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Emission-based Interest Rates and the Transition to a Low-carbon Economy

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Abstract

We use a dynamic general equilibrium model to study a climate-oriented monetary policy in the form of emission-based interest rates set by the central bank. Liquidity costs of banks increase with the emission intensity of their asset portfolio, leading banks to favor low-carbon assets and to improve the financing conditions for clean sectors. We show that such a monetary policy supports the decarbonization of the economy and reduces climate damage, as more resources are channeled to low-carbon sectors and incentives to adopt cleaner technologies increase across all sectors. We illustrate these effects by calibrating our model to data for the Euro Area.

Keywords: climate change, monetary policy, banks, innovation, financial stability

JEL codes: E42, E52, E58, O44.

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1 Introduction

As damage from weather anomalies ratchets up, climate change and global warming are widely recognized as a threat for the environment, the economy and the society as a whole (IPCC, 2018). Carbon emissions, which have been identified as the main driver of global warming, need to be reduced in order to limit the average global temperature increase, as outlined in the Paris Agreement of 2015.[1] Accordingly, developing and adopting clean technologies across sectors, as for example energy generation[2] and transportation, is crucial in order to lower the emission intensity of the global economy and to achieve the agreed climate targets.

To foster the development and adoption of clean technologies, climate policies have so far mostly encompassed fiscal policies. Specifically, the measures adopted have aimed at reducing the costs of clean technologies and discouraging dirty production activities. Relevant measures include, among others, carbon taxes (Nordhaus, 2013; Weitzman, 2014; Borissov et al., 2019), cap-and-trade systems for emission certificates (Gersbach and Winkler, 2011; Goulder and Schein, 2013; Greaker and Hagem, 2014), subsidies for clean investments (Acemoglu et al., 2012, 2016; Gerlagh et al., 2018; Greaker et al., 2018; Ramstein et al., 2019) and feed-in tariffs (Proença and Aubyn, 2013).[3] In particular, carbon prices should reflect the social cost of carbon emissions and are considered to be a critical instrument for the transition to a low-carbon economy (Aghion et al., 2016; IMF, 2019). However, carbon pricing might not always be applicable in the absence of cleaner alternatives or due to low credibility (Fay et al., 2015). In addition, it has been stressed that the lack of political acceptability, government and market failures as well as distributive effects limit the feasibility of this instrument (Rozenberg et al., 2013; Baranzini et al., 2017; Krogstrup and Oman, 2019; Maestre-Andrés et al., 2019).

Thus, there is an increasing debate about which additional tools policymakers can use to induce the transition to a low-carbon economy. Complementary policies discussed among academics and policymakers include the integration of climate objectives into monetary policy (Rozenberg et al., 2013; Campiglio, 2016; Volz, 2017). Currently, central banks play a rather passive role in the fight against climate change, as they are, if at all, primarily concerned about including climate risk in their investment decisions and urging commercial banks to apply adequate risk management procedures. In their interaction with the financial sector, central banks do not take the emission intensity of financial assets and of financial institutions into account. On the opposite, it has been argued that central banks undermine existing efforts to

[1]See https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&lang=_en&clang=_en, accessed on 23/11/2019.

[2]The importance of this issue is emphasized, for instance, by the implementation of the EU energy union strategy (https://ec.europa.eu/commission/priorities/energy-union-and-climate_en, accessed on 23/11/2019), the German Energiewende (https://www.bmwi.de/Redaktion/EN/Dossier/energy-transition.html, accessed on 23/11/2019) or the Swiss Energiestrategie 2050 (https://www.bfe.admin.ch/bfe/en/home/policy/energy-strategy-2050.html, accessed on 23/11/2019).

[3]Public investment in the form, for instance, of public transportation networks, expansion of the power grid to renewable sites and infrastructure for carbon capture and storage can also play a crucial role.

induce the transition to a low-carbon economy by holding portfolios which overweight emission-intensive compared to low-carbon assets (Matikainen et al., 2017; Jourdan and Kalinowski, 2019). Instead, central banks could support the decarbonization of the economy by adopting investment guidelines, when purchasing assets, which favor financial assets with a relatively lower carbon footprint. These types of policies could also reduce the exposure of central banks to potential negative financial asset reevaluations as a result of the introduction of other climate policies. Central banks justify their current approach based on their mandate, which is generally centered around price and economic stability in the short term. Climate change, in turn, constitutes a negