial banks accumulate capital and distribute part of their profits to households. Central banks determine the base interest rate, provide liquidity to the commercial banks and purchase government securities

[2] The socio-economic stock includes capital goods and durable consumption goods.

and corporate bonds. Governments collect taxes and conduct fiscal policy. Inflation has been assumed away and, for simplicity, the price of goods is equal to unity. We use US dollar ($) as a reference currency.

The skeleton of the model is captured by four matrices:

(1) The physical flow matrix (Table 1) which portrays the inflows and the outflows of matter and energy that take place as a result of the production process. The First Law of Thermodynamics implies that energy and matter cannot be created or destroyed. This is reflected in the material and energy balance.

Table 1: Physical flow matrix

	Material balance	Energy balance
Inputs		
Extracted matter	$+M$	
Renewable energy		$+ER$
Non-renewable energy	$+CEN$	$+EN$
Oxygen	$+O2$	
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.

(2) The physical stock-flow matrix (Table 2) which presents the dynamic change in 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. Additions to stocks are denoted by a plus sign. Reductions of stocks 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	$+CONV_M$	$+CONV_E$			
CO_2 emissions			$+EMIS$		
Production of material goods				$+MY$	
Non-recycled hazardous waste					$+hazW$
Reductions of stock					
Extraction	$-M$	$-EN$			
Net transfer to oceans/bioshpere			$+(\phi_{11}-1)CO2_{AT-1}+\phi_{21}CO2_{UP-1}$		
Demolished/disposed material goods				$-DEM$	
Closing stock	REV_M	REV_E	$CO2_{AT}$	SES	HWS

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

(3) The transactions flow matrix (Table 3) which shows the transactions that take place between the various sectors of the economy. Inflows are denoted by a plus sign and outflows are denoted by a minus sign.

(4) The balance sheet matrix (Table 4) which includes the assets and the liabilities of the sectors. We use a plus sign for the assets and a minus sign for the liabilities.

Table 3: Transactions flow matrix

	Households	Firms		Commercial banks		Government sector	Central banks		Total
		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
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
Capital depreciation		$-\delta K_{-1}$	$+\delta K_{-1}$						0
Interest on conventional loans		$-int_C L_{C-1}$		$+int_C L_{C-1}$					0
Interest on green loans		$-int_G L_{G-1}$		$+int_G L_{G-1}$					0
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
Central bank's profits						$+CBP$	$-CBP$		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	$-p_C \Delta b_{CH}$		$+p_C \Delta b_C$					$-p_C \Delta b_{CCB}$	0
Δgreen bonds	$-p_G \Delta b_{GH}$		$+p_G \Delta b_G$					$-p_G \Delta b_{GCB}$	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

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

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$.

The model extends the model developed by Dafermos et al. (2017) by including a bond market, central banking, the government sector, the household portfolio choice and an endogenous rate of default for firms. In what follows we present the equations of the model that are more relevant for the interactions between climate change, financial stability and monetary policy. The full list of equations is reported in Appendix A. Additional details about the foundations of the model and the justification of the equations can be found in Dafermos et al. (2017).

2.1. *Emissions and climate change*

The equations about emissions and climate change draw on the integrated assessment modelling (see Nordhaus and Sztorc, 2013). Every year industrial CO_2 emissions ($EMIS_{IN}$) are generated due to the use of non-renewable energy sources (EN):

$$EMIS_{IN} = \omega EN \tag{1}$$

where ω is the CO_2 intensity, 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. 2). These emissions are assumed to decline exogenously at a rate lr:

$$EMIS_L = EMIS_{L-1}(1 - lr) \tag{2}$$

Total emissions ($EMIS$) are given by:

$$EMIS = EMIS_{IN} + EMIS_L \tag{3}$$

The carbon cycle, represented by Eqs. (4)-(6), 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. In particular, we have:

$$CO2_{AT} = EMIS + \phi_{11} CO2_{AT-1} + \phi_{21} CO2_{UP-1} \tag{4}$$

$$CO2_{UP} = \phi_{12} CO2_{AT-1} + \phi_{22} CO2_{UP-1} + \phi_{32} CO2_{LO-1} \tag{5}$$

$$CO2_{LO} = \phi_{23} CO2_{UP-1} + \phi_{33} CO2_{LO-1} \tag{6}$$

where $CO2_{AT}$ is the atmospheric CO_2 concentration, $CO2_{UP}$ is the upper ocean/biosphere CO_2 concentration and $CO2_{LO}$ is the lower ocean CO_2 concentration.

The accumulation of atmospheric CO_2 and other greenhouse gases increases radiative forcing F, as follows:

$$F = F_{2\times CO2} \, log_2 \frac{CO2_{AT}}{CO2_{AT-PRE}} + F_{EX} \tag{7}$$

where $F_{2\times CO_2}$ is the increase in radiative forcing (since the pre-industrial period) due to doubling of CO_2 concentrations from pre-industrial levels ($CO2_{AT-PRE}$). For simplicity, the radiative forcing due to non-CO_2 greenhouse gas emissions (F_{EX}) is determined exogenously:

$$F_{EX} = F_{EX-1} + fex \tag{8}$$

where fex is the annual increase in radiative forcing (since the pre-industrial period) due to non-CO_2 agents.

As shown in Eq. (9), the rise in radiative forcing places upward pressures on the atmospheric temperature (T_{AT}):

$$T_{AT} = T_{AT-1} + t_1\left(F - \frac{F_{2\times CO2}}{S} T_{AT-1} - t_2\left(T_{AT-1} - T_{LO-1}\right)\right) \tag{9}$$

where S is the equilibrium climate sensitivity, i.e. the increase in equilibrium temperature due to doubling of CO_2 concentration from pre-industrial levels.

The temperature of the lower oceans (T_{LO}) is given by:

$$T_{LO} = T_{LO-1} + t_3\left(T_{AT-1} - T_{LO-1}\right) \tag{10}$$

2.2. Green capital, energy intensity and renewable energy

Green capital allows firms to produce the same output with less energy. This is captured by the following logistic function:

$$\varepsilon = \varepsilon_{max} - \frac{\varepsilon_{max} - \varepsilon_{min}}{1 + \pi_5 e^{-\pi_6 (K_G/K_C)}} \tag{11}$$

where ε_{max} and ε_{min} are, respectively, the maximum and the minimum potential values of energy intensity. As the ratio of green capital to conventional capital increases, energy intensity goes down. The use of the logistic function implies that the installation of green capital (relative to conventional capital) initially generates a slow improvement in energy intensity. However, as installation expands further, the improvement reaches a take-off point after which energy intensity improves much more rapidly due to the learning obtained from installation experience and the overall expansion of green capital infrastructure. Finally, as energy intensity approaches its potential minimum, improvement starts to slow.

A similar logistic function is used for the effects of green capital accumulation on the share of renewable energy in total energy produced (θ):

$$\theta = \frac{1}{1 + \pi_7 e^{-\pi_8 (K_G/K_C)}} \tag{12}$$

By definition, the maximum potential value of θ is 1. Note that in Dafermos et al. (2017) the formulation of the links between green capital and ecological efficiency indicators is quite different since it does not rely on logistic functions. The use of logistic functions in the model presented here allows for a more realistic representation that takes into account the processes of learning-by-doing and learning-by-installation which play a key role in the diffusion of new technologies.

2.3. Output determination and damages

Eq. (13) shows our Leontief-type production function:

$$Y^* = min(Y_M^*, Y_E^*, Y_K^*, Y_N^*) \tag{13}$$

where Y^* is the potential output. The potential output is the minimum of (i) the matter-determined potential output (Y_M^*) which depends on material reserves, (ii) the energy-determined potential output (Y_E^*) which is a function of non-renewable energy reserves, (iii) the capital-determined potential output (Y_K^*) that relies on capital stock and capital productivity (iv) the labour-determined potential output (Y_N^*) which depends on labour force and labour productivity.

The actual output (Y) is demand-determined. Aggregate demand is equal to consumption expenditures (C) plus investment expenditures (I) plus government expenditures (G):

$$Y = C + I + G \tag{14}$$

However, demand is not independent of supply. When Y approaches Y^*, demand tends to decline due to supply-side constraints (for example, capital and labour shortages might lead to less investment).

Output determination is affected by climate change as follows: global warming causes damages to capital stock and capital productivity, decreasing Y_K^*; it also causes damages to labour force and labour productivity, reducing Y_N^* (see Dafermos et al. (2017) and the references therein). These damages (a) deteriorate the expectations of households and firms, reducing consumption and investment, and, hence aggregate demand and (b) increase the scarcity of capital and labour placing downward pressures on aggregate demand via the supply constraints.

Eq. (15) is the damage function, which shows how atmospheric temperature and damages are linked:

$$D_T = 1 - \frac{1}{1 + \eta_1 T_{AT} + \eta_2 T_{AT}^{\ 2} + \eta_3 T_{AT}^{\ 6.754}} \tag{15}$$

D_T is the proportional damage which lies between 0 (no damage) and 1 (complete catastrophe). Eq. (15) has been proposed by Weitzman (2012). The variable D_T enters into both (i) the determination of capital and labour and their productivities and (ii) the consumption and investment demand. In our baseline scenario we assume that $D_T = 0.5$ when $T = 6^0 C$.

2.4. The financing of investment

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. (16) captures the first stage:

$$I^D = \left[(\alpha_0 + \alpha_1 r_{-1} + \alpha_2 u_{-1} - \alpha_3 g_{\varepsilon-1}) K_{-1} + \delta K_{-1} \right] (1 - D_{T-1}) \tag{16}$$

The desired investment (I^D), adjusted for the damage effect, is given by net investment plus the depreciated capital; δ is the depreciation rate of capital stock. Following the Kaleckian tradition (see e.g. Blecker, 2002), net investment depends positively on the rate of (retained) profits (r) and the rate of capacity utilisation (u). Investment is also a function of the growth rate of energy intensity (g_ε). This captures the rebound effect linked to the fact that firms invest more when energy intensity declines, since the energy cost goes down. This higher investment increases the use of energy, partially offsetting the positive effects of energy efficiency improvements.[3]

Eqs. (17) and (18) refer to the second stage:

$$I_G^D = \beta I^D \tag{17}$$

[3] For a description of the rebound effects see Barker et al. (2009).

$$I_C^D = I^D - I_G^D \tag{18}$$

where β is the proportion of green investment (I_G^D) in the overall desired investment (Eq. 17). Desired conventional investment (I_C^D) is determined as a residual (Eq. 18).

Eq. (19) shows that the proportion of green investment depends on three factors:

$$\beta = \beta_0 + \beta_1 - \beta_2\left[sh_{L-1}\left(int_G - int_C\right) + \left(1 - sh_{L-1}\right)\left(yield_{G-1} - yield_{C-1}\right)\right] + \beta_3 D_{T-1} \tag{19}$$

where int_C is the interest rate on conventional loans, int_G is the interest rate on green loans, $yield_C$ 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).

The first factor, captured by the term $\beta_0 + \beta_1$, reflects exogenous institutional or technological developments that affect the investment in green capital. The second factor, captured by the term $\beta_2\left[sh_{L-1}\left(int_G - int_C\right) + \left(1 - sh_{L-1}\right)\left(yield_{G-1} - yield_{C-1}\right)\right]$, reflects the borrowing cost of investing in green capital relative to conventional capital. As the cost of borrowing of green capital (via bank lending or bonds) declines compared to conventional capital, firms tend to increase green investment. Finally, we posit that climate change damages lead to more green investment since these damages induce firms to increase mitigation and might lead governments to adopt stricter regulation against the investment in conventional capital.

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. For simplicity, the long-term bonds issued by firms are never redeemed. The proportion of firms' desired investment which is funded via bonds is given by:

$$b_C = b_{C-1} + \frac{x_1 I_C^D}{p_C} \tag{20}$$

$$b_G = b_{G-1} + \frac{x_2 I_G^D}{p_G} \tag{21}$$

where b_C is the number of conventional bonds, b_G is the number of green bonds, 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, p_C is the price of conventional bonds and p_G is the price of green bonds.

The proportion of desired investment covered by green bonds is a negative function of the bond yield. Formally:

$$x_1 = x_{10} - x_{11} yield_C \tag{22}$$

$$x_2 = x_{20} - x_{21} yield_G \tag{23}$$

We postulate a price-clearing mechanism in the bond market:

$$p_C = \frac{B_C}{b_C} \tag{24}$$

$$p_G = \frac{B_G}{b_G} \tag{25}$$

where B_C and B_G denote the value of conventional and green bonds held by households and central banks. Prices tend to increase whenever households and central banks hold a higher amount of corporate bonds in their portfolio. A rise in the price of bonds produces a decline in the bond yield, which has two effects on firms' investment. First, since firms pay a lower interest rate on bonds, their profitability improves increasing their desired investment. Second, a lower bond yield (which might result from a rise in bond prices) induces firms to increase the proportion of desired investment covered via bonds. This is crucial because firms need to rely less on bank lending in order to finance their investment. The disadvantage of bank lending is that, due to credit rationing, banks provide only a proportion of the loans demanded by firms. Accordingly, the less firms rely on bank loans in order to finance their desired investment the higher their ability to make their desired investment expenditures.

Based on firms' budget constraint, the new loans are determined as follows:

$$NL_G^D = I_G^D - \beta RP + repL_{G-1} - \delta K_{G-1} - p_G \Delta b_G \tag{26}$$

$$NL_C^D = I_C^D - (1-\beta) RP + repL_{C-1} - \delta K_{C-1} - p_C \Delta b_C \tag{27}$$

where NL_G^D is the desired new green loans, NL_C^D is the desired new conventional loans and RP are the retained profits of firms.

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 aggregate amount of defaulted loans (DL) is equal to:

$$DL = defL_{-1} \tag{28}$$

where L denotes the total loans of firms.

The rate of default (def) is a positive function of the lagged burden of debt of firms and a positive function of the lagged degree of credit rationing for green and conventional loans:

$$def = def_0 + def_1 bur_{-1} + def_2 \left[sh_{C-1} CR_{C-1} + \left(1 - sh_{C-1}\right) CR_{G-1}\right] \tag{29}$$

where bur is the burden of debt of firms, CR_C is the degree of credit rationing for conventional loans, CR_G is the degree of credit rationing for green loans and sh_C is the share of conventional loans in total loans. The burden of debt expresses the financial commitments of firms relative to their profits. When the burden of debt of this sector increases, more firms are expected to face liquidity problems. Accordingly, at the aggregate level, a higher burden of debt translates into a higher rate of default. Additionally, firms' liquidity problems are assumed to increase when credit availability declines, that is when there is a rise in the proportion of new green loans and conventional loans that is credit rationed. A lower credit availability implies that more firms cannot attain their desired liquidity position. This is crucial because the liquidity created via new credit can be partially employed for the repayment of existing debt. Hence, the higher the unwillingness of banks to satisfy the demand for new corporate loans the higher the rate of default.

2.5. The portfolio choice of households

Households invest their expected financial wealth (V_{HF}) in four different assets: government securities (SEC_H), conventional corporate bonds (B_{CH}), green corporate bonds (B_{GH}) and deposits (D); int_S is the interest rate on government securities and int_D is the interest rate on deposits. In the portfolio choice, captured by Eqs. (30)-(33n), Godley's (1999) imperfect asset substitutability framework is adopted.[4]

$$\frac{SEC_H}{V_{HF-1}} = \lambda_{10} + \lambda'_{10} D_{T-1} + \lambda_{11} int_S + \lambda_{12} yield_{C-1} + \lambda_{13} yield_{G-1} + \lambda_{14} int_D + \lambda_{15} \frac{Y_{H-1}}{V_{HF-1}} \tag{30}$$

$$\frac{B_{CH}}{V_{HF-1}} = \lambda_{20} + \lambda'_{20} D_{T-1} + \lambda_{21} int_S + \lambda_{22} yield_{C-1} + \lambda_{23} yield_{G-1} + \lambda_{24} int_D + \lambda_{25} \frac{Y_{H-1}}{V_{HF-1}} \tag{31}$$

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

$$\frac{D}{V_{HF-1}} = \lambda_{40} + \lambda'_{40} D_{T-1} + \lambda_{41} int_S + \lambda_{42} yield_{C-1} + \lambda_{43} yield_{G-1} + \lambda_{44} int_D + \lambda_{45} \frac{Y_{H-1}}{V_{HF-1}} \tag{33n}$$

$$D = D_{-1} - C - \Delta SEC_H - p_C \Delta b_{CH} - p_G \Delta b_{GH} \tag{33}$$

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 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.[5] 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 asset's 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.[6]

2.6. Credit rationing and bank leverage

As mentioned above, banks impose credit rationing on the loans demanded by firms: they supply only a proportion of demanded loans. The degree of credit rationing is a positive function of the rate of default on firm loans and the financial position of the banks, reflected in their leverage ratio, lev_B:

---

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

[5] 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 have decided to assume $\lambda'_{30} = 0$ in our simulations.

[6] Note that balance sheet restrictions require that Eq. (33n) must be replaced by Eq. (33) in the computer simulations.

$$CR_C = r_0 + r_1 def_{-1} + r_2 lev_{B-1} \tag{34}$$

$$CR_G = l_0 + l_1 def_{-1} + l_2 lev_{B-1} \tag{35}$$

The bank leverage ratio is defined as:

$$lev_B = (L_C + L_G + SEC_B + HPM)/K_B \tag{36}$$

where SEC_B is the government securities that banks hold, HPM is high-powered money and K_B is the capital of banks.

2.7. Central banks and green QE

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 QE programmes, they buy bonds issued by the firm sector. 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. The value of conventional corporate bonds held be central banks (B_{CCB}) is:

$$B_{CCB} = s_C B_C \tag{37}$$

where s_C is the share of total outstanding conventional bonds that central banks desire to keep on their balance sheet. Currently, this share is very low since the corporate bond purchases of central banks represent a very small proportion of the total bond market.

The central banks' holdings of corporate green bonds (B_{GCB}) are given by:

$$B_{GCB} = s_G B_G \tag{38}$$

where s_C is the share of total outstanding green bonds that central banks desire to keep on their balance sheet. We assume that this share is currently equal to zero since central banks do not implement green QE programmes.

3. Calibration and validation of the model

We have calibrated the model using global data. Parameter values (i) have been taken from other studies or determined based on the available data, (ii) have been calibrated such that the model generates the baseline scenario described below or (ii) have been selected from a reasonable range of values. The details are reported in Appendix B and Appendix C.

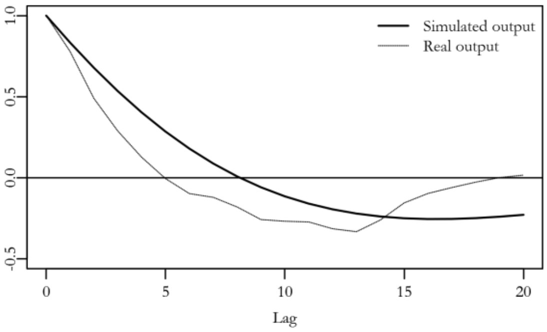
The model is simulated for the period 2015-2115. The aim of the simulations is to illuminate the long-run interactions between the financial system and climate change. Hence, no attention is paid to short-run fluctuations and business cycles. In the baseline scenario we assume that the economic expansion in the next decades is quite smooth: the economy grows at around 2.8-3% till 2050, as it has been observed on average over the last two decades or so. Drawing on the United Nations (2015) population projections (medium fertility variant), the labour force is assumed to grow at a declining rate, becoming equal to around 4.5bn people in 2050 (assuming a constant labour force-population ratio). The improvement in the ecological efficiency indicators is quite modest: for example, the share of renewable energy is increased to about 18% 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 2015 level. The improvement in ecological efficiency is associated with the accumulation of green capital. The cumulative green investment in the period 2015-2050 is equal to around US$35 trillion. Note that this figure includes both climate investment and other types of green investment that, for example, are conducive to lower material intensity and higher recycling rate. We also assume that in the baseline scenario the conventional bond market is relatively stable and the price of conventional bonds remains close to its current level till 2050.

We do not expect that the structure of the time series data in the next decades will necessarily be the same with the structure of past times series. However, it is a useful exercise to compare the auto- and cross-correlation structure of our simulated data with the real one in order to check whether the model produces data with reasonable time-series properties.[7] This is done in Fig. 1. Figs. 1a-1c show the auto-correlations in the simulated and observed time series for output, consumption and investment up to 20 lags. Figs. 1d-1f show the correlation between output at time *t* and output, investment and consumption at time *t-lag.* The series are expressed in logs and the HP filter has been used to remove the cyclical component.

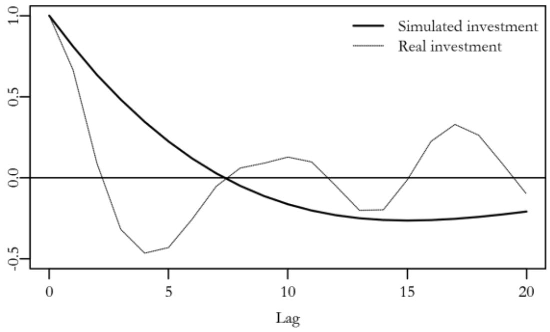
[7] For similar validation exercises see Assenza et al. (2015) and Caiani et al. (2016).

Fig. 1: Auto-correlations and cross-correlations of real and simulated data

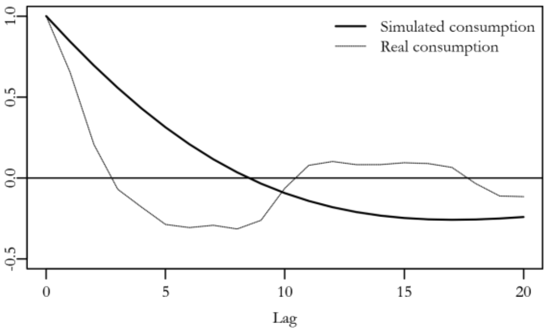
(a) Auto-correlation: output



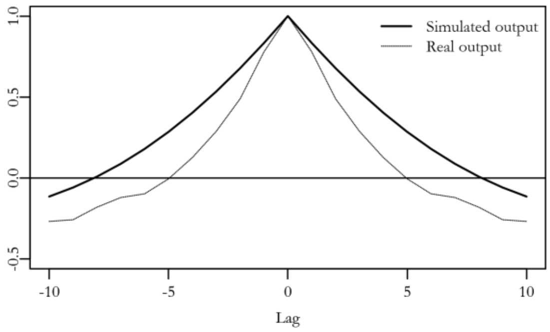
(b) Auto-correlation: investment



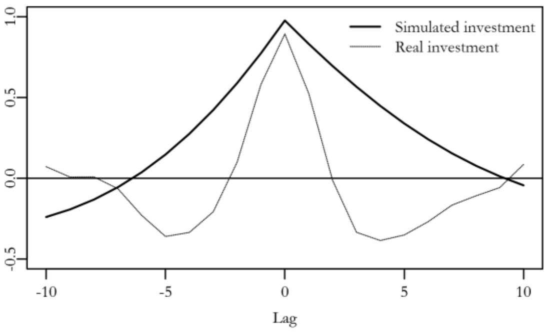
(c) Auto-correlation: consumption



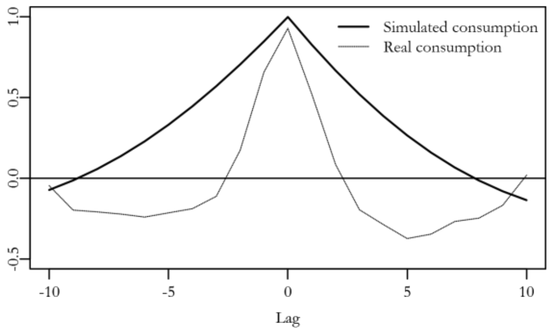
(d) Cross-correlation: output



(e) Cross-correlation: investment



(f) Cross-correlation: consumption



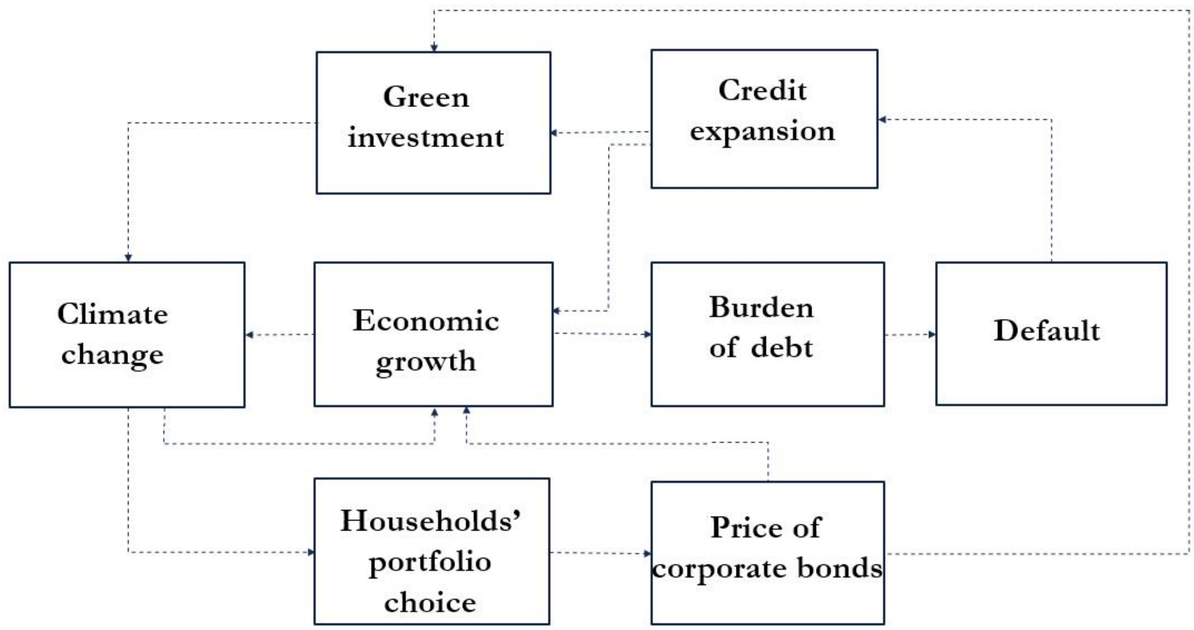
Note: The series are expressed in logs and the HP filter has been used to remove the cyclical component. The data for the real variables have been taken from the World Bank database. Output is available for the period 1960-2014 and consumption and investment are available for the period 1970-2013.

The auto-correlation structure of our simulated data is similar to the auto-correlation structure of the real data. This is especially the case for the structure of our simulated output which looks remarkably close to the empirically observed structure. Moreover, simulated consumption and investment appear to be pro-cyclical, in tune with the empirical data, and their peak behaviour resembles the behaviour observed in the real data. These results suggest that our model generates data with empirically reasonable properties.

4. Climate change and financial stability

Fig. 2 summarises the main channels through which climate change and financial stability interact. Fig. 3 plots the simulation results. In the baseline scenario CO_2 emissions increase significantly over the next decades (Fig. 3c). This rise is driven both by the exponential increase in output (Fig. 3a) and the very slow improvement in the share of renewable energy in total energy (Fig 3b). Hence, CO_2 concentration in the atmposphere increases, leading to severe global warming: as Fig. 3d indicates, in 2100 temperature becomes about 4^0C higher than the pre-industrial levels. The rise in atmospheric temperature leads to climate change damages. Accordingly, the growth rate of output starts declining. This slowdown of economic activity becomes more intense after the mid of the 21st century. Declining economic growth harms the profitability of firms (Fig. 3e) and leads to a gradual rise in firms' burden of debt (Fig. 3f), which in turn increases the rate of default (Fig. 3g) and thereby the bank leverage (Fig. 3h). The overall result is an increase in credit rationing which affects adversely the financing of investment. This slows down the investment in green capital, disrupting the transition to a low-carbon and more ecologically efficient economy.

Fig. 2: Channels through which climate change and financial stability interact in the model

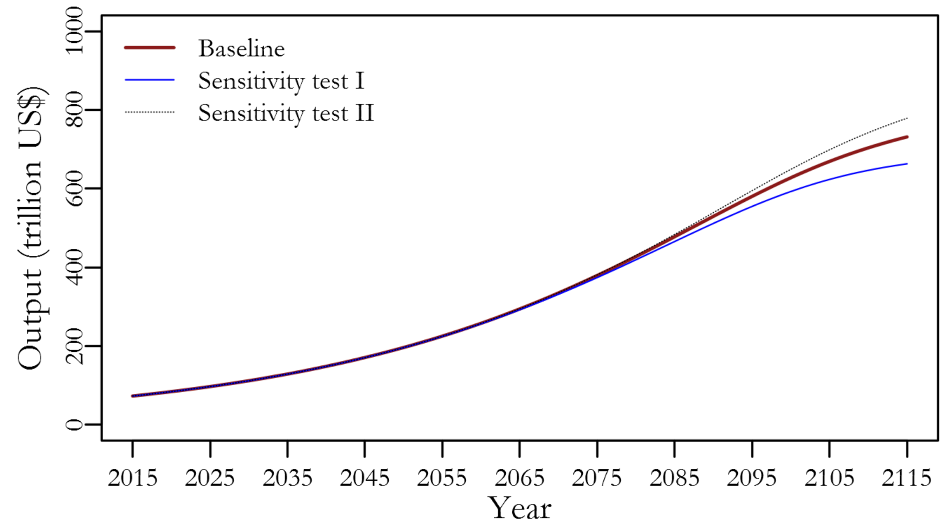


Climate damages affect the liquidity preference of households. The destruction of capital and the decline in the profitability of firms induces a reallocation of household financial wealth from corporate bonds towards deposits and government securities, which are deemed much safer. This is shown in Fig. 3i. The result is a decline in the price of corporate conventional bonds in the last decades of our simulation period (Fig. 3j). This is an example of a climate-induced asset price deflation. Remarkably, the price of green corporate bonds also falls in our baseline scenario (Fig. 3k). However, the main reason behind this fall is not the decline in the demand for green bonds from households. This fall is primarily explained by the increase in the supply of green bonds since green investment continuously increases in our simulation period (Fig. 3l).

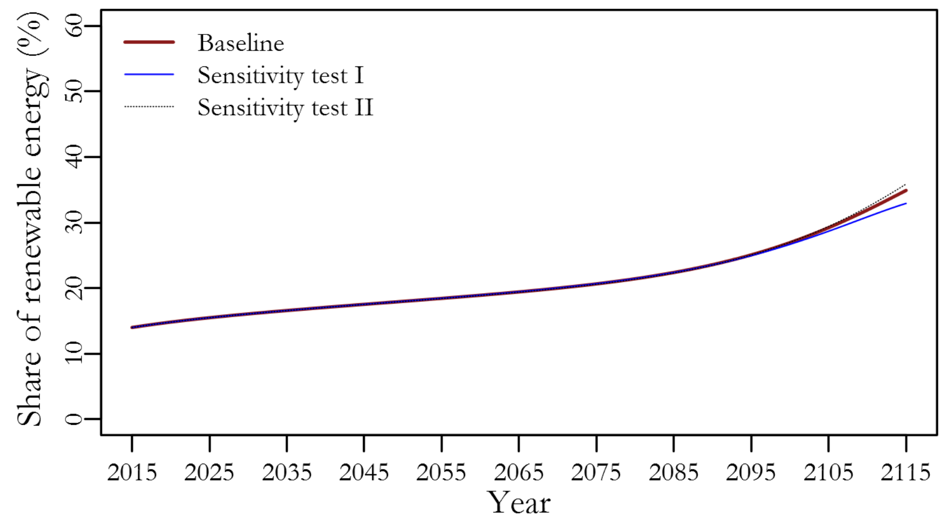
Bond price deflation has negative effects on economic growth because it reduces both the wealth-related consumption and the ability of firms to rely on the bond market in order to fund their desired investment. It also leads to less green investment which affects adversely the improvement in ecological efficiency.

Fig. 3: Evolution of environmental, macroeconomic and financial variables, baseline scenario and sensitivity analysis

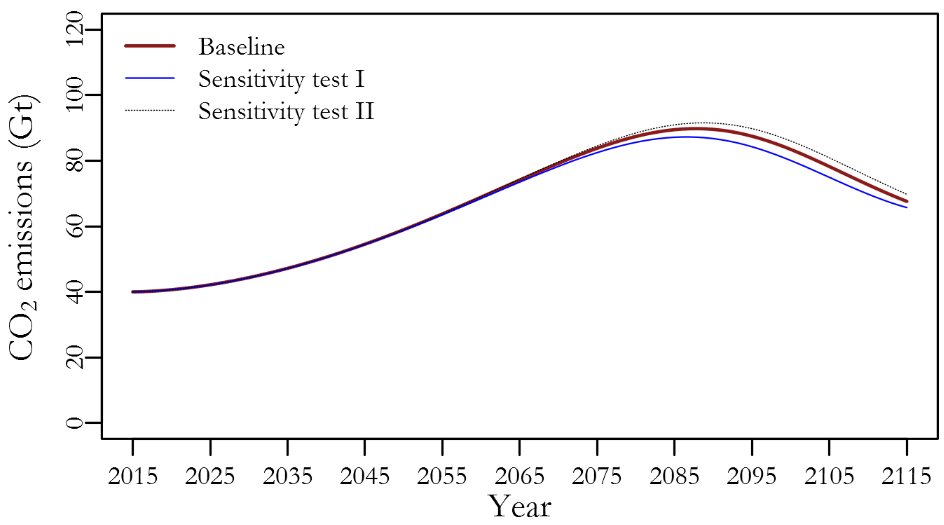
(a) Output



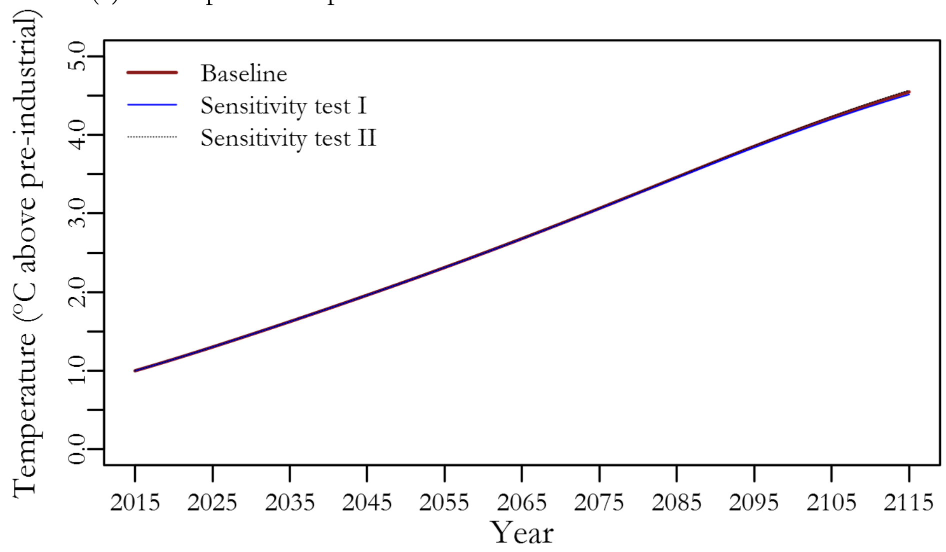
(b) Share of renewable energy in total energy



(c) CO_2 emissions



(d) Atmospheric temperature



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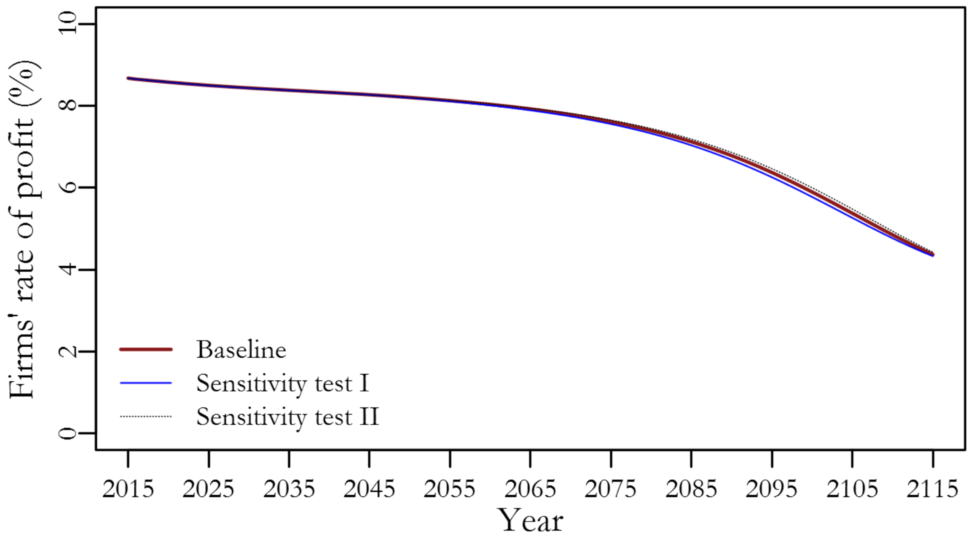
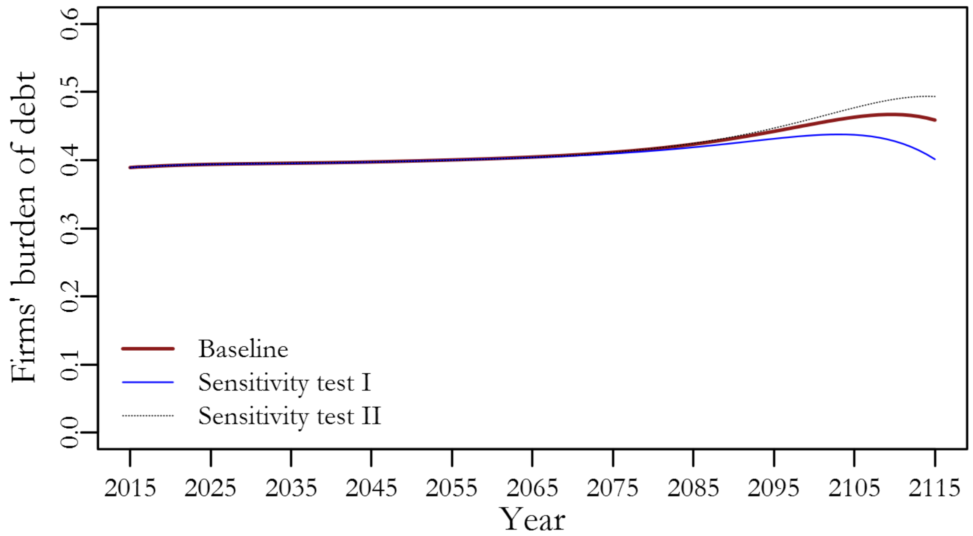
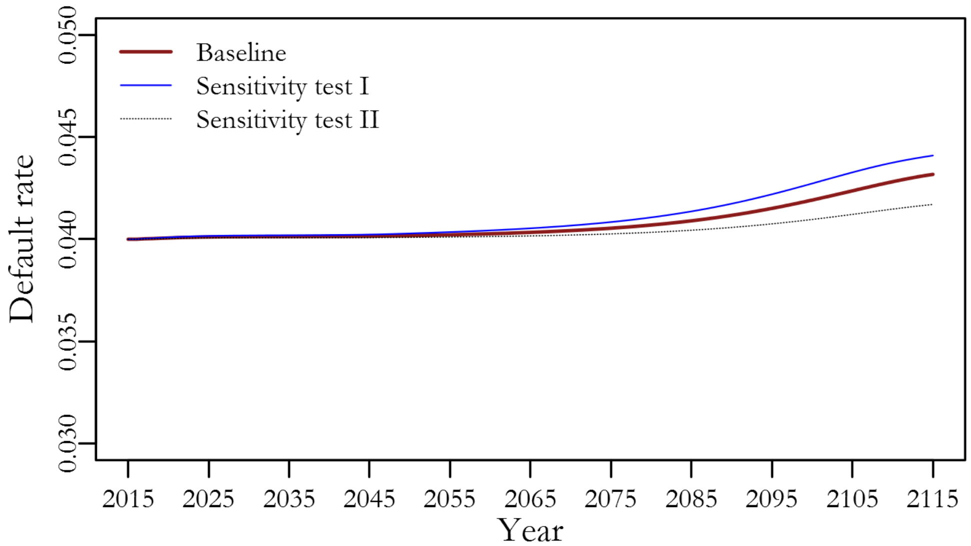
(e) Firms' rate of profit



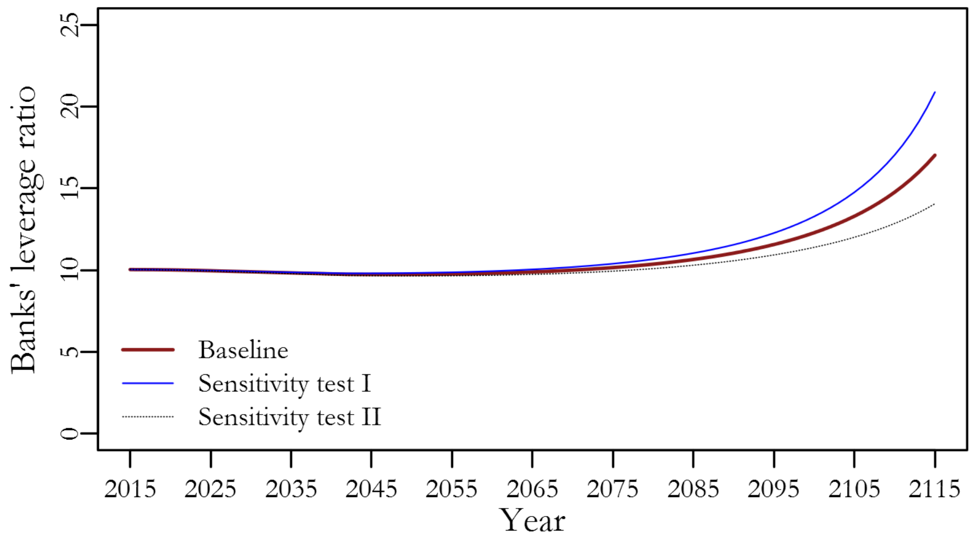
(f) Firms' burden of debt



(g) Default rate



(h) Banks' leverage ratio



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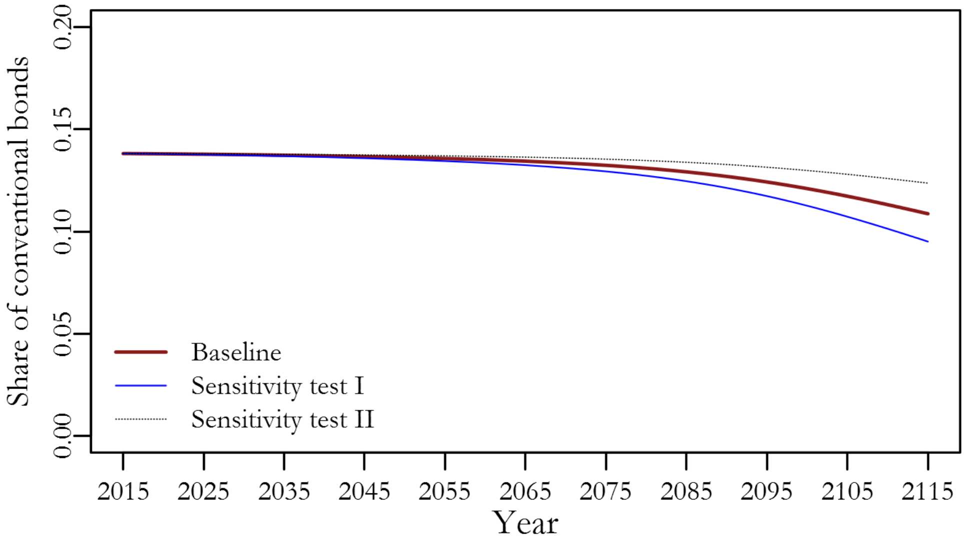
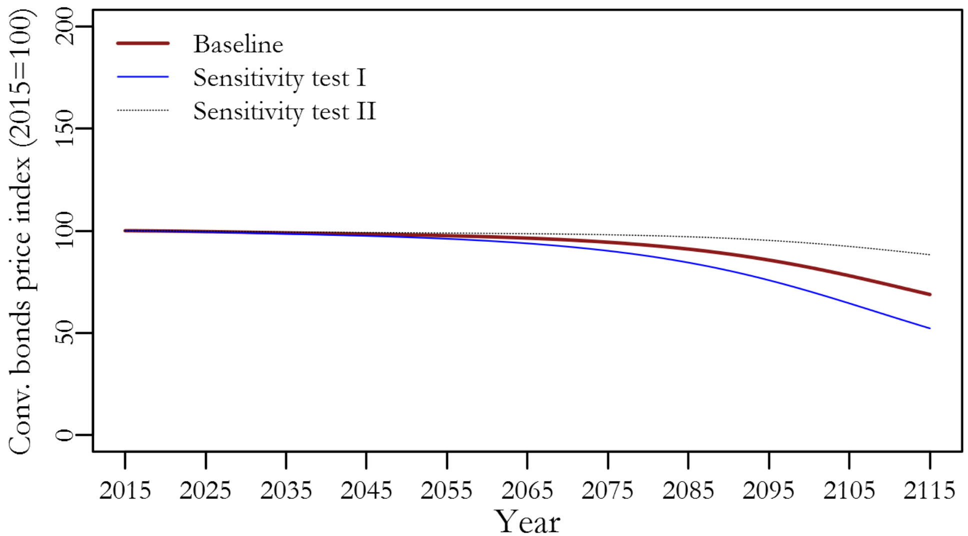
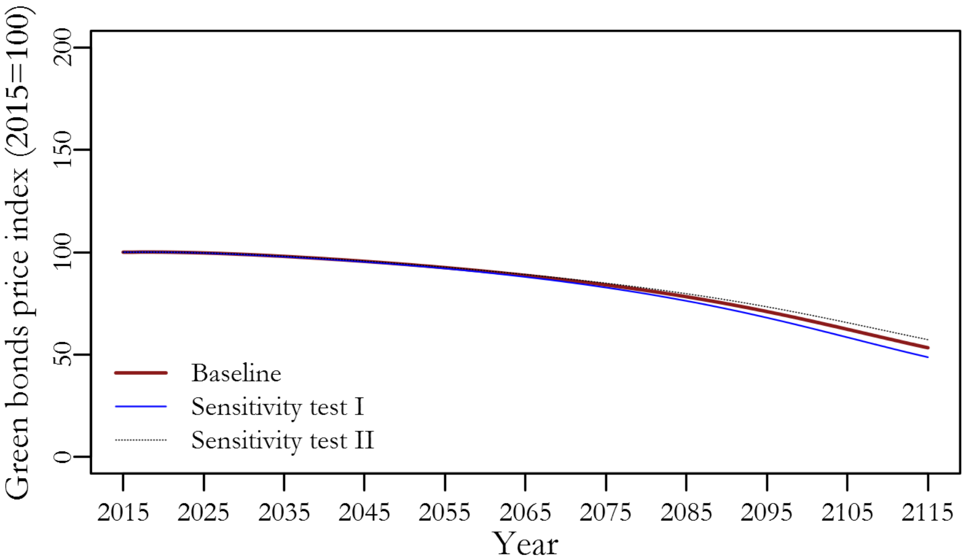
(i) Share of conventional bonds in households' wealth



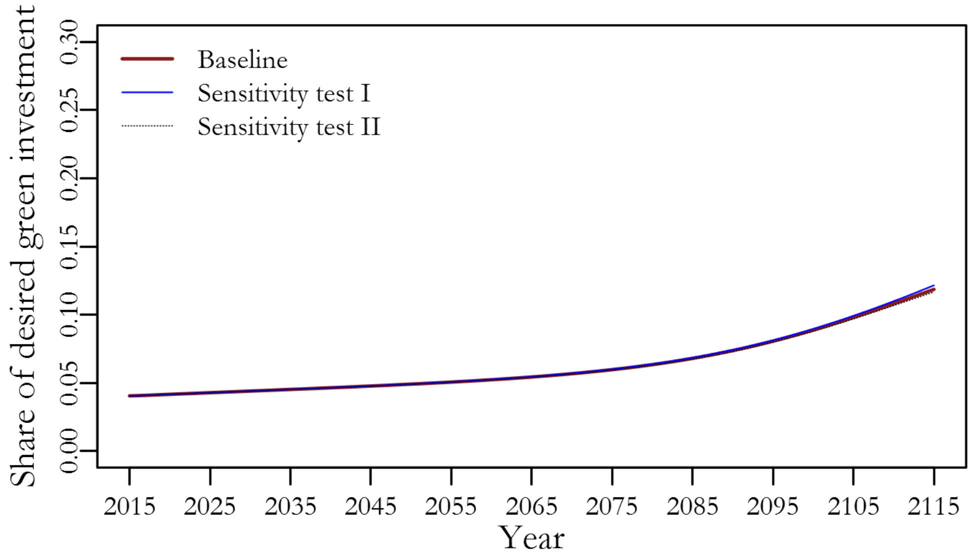
(j) Conventional bonds price index



(k) Green bonds price index



(l) Share of desired green investment in total investment



Note: The values used in the simulations are reported in Appendix B, Appendix C and Table 5.

How does the baseline scenario change when key parameters are modified? Space limitations do not allow us to explore this question in detail. However, we conduct a sensitivity analysis that concentrates on the following set of parameters (see Table 5): (i) the sensitivity of the default rate to the burden of debt (def_1); (ii) the sensitivity of credit rationing to the default rate (r_1 and l_1) and bank leverage (r_2 and l_2); (iii) the parameters of the portfolio choice that capture the sensitivity of the liquidity preference of households to the global warming damages (λ'_{10}, λ'_{20} and λ'_{40}).

Table 5: Values of key parameters: baseline scenario and sensitivity tests

Parameter	**Baseline scenario**	**Sensitivity test I**	**Sensitivity test II**
Sensitivity of the default rate to the burden of debt (def_1)	0.02	0.03	0.01
Sensitivity of conventional loans' credit rationing to the default rate of firms (r_1)	10	15	5
Sensitivity of green loans' credit rationing to the default rate of firms (l_1)	10	15	5
Sensitivity of conventional loans' credit rationing to the leverage ratio of banks (r_2)	0.02	0.03	0.01
Sensitivity of green loans' credit rationing to the leverage ratio of banks (l_2)	0.02	0.03	0.01
Parameter of households' portfolio choice (λ_{10}')	0.1	0.15	0.05
Parameter of households' portfolio choice (λ_{20}')	-0.2	-0.3	-0.1
Parameter of households' portfolio choice (λ_{40}')	0.1	0.15	0.05

As expected, the default rate increases (decreases) more when its sensitivity to the burden of debt is higher (lower) compared to the baseline (Fig. 3g). The same holds for the bank leverage ratio. (Fig. 3h). Also, the price of green corporate bonds declines more rapidly when the portfolio choice of households is more responsive to climate change damages (Fig 3k). Nonetheless, the effects of climate change on financial stability are overall qualitatively similar.

5. Effects of a green QE programme

In this section we analyse how our results change when a green QE programme is implemented. We suppose that in 2020 central banks around the globe announce that they will purchase 20% of the outstanding green bonds and they commit themselves that they will keep the same share of the green bond market over the next decades. In 2020 this translates into an amount equal to around US$180 billion. We also assume that the proportion of conventional corporate bonds held by central banks remains equal to its current level.[8]

Experimentation with various parameter values has shown that the parameter that plays a key role in determining the effectiveness of a green QE programme is the sensitivity of the share of desired green investment to the divergence between the green bond yield and the conventional bond yield (β_2) – see Eq. (19). The higher the value of β_2 the more firms' green investment responds to a monetary policy-induced decline in the yield of green bonds. Consequently, in our simulations we consider a green QE scenario whereby β_2 is equal to its baseline value and another green QE scenario in which a more optimistic value of β_2 is assumed.

The effects of the green QE programme are portrayed in Fig. 4. As Fig. 4k shows, green QE boosts the price of green corporate bonds. This has various positive implications for climate change and financial stability. Regarding climate change, the resulting reduction in the green bond yield leads to a lower cost of borrowing for firms and a lower reliance on bank lending. This increases overall investment, including green investment. More importantly, since the price of green bonds increases relative to the price of conventional bonds (Figs. 4j and 4k), the share of desired green investment in total investment goes up (Fig. 4l). As firms invest more in green capital, the use of renewable energy increases (Fig. 4b). This leads to lower CO_2 emissions and slower global warming from what would otherwise be the case.

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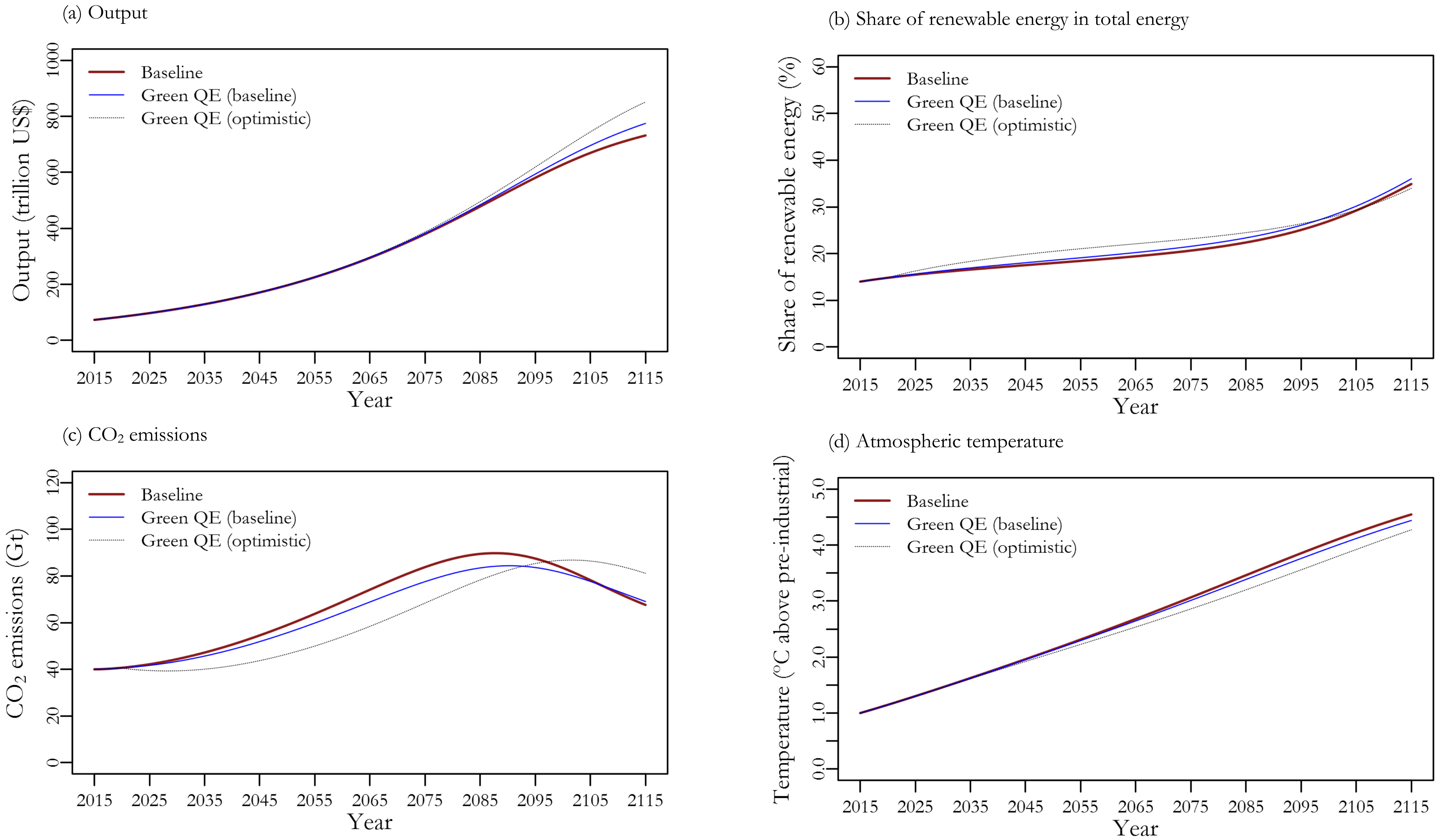
[8] We find that the effects of a green QE programme do not differ significantly if we assume that central banks stop holding conventional corporate bonds.

Fig. 4: Effects of the implementation of a green QE programme



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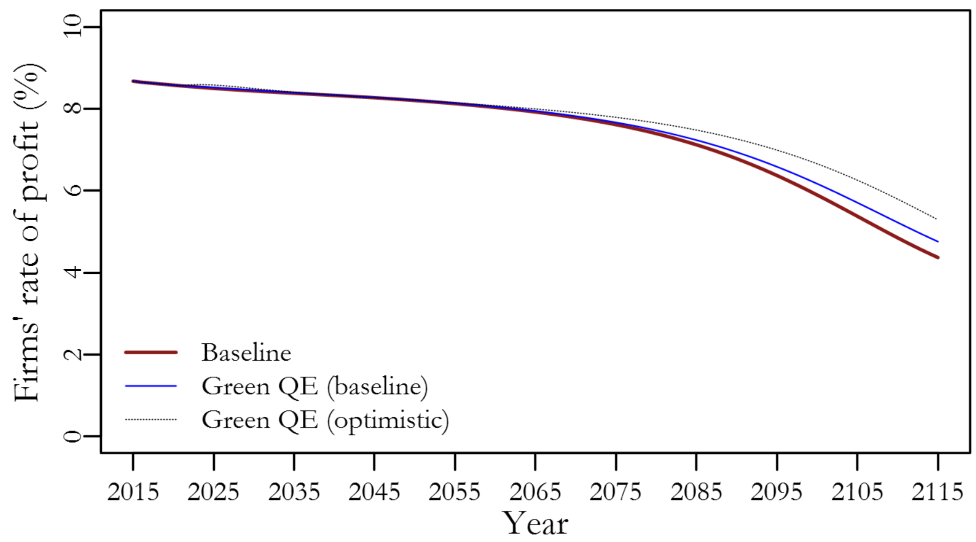
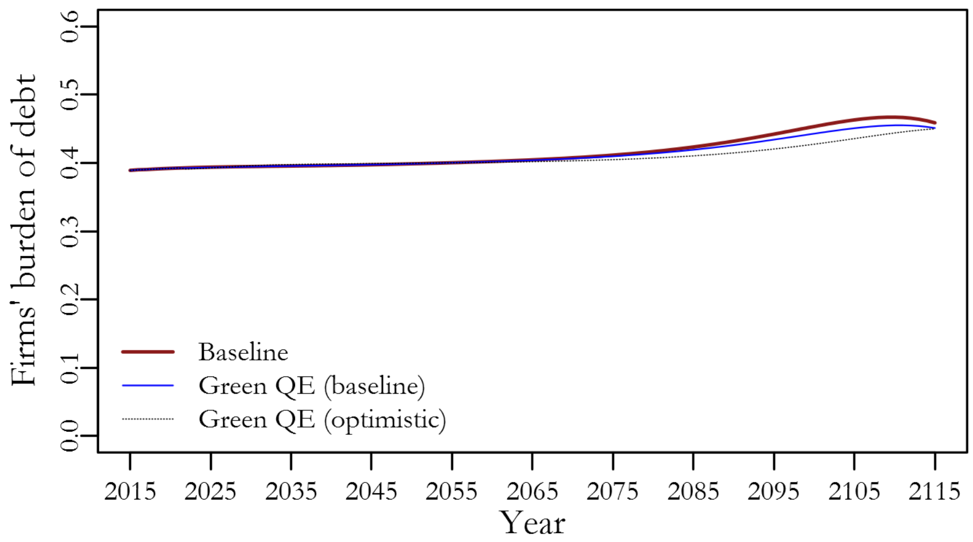
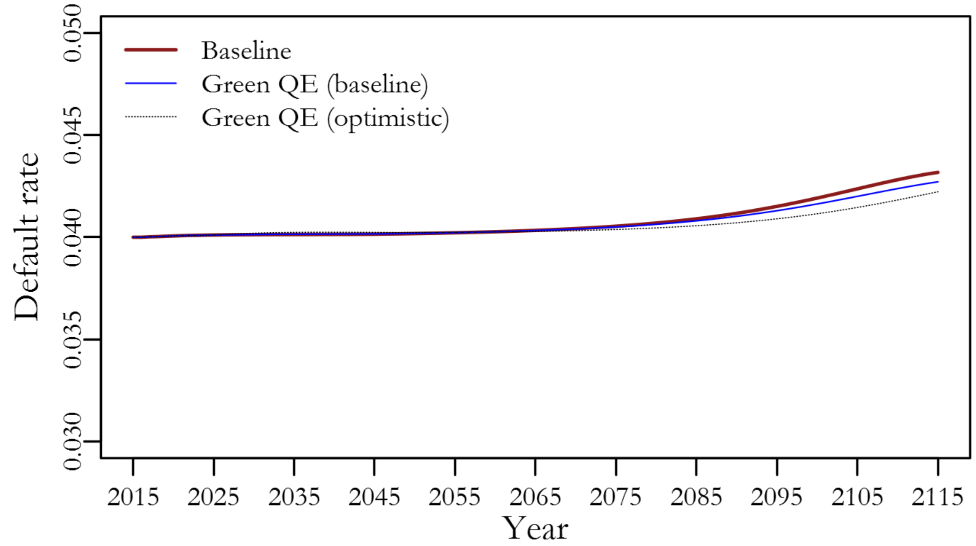
(e) Firms' rate of profit



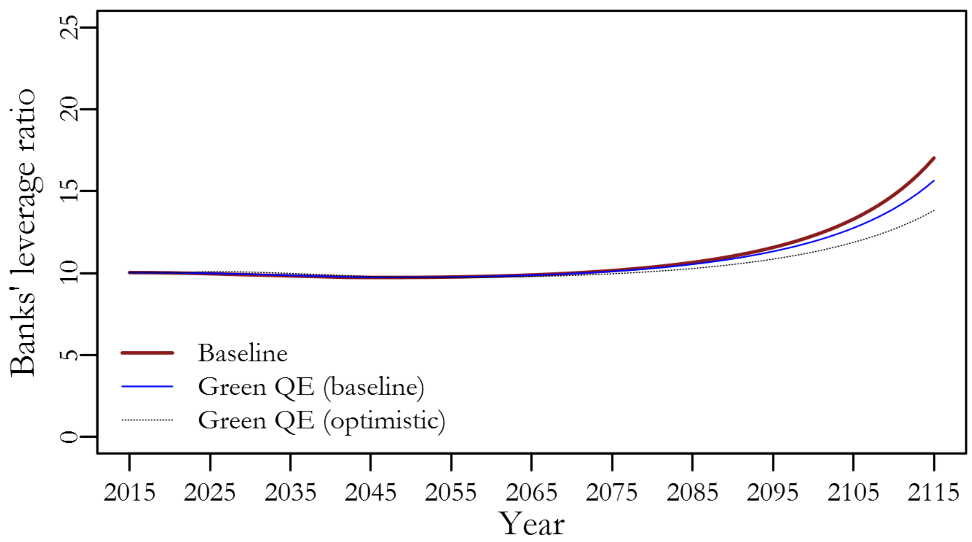
(f) Firms' burden of debt



(g) Default rate



(h) Banks' leverage ratio



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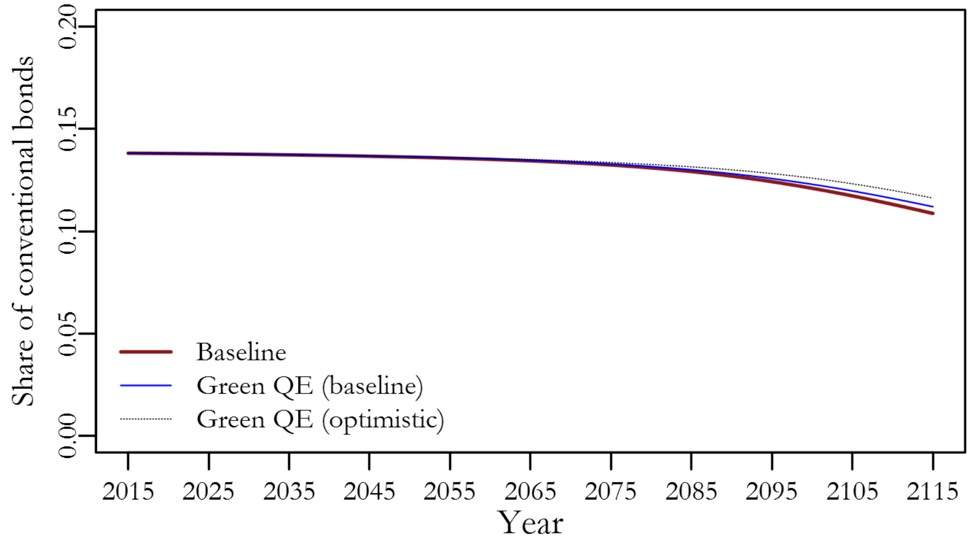
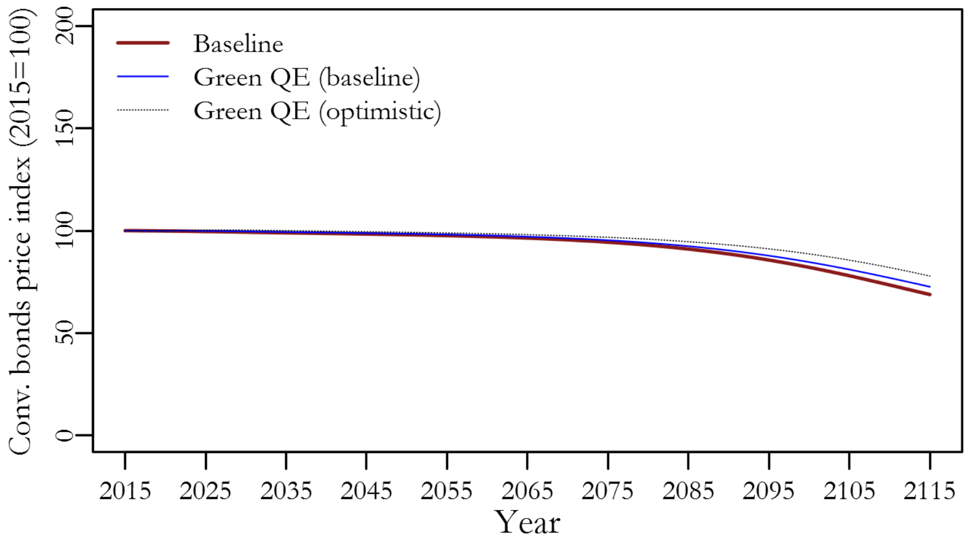
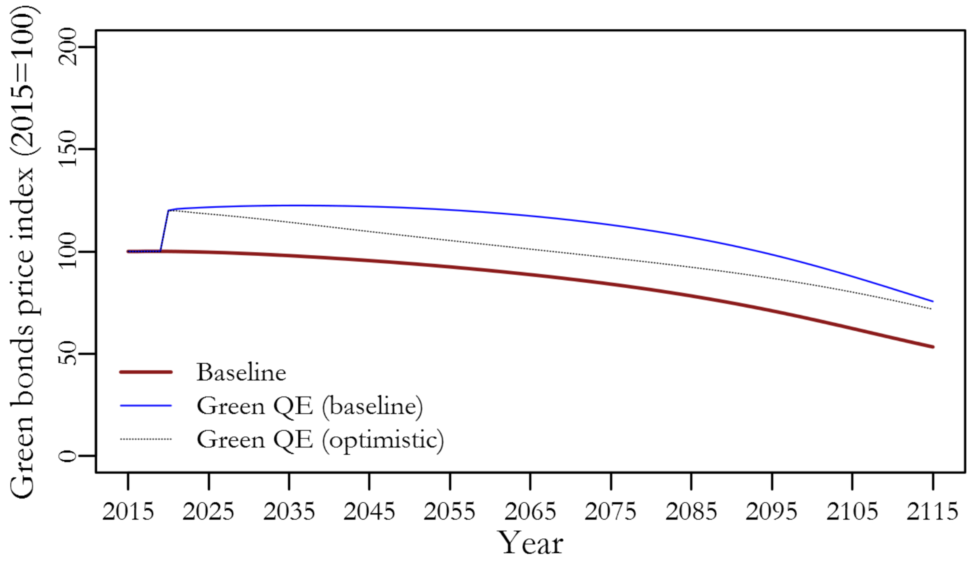
(i) Share of conventional bonds in households' wealth



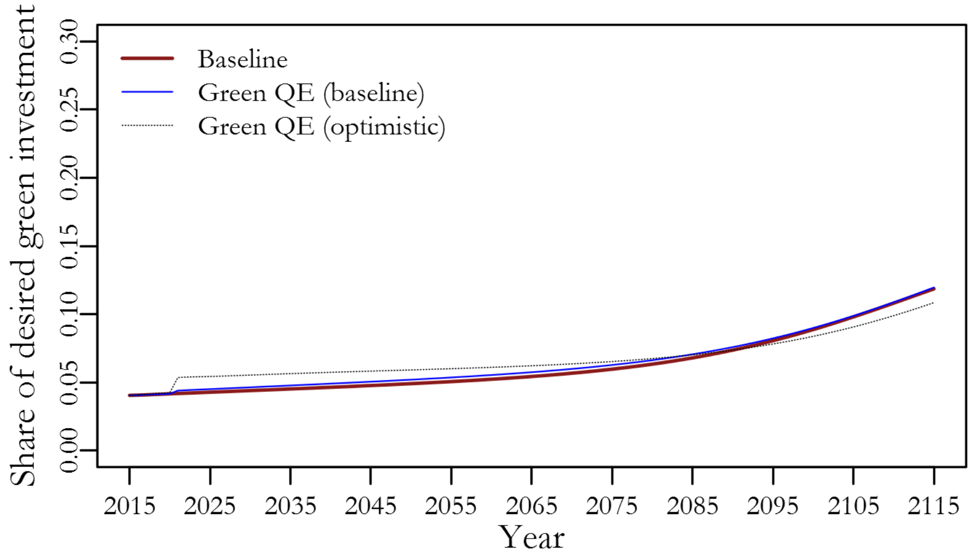
(j) Conventional bonds price index



(k) Green bonds price index



(l) Share of desired green investment in total investment



Note: The values used in the simulations are reported in Appendix B and Appendix C. In Green QE (baseline) the sensitivity of the desired green investment to the divergence between the green bond yield and the conventional bond yield (β_2) is equal to 1. In Green QE (optimistic) we have that $\beta_2 = 5$. The implementation of Green QE starts in 2020. This is captured by an increase in s_G from 0 to 0.2.

It should, however, be pointed out that in our simulations green QE cannot by itself prevent a substantial rise in atmospheric temperature: even with the optimistic value of β_2, global warming is still higher than 3.5^{0}C at the end of the century. There are two main channels through which the beneficial climate effects of a higher β_2 are attenuated. First, a higher β_2 is conducive to lower damages, allowing economic activity to expand more rapidly in the optimistic green QE scenario (Fig. 4a). This higher economic activity places upward pressures on CO_2 emissions. Second, lower damages provide less incentives for the materialisation of green investment projects. This is shown in Fig. 4l: over the last decades of the simulation period the share of desired green investment in total investment becoms higher when β_2 has a lower value.

Regarding financial stability, green QE increases profitability and reduces the burden of debt, the default rate and the bank leverage compared with the baseline (Figs. 4e, 4f, 4g and 4h). These beneficial effects on financial stability stem from (i) the reduction in economic damages as a result of slower global warming and (ii) the lower reliance of firms' green investment on bank lending stability. A higher value of β_2 reinforces generally the financial stability effects of green QE. However, the rise in the price of green bonds is lower compared to the baseline green QE scenario (Fig. 4k). The reason is that firms issue more green bonds in order to fund their higher desired green investment. For a given demand for green bonds, this tends to reduce the bond price.

6. Conclusion

The fundamental changes that are expected to take place in the climate system in the next decades are likely to have severe implications for the stability of the financial system. The purpose of this article was to analyse these implications by using a stock-flow-fund ecological macroeconomic model. Emphasis was placed on the effects of climate change damages on the financial position of firms and asset price deflation. The model was calibrated using global data and simulations were conducted for the period 2015-2115.

Our simulation analysis for the interactions between climate change and financial stability produced three key results. First, by destroying the capital of firms and reducing their profitability, climate change is likely to increase gradually the burden of debt of firms, leading to a higher rate of default that could harm both the financial and the non-financial corporate sector. Second, the damages caused by climate change can lead to a portfolio reallocation that can cause a gradual decline in the price of corporate bonds. Third, financial instability might adversely affect credit expansion and the investment in green capital, with adverse feedback effects on climate change. The sensitivity analysis illustrated that these results do not change qualitatively when key parameter values are modified. However, a deeper exploration of the parameter space of our model is necessary in order to get a more detailed insight into the links between climate change and finance.

The article also investigated how a green QE programme could reduce the risks imposed on the financial system by climate change. The simulation results showed that, by increasing the price of green corporate bonds, the implementation of a green QE programme can reduce climate-induced financial instability and restrict global warming. However, green QE does not turn out to be by itself capable of preventing a substantial reduction in atmospheric temperature. Even with an optimistic assumption about the sensitivity of green investment to the divergence between the green bond yield and the conventional bond yield, global warming is still quite severe. Hence, many other types of environmental policies need to be implemented in conjunction with a green QE programme in order to keep atmospheric temperature close to 2^{0}C and prevent climate-induced financial instability.

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Appendix A

3.1 Ecosystem

3.1.1 Matter, recycling and waste

$$MY = \mu Y \tag{A1}$$
$$M = MY - REC \tag{A2}$$
$$REC = \rho DEM \tag{A3}$$
$$DEM = \mu(\delta K_{-1} + \xi DC_{-1}) \tag{A4}$$
$$SES = SES_{-1} + MY - DEM \tag{A5}$$
$$W = M + CEN + O2 - EMIS_{IN} - \Delta SES \tag{A6}$$
$$CEN = \frac{EMIS_{IN}}{car} \tag{A7}$$
$$O2 = EMIS_{IN} - CEN \tag{A8}$$
$$HWS = HWS_{-1} + hazW \tag{A9}$$
$$hazrario = \frac{HWS}{SURF} \tag{A10}$$
$$REV_M = REV_{M-1} + CON_M - M \tag{A11}$$
$$CON_M = con_M RES_{M-1} \tag{A12}$$
$$RES_M = RES_{M-1} - CON_M \tag{A13}$$
$$dep_M = \frac{M}{REV_{M-1}} \tag{A14}$$

3.1.2 Energy

$$E = \varepsilon Y \tag{A15}$$
$$ER = \theta E \tag{A16}$$
$$EN = E - ER \tag{A17}$$
$$ED = EN + ER \tag{A18}$$
$$REV_E = REV_{E-1} + CON_E - EN \tag{A19}$$
$$CON_E = con_E RES_{E-1} \tag{A20}$$
$$RES_E = RES_{E-1} - CON_E \tag{A21}$$
$$dep_E = \frac{EN}{REV_{E-1}} \tag{A22}$$

3.1.3 Emissions and climate change

$$EMIS_{IN} = \omega EN \tag{A23}$$
$$EMIS_L = EMIS_{L-1}(1 - lr) \tag{A24}$$
$$EMIS = EMIS_{IN} + EMIS_L \tag{A25}$$
$$CO2_{AT} = EMIS + \phi_{11} CO2_{AT-1} + \phi_{21} CO2_{UP-1} \tag{A26}$$
$$CO2_{UP} = \phi_{12} CO2_{AT-1} + \phi_{22} CO2_{UP-1} + \phi_{32} CO2_{LO-1} \tag{A27}$$
$$CO2_{LO} = \phi_{23} CO2_{UP-1} + \phi_{33} CO2_{LO-1} \tag{A28}$$
$$F = F_{2\times CO2} \log_2 \frac{CO2_{AT}}{CO2_{AT-PRE}} + F_{EX} \tag{A29}$$
$$F_{EX} = F_{EX-1} + fex \tag{A30}$$

$$T_{AT} = T_{AT-1} + t_1\left(F - \frac{F_{2\times CO2}}{S} T_{AT-1} - t_2\left(T_{AT-1} - T_{LO-1}\right)\right) \quad (A31)$$

$$T_{LO} = T_{LO-1} + t_3\left(T_{AT-1} - T_{LO-1}\right) \quad (A32)$$

3.1.4 Ecological efficiency and technology

$$\omega = \omega_{-1}\left(1 + g_{\omega}\right) \quad (A33)$$

$$g_{\omega} = g_{\omega-1}\left(1 - \zeta_1\right) \quad (A34)$$

$$\mu = \mu_{max} - \frac{\mu_{max} - \mu_{min}}{1 + \pi_1 e^{-\pi_2 (K_G/K_C)}} \quad (A35)$$

$$\rho = \frac{\rho_{max}}{1 + \pi_3 e^{-\pi_4 (K_G/K_C)}} \quad (A36)$$

$$\varepsilon = \varepsilon_{max} - \frac{\varepsilon_{max} - \varepsilon_{min}}{1 + \pi_5 e^{-\pi_6 (K_G/K_C)}} \quad (A37)$$

$$\theta = \frac{1}{1 + \pi_7 e^{-\pi_8 (K_G/K_C)}} \quad (A38)$$

3.2 Macroeconomy and financial system

3.2.1 Output determination and damages

$$Y_M^* = \frac{REV_{M-1} + REC}{\mu} \quad (A39)$$

$$Y_E^* = \frac{REV_{E-1}}{(1-\theta)\varepsilon} \quad (A40)$$

$$Y_K^* = vK \quad (A41)$$

$$Y_N^* = \lambda hLF \quad (A42)$$

$$Y^* = min\left(Y_M^*, Y_E^*, Y_K^*, Y_N^*\right) \quad (A43)$$

$$Y = C + I + G \quad (A44)$$

$$um = \frac{Y}{Y_M^*} \quad (A45)$$

$$ue = \frac{Y}{Y_E^*} \quad (A46)$$

$$u = \frac{Y}{Y_K^*} \quad (A47)$$

$$re = \frac{Y}{Y_N^*} \quad (A48)$$

$$D_T = 1 - \frac{1}{1 + \eta_1 T_{AT} + \eta_2 T_{AT}{}^2 + \eta_3 T_{AT}{}^{6.754}} \quad (A49)$$

$$D_{TP} = pD_T \quad (A50)$$

$$D_{TF} = 1 - \frac{1 - D_T}{1 - D_{TP}} \quad (A51)$$

3.2.2 Firms

$$TP_G = Y - wN - int_C\, L_{C-1} - int_G\, L_{G-1} - \delta K_{-1} - coupon_C b_{C-1} - coupon_G b_{G-1} \quad (A52)$$

$$TP = TP_G - T_F \quad \text{(A53)}$$
$$RP = s_F TP_{-1} \quad \text{(A54)}$$
$$DP = TP - RP \quad \text{(A55)}$$
$$r = RP/K \quad \text{(A56)}$$
$$I^D = \left[\left(\alpha_0 + \alpha_1 r_{-1} + \alpha_2 u_{-1} - \alpha_3 g_{\varepsilon -1}\right)K_{-1} + \delta K_{-1}\right]\left(1 - D_{T-1}\right) \quad \text{(A57)}$$
$$\alpha_0 = \alpha_{00} - \gamma_1\left(um_{-1} - um_T\right) - \gamma_2\left(ue_{-1} - ue_T\right) - \gamma_3\left(u_{-1} - u_T\right) - \gamma_4\left(re_{-1} - re_T\right) \quad \text{(A58)}$$
$$\gamma_1 = \gamma_{10} \quad iff \quad um_{-1} \geq um_T; \quad otherwise \quad \gamma_1 = 0 \quad \text{(A59)}$$
$$\gamma_2 = \gamma_{20} \quad iff \quad ue_{-1} \geq ue_T; \quad otherwise \quad \gamma_2 = 0 \quad \text{(A60)}$$
$$\gamma_3 = \gamma_{30} \quad iff \quad u_{-1} \geq u_T; \quad otherwise \quad \gamma_3 = 0 \quad \text{(A61)}$$
$$\gamma_4 = \gamma_{40} \quad iff \quad re_{-1} \geq re_T; \quad otherwise \quad \gamma_4 = 0 \quad \text{(A62)}$$
$$I_G^D = \beta I^D \quad \text{(A63)}$$
$$I_C^D = I^D - I_G^D \quad \text{(A64)}$$
$$\beta = \beta_0 + \beta_1 - \beta_2\left[sh_{L-1}\left(int_G - int_C\right) + \left(1 - sh_{L-1}\right)\left(yield_{G-1} - yield_{C-1}\right)\right] + \beta_3 D_{T-1} \quad \text{(A65)}$$
$$\beta_0 = \beta_{0-1}(1 + g_{\beta 0}) \quad \text{(A66)}$$
$$g_{\beta 0} = g_{\beta 0-1}\left(1 - \zeta_2\right) \quad \text{(A67)}$$
$$NL_G^D = I_G^D - \beta RP + repL_{G-1} - \delta K_{G-1} - p_G \Delta b_G \quad \text{(A68)}$$
$$NL_C^D = I_C^D - \left(1 - \beta\right)RP + repL_{C-1} - \delta K_{C-1} - p_C \Delta b_C \quad \text{(A69)}$$
$$I_G = \beta RP + \left(L_G - L_{G-1}\right) + \delta K_{G-1} + p_G \Delta b_G + defL_{G-1} \quad \text{(A70)}$$
$$I_C = RP + \left(L_C - L_{C-1}\right) + \left(L_G - L_{G-1}\right) + \delta K_{-1} - I_G + p_G \Delta b_G + p_C \Delta b_C + DL \quad \text{(A71)}$$
$$I = I_C + I_G \quad \text{(A72)}$$
$$L = L_C + L_G \quad \text{(A73)}$$
$$K_G = K_{G-1} + I_G - \delta K_{G-1} \quad \text{(A74)}$$
$$K_C = K_{C-1} + I_C - \delta K_{C-1} \quad \text{(A75)}$$
$$K = K_C + K_G \quad \text{(A76)}$$
$$\kappa = K_G / K \quad \text{(A77)}$$
$$\delta = \delta_0 + \left(1 - \delta_0\right)\left(1 - ad_K\right)D_{TF-1} \quad \text{(A78)}$$
$$v = v_{-1}\left(1 + g_v\right)\left[1 - \left(1 - ad_P\right)D_{TP-1}\right] \quad \text{(A79)}$$
$$g_\lambda = \sigma_0 + \sigma_1 + \sigma_2 g_{Y-1} \quad \text{(A80)}$$
$$\sigma_0 = \sigma_{0-1}\left(1 - \zeta_3\right) \quad \text{(A81)}$$
$$\lambda = \lambda_{-1}\left(1 + g_\lambda\right)\left[1 - \left(1 - ad_P\right)D_{TP-1}\right] \quad \text{(A82)}$$
$$w = s_W \lambda h \quad \text{(A83)}$$
$$N = \frac{Y}{h\lambda} \quad \text{(A84)}$$
$$ur = 1 - re \quad \text{(A85)}$$
$$b_C = b_{C-1} + \frac{x_1 I_C^D}{p_C} \quad \text{(A86)}$$
$$b_G = b_{G-1} + \frac{x_2 I_G^D}{p_G} \quad \text{(A87)}$$
$$x_1 = x_{10} - x_{11} yield_C \quad \text{(A88)}$$
$$x_2 = x_{20} - x_{21} yield_G \quad \text{(A89)}$$
$$yield_C = \frac{coupon_C}{p_C} \quad \text{(A90)}$$
$$yield_G = \frac{coupon_G}{p_G} \quad \text{(A91)}$$

$$B_C = B_{CH} + B_{CCB} \tag{A92}$$
$$B_G = B_{GH} + B_{GCB} \tag{A93}$$
$$p_C = \frac{B_C}{b_C} \tag{A94}$$
$$p_G = \frac{B_G}{b_G} \tag{A95}$$
$$B = B_C + B_G \tag{A96}$$
$$bur = \frac{(int_C + rep)L_{C-1} + (int_G + rep)L_{G-1} + coupon_C b_{C-1} + coupon_G b_{G-1}}{TP + int_C L_{C-1} + int_G L_{G-1} + coupon_C b_{C-1} + coupon_G b_{G-1}} \tag{A97}$$
$$DL = def L_{-1} \tag{A98}$$
$$def = def_0 + def_1 bur_{-1} + def_2 \left[sh_{C-1} CR_{C-1} + (1 - sh_{C-1}) CR_{G-1}\right] \tag{A99}$$

2.2 Households

$$Y_{HG} = wN + DP + BP_D + int_D D_{-1} + int_S SEC_{H-1} + coupon_C b_{CH-1} + coupon_G b_{GH-1} \tag{A100}$$
$$Y_H = Y_{HG} - T_H \tag{A101}$$
$$C = (c_1 Y_{H-1} + c_2 V_{HF-1})(1 - D_{T-1}) \tag{A102}$$
$$V_{HF} = V_{HF-1} + Y_H - C + b_{CH-1} \Delta p_C + b_{GH-1} \Delta p_G \tag{A103}$$
$$\frac{SEC_H}{V_{HF-1}} = \lambda_{10} + \lambda'_{10} D_{T-1} + \lambda_{11} int_S + \lambda_{12} yield_{C-1} + \lambda_{13} yield_{G-1} + \lambda_{14} int_D + \lambda_{15} \frac{Y_{H-1}}{V_{HF-1}} \tag{A104}$$
$$\frac{B_{CH}}{V_{HF-1}} = \lambda_{20} + \lambda'_{20} D_{T-1} + \lambda_{21} int_S + \lambda_{22} yield_{C-1} + \lambda_{23} yield_{G-1} + \lambda_{24} int_D + \lambda_{25} \frac{Y_{H-1}}{V_{HF-1}} \tag{A105}$$
$$\frac{B_{GH}}{V_{HF-1}} = \lambda_{30} + \lambda'_{30} D_{T-1} + \lambda_{31} int_S + \lambda_{32} yield_{C-1} + \lambda_{33} yield_{G-1} + \lambda_{34} int_D + \lambda_{35} \frac{Y_{H-1}}{V_{HF-1}} \tag{A106}$$
$$\frac{D}{V_{HF-1}} = \lambda_{40} + \lambda'_{40} D_{T-1} + \lambda_{41} int_S + \lambda_{42} yield_{C-1} + \lambda_{43} yield_{G-1} + \lambda_{44} int_D + \lambda_{45} \frac{Y_{H-1}}{V_{HF-1}} \tag{A107n}$$
$$D = D_{-1} + Y_H - C - \Delta SEC_H - p_C \Delta b_{CH} - p_G \Delta b_{GH} \tag{A107}$$
$$b_{CH} = \frac{B_{CH}}{p_C} \tag{A108}$$
$$b_{GH} = \frac{B_{GH}}{p_G} \tag{A109}$$
$$DC = DC_{-1} + C - \xi DC_{-1} \tag{A110}$$
$$LF = LF_{-1}(1 + g_{LF})\left[1 - (1 - ad_{LF}) D_{TF-1}\right] \tag{A111}$$
$$g_{LF} = lf_0 + lf_1 - lf_2 ur_{-1} - lf_3 hazratio_{-1} \tag{A112}$$
$$lf_0 = lf_{0-1}(1 - \zeta_4) \tag{A113}$$

2.3 Banks

$$BP = int_C L_{C-1} + int_G L_{G-1} + int_S SEC_{B-1} - int_D D_{-1} - int_A A_{-1} \tag{A114}$$
$$K_B = L_C + L_G + HPM + SEC_B - A - D \tag{A115}$$
$$BP_U = s_B BP_{-1} \tag{A116}$$
$$BP_D = BP - BP_U \tag{A117}$$
$$HPM = h_1 D \tag{A118}$$
$$SEC_B = h_2 D \tag{A119}$$
$$A = A_{-1} + \Delta HPM + \Delta L_G + \Delta L_C + \Delta SEC_B + DL - \Delta D - BP_U \tag{A120}$$

$$CR_C = r_0 + r_1 def_{-1} + r_2 lev_{B-1} \quad \text{(A121)}$$

$$CR_G = l_0 + l_1 def_{-1} + l_2 lev_{B-1} \quad \text{(A122)}$$

$$L_C = L_{C-1} + (1 - CR_C) NL_C^D - repL_{C-1} - defL_{C-1} \quad \text{(A123)}$$

$$L_G = L_{G-1} + (1 - CR_G) NL_G^D - repL_{G-1} - defL_{G-1} \quad \text{(A124)}$$

$$lev_B = (L_C + L_G + SEC_B + HPM)/K_B \quad \text{(A125)}$$

2.4 Government sector

$$SEC = SEC_{-1} + G - T + int_S \, SEC_{-1} - CBP \quad \text{(A126)}$$

$$G = govY_{-1} \quad \text{(A127)}$$

$$T_H = \tau_H YH_{G-1} \quad \text{(A128)}$$

$$T_F = \tau_F TP_{G-1} \quad \text{(A129)}$$

$$T = T_H + T_F \quad \text{(A130)}$$

2.5 Central banks

$$CBP = coupon_C b_{CCB-1} + coupon_G b_{GCB-1} + int_A A_{-1} + int_S \, SEC_{CB-1} \quad \text{(A131)}$$

$$B_{GCB} = s_G B_G \quad \text{(A132)}$$

$$B_{CCB} = s_C B_C \quad \text{(A133)}$$

$$b_{CCB} = \frac{B_{CCB}}{p_C} \quad \text{(A134)}$$

$$b_{GCB} = \frac{B_{GCB}}{p_G} \quad \text{(A135)}$$

$$SEC_{CB} = SEC - SEC_H - SEC_B \quad \text{(A136)}$$

$$SEC_{CB} = SEC_{CB-1} + \Delta HPM - \Delta A - p_C \Delta b_{CCB} - p_G \Delta b_{GGB} \quad \text{(A137-red)}$$

Appendix B. Initial values for endogenous variables

Symbol	Description	Value	Remarks/sources
A	Advances (trillion US$)	1.5	Calculated from Eq. (A115) using the initial values of K_B, L_C, L_G, HPM, SEC_B and D
B	Value of total corporate bonds (trillion US$)	17	Calculated from Eq. (A96) using the initial values of B_C and B_G
B_C	Value of conventional corporate bonds (trillion US$)	16	Based on Tendulkar and Hancock (2014); we use the figures for the non-financial corporate bonds
b_C	Number of total conventional bonds (trillion)	0.2	Calculated from Eq. (A94) using the initial values of p_C and B_C
B_{CCB}	Value of conventional corporate bonds held by central banks (trillion US$)	0.1	Selected from a reasonable range of values
b_{CCB}	Number of conventional corporate bonds held by central banks (trillion)	0.001	Calculated from Eq. (A134) using the initial values of p_C and B_{CCB}
B_{CH}	Value of conventional corporate bonds held by households (trillion US$)	15.9	Calculated from Eq. (A92) using the initial values of B_{CCB} and B_C
b_{CH}	Number of conventional corporate bonds held by households (trillion)	0.2	Calculated from Eq. (A108) using the initial values of p_C and B_{CH}
B_G	Value of green corporate bonds (trillion US$)	1	Based on Climate Bonds Initiative (2016)
b_G	Number of green corporate bonds (trillion)	0.01	Calculated from Eq. (A95) using the initial values of p_G and B_G
B_{GCB}	Value of green corporate bonds held by central banks (trillion US$)	0	There was no QE programme in 2015
b_{GCB}	Number of green corporate bonds held by central banks	0	Calculated from Eq. (A135) using the initial values of p_G and B_{GCB}
B_{GH}	Value of green corporate bonds held by households (trillion US$)	1	Calculated from Eq. (A93) using the initial values of B_G and B_{GCB}
b_{GH}	Number of green corporate bonds held by households (trillion)	0.01	Calculated from Eq. (A109) using the initial values of p_G and B_{GH}
BP	Profits of banks (trillion US$)	2.5	Calculated from Eq. (A114) using the initial values of L_C, L_G, SEC_B, D and A
BP_D	Distributed profits of banks (trillion US$)	0.4	Calculated from Eq. (A117) using the initial values of BP and BP_U
BP_U	Retained profits of banks (trillion US$)	2.2	Calculated from Eq. (A116) using the initial value of BP
bur	Firms' burden of debt	0.4	Calculated from Eq. (A97) using the initial values of L_C, L_G, b_C, b_G and TP_G
C	Consumption (trillion US$)	46.8	Calculated from Eq. (A44) using the initial values of Y, G and I
CBP	Central banks' profits (trillion US$)	0.2	Calculated from Eq. (A131) using the initial values of b_{CCB}, b_{GCB}, A and SEC_{CB}
CEN	Carbon mass of the non-renewable energy sources (Gt)	9.8	Calculated from Eq. (A7) using the initial value of $EMIS_{IN}$
$CO2_{AT}$	Atmospheric CO_2 concentration (Gt)	3120	Taken from NOAA/ESRL (National Oceanic & Atmospheric Administration/Earth System Research Laboratory)
$CO2_{UP}$	Upper ocean/biosphere CO_2 concentration (Gt)	5628.8	Based on Nordhaus and Sztorc (2013); Gt of carbon have been transformed into Gt of CO_2
$CO2_{LO}$	Lower ocean CO_2 concentration (Gt)	36706.7	Based on Nordhaus and Sztorc (2013); Gt of carbon have been transformed into Gt of CO_2
CON_E	Amount of non-renewable energy resources converted into non-renewable energy reserves (EJ)	1626.0	Calculated from Eq. (A20) using the initial value of RES_E
CON_M	Amount of material resources converted into material reserves (Gt)	194	Calculated from Eq. (A12) using the initial value of RES_M
CR_C	Degree of credit rationing for conventional loans	0.2	Calculated from Eq. (A121) using the initial values of def and lev_B
CR_G	Degree of credit rationing for green loans	0.4	Calculated from Eq. (A122) using the initial values of def and lev_B
D	Deposits (trillion US$)	66.0	Based on Allianz (2015)
DC	Stock of durable consumption goods (trillion US$)	1017	Calculated from Eq. (A4) using the initial values of K, DEM, δ and μ
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. (A22) 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$)	1.9	Calculated from Eq. (A98) using the initial values of L and def
DP	Distributed profits of firms (trillion US$)	16.5	Calculated from Eq. (A55) using the initial values of TP and RP
D_T	Total proportional damage caused by global warming	0.0028	Calculated from Eq. (A49) using the initial value of T_{AT}
D_{TF}	Part of damage that affects directly the fund-service resources	0.0026	Calculated from Eq. (A51) 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. (A50) using the initial value of D_T
E	Energy necessary for the production of output (EJ)	580.0	Based on IEA (International Energy Agency); total primary energy supply is used
ED	Dissipated energy (EJ)	580.0	Calculated from Eq. (A18) using the initial values of EN and ER
$EMIS$	Total CO_2 emissions (Gt)	40.0	Calculated from Eq. (A25) using the initial values of $EMIS_{IN}$ and $EMIS_L$
$EMIS_{IN}$	Industrial CO_2 emissions (Gt)	36.0	Based on CDIAC (Carbon Dioxide Information Analysis Center)
$EMIS_L$	Land-use CO_2 emissions (Gt)	4.0	Based on CDIAC (Carbon Dioxide Information Analysis Center)
EN	Energy produced from non-renewable sources (EJ)	498.8	Calculated from Eq. (A17) using the initial values of E and ER
ER	Energy produced from renewable sources (EJ)	81.2	Calculated from Eq. (A16) using the initial values of θ and E
F	Radiative forcing over pre-industrial levels (W/m^2)	2.30	Calculated from Eq. (A29) 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)	0.28	Based on Nordhaus and Sztorc (2013)
G	Government expenditures (trillion US$)	11.4	Calculated from Eq. (A127) using the initial value of Y
g_{LF}	Growth rate of labour force before global warming damages	0.012	Based on United Nations
g_Y	Growth rate of output	0.030	Calibrated such that the model generates the baseline scenario
$g_{\beta 0}$	Growth rate of the autonomous share of green investment in total investment	0.006	Calibrated such that the model generates the baseline scenario
g_λ	Growth rate of labour productivity	0.0182	Calculated from Eq. (A80) using the initial values of g_Y and σ_0

(continued from the previous page)

Symbol	Description	Value	Remarks/sources
g_{ω}	Growth rate of CO_2 intensity	-0.005	Calibrated such that the model generates the baseline scenario
hazratio	Hazardous waste accumulation ratio (Gt/million km^2)	0.03	Calculated from Eq. (A10) using the initial value of HWS
HPM	High-powered money	13.20	Calculated from Eq. (A118) 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$)	15.0	Calibrated such that the model generates the baseline scenario
I_C	Conventional investment (trillion US$)	14.5	Calculated from Eq. (A72) 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$)	17.3	Calibrated such that the model generates the baseline scenario
I_G	Green investment (trillion US$)	0.5	Based on CPI (2015); we use a higher value than the one reported in CPI (2015) since green investment in our model includes both climate and non-climate investment
I_G^D	Desired green investment (trillion US$)	0.7	Calculated such that it is reasonably higher than I_G
K	Total capital stock of firms (trillion US$)	219.6	Calculated from the identity $K=(K/Y)*Y$ by using the initial value of Y and assuming that $K/Y=3$ (based on Penn World Table 8.1)
K_B	Capital of banks (trillion US$)	7.5	Calculated from Eq. (A125) using the initial values of lev_B, L_C, L_G, SEC_B and HPM
K_C	Conventional capital stock (trillion US$)	214.5	Calculated from Eq. (A76) using the initial values of K and K_G
K_G	Green capital stock (trillion US$)	5.1	Calculated from Eq. (A77) using the initial values of K and κ
L	Total loans of firms (trillion US$)	49.8	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$)	48.7	Calculated from Eq. (A73) using the initial values of L and L_G
L_G	Green loans (trillion US$)	1.2	Calculated by assuming that $L_G/L=K_G/K=\kappa$; we use the initial values of κ and L
lev_B	Banks' leverage ratio	10.0	Based on World Bank
LF	Labour force (billion people)	3.4	Based on World Bank
lf_0	Autonomous growth rate of the labour force	0.012	Calibrated such that initial growth rate of the labour force is equal to the current
M	Extraction of new matter from the ground, excluding the matter included in non-renewable energy sources (Gt)	48.0	Based on the data provided by www.materialflows.net; the figure includes industrial and construction minerals plus ores
MY	Output in material terms (Gt)	53.1	Calculated from Eq. (A2) 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$)	9.9	Calculated from Eq. (A69) using the initial values of I_C^D, β, RP, L_C, δ, K_C, p_C, and b_C
NL_G^D	Desired new amount of green loans (trillion US$)	0.5	Calculated from Eq. (A68) using the initial values of I_G^D, β, RP, L_G, δ, K_G, p_G and b_G
$O2$	Oxygen used for the combustion of fossil fuels (Gt)	26.2	Calculated from Eq. (A8) using the initial values of $EMIS_{IN}$ and CEN
p_C	Price of conventional corporate bonds	100	The price has been normalised such that it is equal to 100 in 2015
p_G	Price of green corporate bonds	100	The price has been normalised such that it is equal to 100 in 2015
r	Rate of retained profits	0.012	Calculated from Eq. (A56) using tne initial values of RP and K
re	Rate of employment	0.94	Calculated from Eq. (A85) using the initial value of ur
REC	Recycled socio-economic stock (Gt)	5.1	Calculated from Eq. (A3) using the initial values of ρ and DEM
RES_E	Non-renewable energy resources (EJ)	542000	Based on BGR (2015, p. 33)
RES_M	Material resources (Gt)	388889	Calculated by assuming $RES_M/REV_M=64.8$ (based on UNEP, 2011)
REV_E	Non-renewable energy reserves (EJ)	37000	Based on BGR (2015, p. 33)
REV_M	Material reserves (Gt)	6000	Calculated from Eq. (A14) using the initial values of M and dep_M
RP	Retained profits of firms (trillion US$)	2.6	Calculated from Eq. (A54) using the initial value of TP
SEC	Total amount of government securities	59.5	Calculated from the identity *general government debt-to-GDP*$=SEC/Y$ by using the initial value of Y and the value of the general government debt-to-GDP ratio (taken from IMF)
SEC_B	Government securities held by banks (trillion US$)	11.9	Calculated by assuming that $SEC/SEC_B=0.2$ based on Alli Abbas et al. (2014)
SEC_{CB}	Government securities held by central banks (trillion US$)	11.7	Calculated from the identity $SEC_{CB}=HPM+V_{CB}-p_C b_{CCB}-p_G b_{GCB}-A$ using the initial values of V_{CB}, p_C, b_{CCB}, p_G, b_{GCB}, A and HPM
SEC_H	Government securities held by households (trillion US$)	36.0	Calculated from Eq. (A136) using the initial values of SEC, SEC_{CB} and SEC_B
SES	Socio-economic stock (Gt)	897.3	Calculated from the identity $SES=\mu(K+DC)$ using the initial values of μ, K and DC
sh_C	Share of conventional loans in total loans	0.98	Calculated from the formula $sh_C=L_C/L$
sh_L	Share of loans in total firm liabilities	0.75	Calculated from the formula $sh_L=L/(L+B)$
T	Total taxes (trillion US$)	10.2	Calculated from Eq. (A130) using the initial value of T_H and T_F

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Symbol	Description	Value	Remarks/sources
T_{AT}	Atmospheric temperature over pre-industrial levels (^oC)	1.0	Based on Met Office
T_F	Taxes on firms' profits (trillion US$)	3.2	Calculated from Eq. (A129) using the initial value of TP_G
T_H	Taxes on households' disposable income	6.9	Calculated from Eq. (A130) using the initial value Y_H
T_{LO}	Lower ocean temperature over pre-industrial levels (^oC)	0.0068	Taken from Nordhaus and Sztorc (2013)
TP	Total profits of firms (trillion US$)	19.0	Calculated from Eq. (A53) using the initial values of TP_G and T_F
TP_G	Total gross profits of firms (trillion US$)	22.3	Calculated from Eq. (A52) using the initial values of Y, w, N, L_C, L_G, δ, K, b_C and b_G
u	Rate of capacity utilisation	0.72	Based on World Bank, Enterprise Surveys
ue	Rate of energy utilisation	0.01	Calculated from Eq. (A46) using the initial values of Y and Y_E^*
um	Rate of matter utilisation	0.01	Calculated from Eq. (A45) using the initial values of Y and Y_M^*
ur	Unemployment rate	0.06	Based on World Bank
v	Capital productivity	0.46	Calculated from Eqs. (A41) and (A47) using the initial values of Y, u and K
V_{CB}	Wealth of central banks (trillion US$)	0	It is assumed that there are no accumulated capital gains for the central banks
V_{HF}	Financial wealth of households (trillion US$)	118.7	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)	11.91	Calculated from Eq. (A83) using the initial value of λ
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 investment funded via conventional bonds	0.03	Calibrated such that the model generates the baseline scenario
x_2	Proportion of desired investment funded via green bonds	0.03	Calibrated such that the model generates the baseline scenario
Y	Output (trillion US$)	73.2	Taken from IMF, World Economic Outlook (current prices)
Y^*	Potential output (trillion US$)	77.9	Calculated from Eq. (A43) using the initial values of Y_M^*, Y_E^*, Y_K^* and Y_N^*
Y_E^*	Energy-determined potential output (trillion US$)	5429.8	Calculated from Eq. (A40) using the initial values of REV_E, θ and ε
Y_H	Disposable income of households (trillion US$)	50.2	Calculated from Eq. (A101) using the initial values of Y_{HG} and T_H
Y_{HG}	Gross disposable income of households (trillion US$)	57.1	Calculated from Eq. (A100) using the initial values of w, N, DP, BP_D, D, SEC_H, b_{CH} 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$)	101.7	Calculated from Eq. (A41) using the initial values of v and K
Y_M^*	Matter-determined potential output (trillion US$)	8278.2	Calculated from Eq. (A39) using the initial values of REV_M, REC and μ
Y_N^*	Labour-determined potential output (trillion US$)	77.9	Calculated from Eq. (A42) using the initial values of λ and LF
a_0	Autonomous desired investment rate	0.026	Since there are no supply-side constraints, this is equal to a_{00}
β	Share of desired green investment in total investment	0.04	Calculated by using the initial values of I_G^D and I^D
β_0	Autonomous share of desired green investment in total investment	0.03	Calibrated such that κ=0.07 in 2050
γ_1	Sensitivity of the desired investment rate to the difference between um and um_T	0	Since $um<um_T$, there are no matter-related supply-side constraints
γ_2	Sensitivity of the desired investment rate to the difference between ue and ue_T	0	Since $ue<ue_T$, there are no energy-related supply-side constraints
γ_3	Sensitivity of the desired investment rate to the difference between u and u_T	0	Since $u<u_T$, there are no capital-related supply-side constraints
γ_4	Sensitivity of the desired investment rate to the difference between re and re_T	0	Since $re<re_T$, there are no labour-related supply-side constraints
δ	Depreciation rate of capital stock	0.04	Calculated from Eq. (A78) using the initial value D_{TF}
ε	Energy intensity (EJ/trillion US$)	7.92	Calculated from the definition of energy intensity ($\varepsilon=E/Y$) using the initial values of E and Y
θ	Share of renewable energy in total energy	0.14	Based on IEA (International Energy Agency); total primary energy supply is used
κ	Ratio of green capital to total capital	0.02	Selected such that it is reasonably lower than I_G/I
λ	Hourly labour productivity (trillion US$/(billions of employees*annual hours worked per employee))	0.01	Calculated from Eq. (A84) using the initial values of Y and N
μ	Material intensity (kg/$)	0.73	Calculated from the definition of material intensity ($\mu=MY/Y$) using the initial values of MY and Y
ρ	Recycling rate	0.30	Based on Haas et al. (2015)
σ_0	Autonomous growth rate of labour productivity	-0.02	Calibrated such that the model generates the baseline scenario
ω	CO_2 intensity (Gt/EJ)	0.07	Calculated from Eq. (A23) using the initial values of $EMIS_{IN}$ and EN

Appendix C. 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	0.95	Selected from a reasonable range of values
ad_P	Fraction of gross damages to productivity avoided through adaptation	0.90	Selected from a reasonable range of values
c_1	Propensity to consume out of disposable income	0.78	Calibrated such that the model generates the baseline scenario
c_2	Propensity to consume out of financial wealth	0.075	Selected from a reasonable range of values
car	Coefficient for the conversion of Gt of carbon into Gt of CO_2	3.67	Taken from CDIAC (Carbon Dioxide Information Analysis Center)
$CO2_{AT\text{-}PRE}$	Pre-industrial CO_2 concentration in atmosphere (Gt)	2156.2	Taken from Nordhaus and Sztorc (2013); Gt of carbon have been transformed into Gt of CO_2
$CO2_{LO\text{-}PRE}$	Pre-industrial CO_2 concentration in upper ocean/biosphere (Gt)	36670.0	Taken from Nordhaus and Sztorc (2013); Gt of carbon have been transformed into Gt of CO_2
$CO2_{UP\text{-}PRE}$	Pre-industrial CO_2 concentration in lower ocean (Gt)	4950.5	Taken from Nordhaus and Sztorc (2013); Gt of carbon have been transformed into Gt of CO_2
con_M	Conversion rate of material resources into reserves	0.0005	Selected from a reasonable range of values
con_E	Conversion rate of non-renewable energy resources into reserves	0.003	Selected from a reasonable range of values
$coupon_C$	Coupon rate (%) on conventional corporate bonds	5	Calculated from Eq. (A90) using the initial values of p_C and $yield_C$
$coupon_G$	Coupon rate (%) on green corporate bonds	5	Calculated from Eq. (A91) using the initial values of p_G and $yield_G$
def_0	Autonomous default rate	0.03	Calculated from Eq. (A99) using the initial values of def, bur, sh_C, CR_C and CR_G
def_1	Sensitivity of the default rate to the burden of debt of firms	0.02	Selected from a reasonable range of values
def_2	Sensitivity of the default rate to the degree of credit rationing	0.01	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)	3.8	Taken from Nordhaus and Sztorc (2013)
fex	Annual increase in radiative forcing (since the pre-industrial period) due to non-CO_2 agents (W/m^2)	0.005	Based on Nordhaus and Sztorc (2013)
gov	Share of government expenditures in output	0.16	Based on World Bank; the figure includes only the consumption government
g_v	Growth rate of capital productivity before global warming damages	0.001	Calibrated such that the model generates the baseline scenario
h	Annual working hours per employee	1800	Based on Penn World Table 8.1
h_1	Banks' reserve ratio	0.2	Selected from a reasonable range of values
h_2	Banks' government securities-to-deposits ratio	0.18	Calculated from Eq. (A119) by 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	0.012	Based on Bank of America Merill Lynch (2014)
l_0	Autonomous credit rationing on green loans	-0.20	Selected from a reasonable range of values
l_1	Sensitivity of green loans' credit rationing to the default rate of firms	10	Selected from a reasonable range of values
l_2	Sensitivity of green loans' credit rationing to the leverage ratio of banks	0.02	Selected from a reasonable range of values
lf_1	Autonomous growth rate of labour force	0.012	Calibrated such that the model generates the baseline scenario
lf_2	Sensitivity of the growth rate of labour force to the unemployment rate	0.2	Calibrated such that the model generates the baseline scenario
lf_3	Sensitivity of the growth rate of labour force to the hazardous waste	0.001	Calibrated such that the model generates the baseline scenario
lr	Rate of decline of land-use CO_2 emissions	0.044	Taken from Nordhaus and Sztorc (2013); has been adjusted to reflect a 1-year time step
p	Share of productivity damage in total damage caused by global warming	0.1	Selected from a reasonable range of values
r_0	Autonomous credit rationing on conventional loans	-0.40	Selected from a reasonable range of values
r_1	Sensitivity of conventional loans' credit rationing to the default rate of firms	10	Selected from a reasonable range of values
r_2	Sensitivity of conventional loans' credit rationing to the leverage ratio of banks	0.02	Selected from a reasonable range of values
rep	Loan repayment ratio	0.1	Selected from a reasonable range of values
re_T	Threshold rate of employment above which supply-side constraints arise	0.96	Selected from a reasonable range of values
S	Equilibrium climate sensitivity, i.e. increase in equilibrium temperature due to doubling of CO_2 concentration from pre-industrial levels (^{o}C)	3	Taken from Dietz and Stern (2015)
s_B	Banks' retention rate	0.87	Calibrated such that the model generates the baseline scenario
s_C	Share of conventional corporate bonds held by central banks (trillion US$)	0.01	Calculated from Eq. (133) using the initial values of B_{CCB} and B_C
s_F	Firms' retention rate	0.14	Calibrated such that the model generates the baseline scenario
s_G	Proportion of green corporate bonds held by central banks (trillion US$)	0.00	There was no green QE programme in 2015
$SURF$	Earth surface (million km^2)	510.1	Taken from the World Factbook
s_W	Wage income share	0.52	Based on Penn World Table 8.1
t_1	Speed of adjustment parameter in the atmospheric temperature equation	0.027	Calculated using the formula in Calel et al. (2015, p. 132); effective heat capacity is assumed to be equal to 1.2 GJm^{-2}K^{-1}

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Symbol	Description	Value	Remarks/sources
t_2	Coefficient of heat loss from the atmosphere to the lower ocean (atmospheric temperature equation)	0.018	Taken from Nordhaus and Sztorc (2013); has been adjusted to reflect a 1-year time step
t_3	Coefficient of heat loss from the atmosphere to the lower ocean (lower ocean temperature equation)	0.005	Taken from Nordhaus and Sztorc (2013); has been adjusted to reflect a 1-year time step
u_T	Threshold rate of capacity utilisation above which supply-side constraints arise	0.85	Selected from a reasonable range of values
ue_T	Threshold rate of energy utilisation above which supply-side constraints arise	0.05	Selected from a reasonable range of values
um_T	Threshold rate of matter utilisation above which supply-side constraints arise	0.05	Selected from a reasonable range of values
x_{10}	Autonomous proportion of desired conventional investment funded via bonds	0.03	Calculated from Eq. (A88) using the initial value of $yield_C$
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_{20}	Autonomous proportion of desired green investment funded via bonds	0.04	Calculated from Eq. (A89) using the initial value of $yield_G$
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}	Autonomous desired investment rate	0.026	Calibrated such that the model generates the baseline scenario
a_1	Sensitivity of desired investment rate to the rate of retained profits	0.5	Selected from a reasonable range of values
a_2	Sensitivity of desired investment rate to the rate of capacity utilisation	0.01	Selected from a reasonable range of values
a_3	Sensitivity of desired investment rate to the growth rate of energy intensity	0.1	Selected from a reasonable range of values
β_1	Autonomous share of desired green investment in total investment	0.02	Calibrated such that the model generates the baseline scenario
β_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
β_3	Sensitivity of the desired green investment share to global warming damages	0.5	Selected from a reasonable range of values
γ_{10}	Sensitivity of the desired investment rate to the matter-related supply-side	0.5	Selected from a reasonable range of values
γ_{20}	Sensitivity of the desired investment rate to the energy-related supply-side	0.5	Selected from a reasonable range of values
γ_{30}	Sensitivity of the desired investment rate to the capital-related supply-side	0.5	Selected from a reasonable range of values
γ_{40}	Sensitivity of the desired investment rate to the labour-related supply-side	0.5	Selected from a reasonable range of values
δ_0	Depreciation rate of capital stock when there are no global warming damages	0.04	Based on Penn World Table 8.1
ε_{max}	Maximum potential value of energy intensity (EJ/trillion US$)	12	Selected such that it is reasonably higher than initial ε
ε_{min}	Minimum potential value of energy intensity (EJ/trillion US$)	2	Selected such that it is reasonably higher than 0
ζ_1	Rate of decline of the (absolute) growth rate of CO_2 intensity	0.03	Calibrated such that the model generates the baseline scenario
ζ_2	Rate of decline of the growth rate of β_0	0.025	Calibrated such that the model generates the baseline scenario
ζ_3	Rate of decline of the autonomous (absolute) growth rate of labour	0.007	Calibrated such that the model generates the baseline scenario
ζ_4	Rate of decline of the autonomous growth rate of labour force	0.02	Calibrated such that the model generates the baseline scenario
η_1	Parameter of damage function	0	Based on Weitzmann (2012); D_T=50% when T_{AT}=6°C
η_2	Parameter of damage function	0.00284	Based on Weitzmann (2012); D_T=50% when T_{AT}=6°C
η_3	Parameter of damage function	0.000005	Based on Weitzmann (2012); D_T=50% when T_{AT}=6°C
λ_{10}	Parameter of households' portfolio choice	0.32	Calculated from Eq. (A104) using the initial values of SEC_H, V_{HF}, D_T, $yield_C$, $yield_G$ and Y_H
λ_{10}'	Parameter of households' portfolio choice	0.10	Selected from a reasonable range of values
λ_{11}	Parameter of households' portfolio choice	0.03	Calculated from the constraint λ_{11}=-λ_{21}-λ_{31}-λ_{41}
λ_{12}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{13}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{14}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{15}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{20}	Parameter of households' portfolio choice	0.14	Calculated from Eq. (A105) using the initial values of B_{CH}, V_{HF}, D_T, $yield_C$, $yield_G$ and Y_H
λ_{20}'	Parameter of households' portfolio choice	-0.20	Selected from a reasonable range of values
λ_{21}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint λ_{21}=λ_{12}
λ_{22}	Parameter of households' portfolio choice	0.03	Calculated from the constraint λ_{22}=-λ_{12}-λ_{32}-λ_{42}
λ_{23}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{24}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{25}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{30}	Parameter of households' portfolio choice	0.01	Calculated from Eq. (A106) using the initial values of B_{GH}, V_{HF}, D_T, $yield_C$, $yield_G$ and Y_H
λ_{30}'	Parameter of households' portfolio choice	0.00	Global warming damages are assumed to have no impact on the holdings of green bonds
λ_{31}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint λ_{31}=λ_{13}

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Symbol	Description	Value	Remarks/sources
λ_{32}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint $\lambda_{32}=\lambda_{23}$
λ_{33}	Parameter of households' portfolio choice	0.03	Calculated from the constraint $\lambda_{33}=-\lambda_{13}-\lambda_{23}-\lambda_{43}$
λ_{34}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{35}	Parameter of households' portfolio choice	-0.01	Selected from a reasonable range of values
λ_{40}	Parameter of households' portfolio choice	0.53	Calculated from the constraint $\lambda_{40}=1-\lambda_{10}-\lambda_{20}-\lambda_{30}$
λ_{40}'	Parameter of households' portfolio choice	0.10	Selected from a reasonable range of values
λ_{41}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint $\lambda_{41}=\lambda_{14}$
λ_{42}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint $\lambda_{42}=\lambda_{24}$
λ_{43}	Parameter of households' portfolio choice	-0.01	Calculated from the constraint $\lambda_{43}=\lambda_{34}$
λ_{44}	Parameter of households' portfolio choice	0.03	Calculated from the constraint $\lambda_{44}=-\lambda_{14}-\lambda_{24}-\lambda_{34}$
λ_{45}	Parameter of households' portfolio choice	0.03	Calculated from the constraint $\lambda_{45}=-\lambda_{15}-\lambda_{25}-\lambda_{35}$
μ_{max}	Maximum potential value of material intensity (kg/US$)	1.5	Selected such that it is reasonably higher than initial μ
μ_{min}	Minimum potential value of material intensity (kg/US$)	0.3	Selected such that it is reasonably higher than 0
ξ	Proportion of durable consumption goods discarded every year	0.014	Selected such that the initial growth of DC is equal to 3%
π_1	Parameter linking the green capital-conventional capital ratio with material intensity	0.85	Calibrated such that initial ϱ corresponds to initial $\varkappa$ and $\varrho(2050)=1.4\varrho(2015)$ in line with the baseline scenario
π_2	Parameter linking the green capital-conventional capital ratio with material intensity	18.40	Calibrated such that initial ϱ corresponds to initial $\varkappa$ and $\varrho(2050)=1.4\varrho(2015)$ in line with the baseline scenario
π_3	Parameter linking the green capital-conventional capital ratio with recycling rate	4.39	Calibrated such that initial μ corresponds to initial $\varkappa$ and $\mu(2050)=0.9\mu(2015)$ in line with the baseline scenario
π_4	Parameter linking the green capital-conventional capital ratio with recycling rate	40.65	Calibrated such that initial μ corresponds to initial $\varkappa$ and $\mu(2050)=0.9\mu(2015)$ in line with the baseline scenario
π_5	Parameter linking the green capital-conventional capital ratio with energy inetnsity	6.79	Calibrated such that initial ε corresponds to initial $\varkappa$ and $\varepsilon(2050)=0.7\varepsilon(2015)$ in line with the baseline scenario
π_6	Parameter linking the green capital-conventional capital ratio with energy inetnsity	64.70	Calibrated such that initial ε corresponds to initial $\varkappa$ and $\varepsilon(2050)=0.7\varepsilon(2015)$ in line with the baseline scenario
π_7	Parameter linking the green capital-conventional capital ratio with the share of renewable energy	9.87	Calibrated such that initial θ corresponds to initial $\varkappa$ and $\theta(2050)=0.18$ in line with the baseline scenario
π_8	Parameter linking the green capital-conventional capital ratio with the share of renewable energy	19.89	Calibrated such that initial θ corresponds to initial $\varkappa$ and $\theta(2050)=0.18$ in line with the baseline scenario
ϱ_{max}	Minimum potential value of recycling rate	0.8	Selected such that it is reasonably lower than 1
σ_1	Autonomous growth rate of labour productivity	0.023	Calibrated such that the model generates the baseline scenario
σ_2	Sensitivity of labour productivity growth to the growth rate of output	0.6	Calibrated such that the model generates the baseline scenario
τ_F	Firms' tax rate	0.15	Selected from a reasobale range of values
τ_H	Households' tax rate	0.12	Calibrated such that the model generates the baseline scenario
φ_{11}	Transfer coefficient for carbon from the atmosphere to the atmosphere	0.9817	Calculated from the formula $\varphi_{11}=1-\varphi_{12}$ (see Nordhaus and Sztorc, 2013)
φ_{12}	Transfer coefficient for carbon from the atmosphere to the upper ocean/biosphere	0.0183	Taken from Nordhaus and Sztorc (2013); has been adjusted to reflect a 1-year time step
φ_{21}	Transfer coefficient for carbon from the upper ocean/biosphere to the atmosphere	0.0080	Calculated from the formula $\varphi_{21}=\varphi_{12}(CO2_{AT\text{-}PRE}/CO2_{UP\text{-}PRE})$ (see Nordhaus and Sztorc, 2013)
φ_{22}	Transfer coefficient for carbon from the upper ocean/biosphere to the upper ocean/biosphere	0.9915	Calculated from the formula $\varphi_{22}=1-\varphi_{21}-\varphi_{23}$ (see Nordhaus and Sztorc, 2013)
φ_{23}	Transfer coefficient for carbon from the upper ocean/biosphere to the lower ocean	0.0005	Taken from Nordhaus and Sztorc (2013); has been adjusted to reflect a 1-year time step
φ_{32}	Transfer coefficient for carbon from the lower ocean to the upper ocean/biosphere	0.0001	Calculated from the formula $\varphi_{32}=\varphi_{23}(CO2_{UP\text{-}PRE}/CO2_{LO\text{-}PRE})$ (see Nordhaus and Sztorc, 2013)
φ_{33}	Transfer coefficient for carbon from the lower ocean to the lower ocean	0.9999	Calculated from the formula $\varphi_{33}=1-\varphi_{32}$ (see Nordhaus and Sztorc, 2013)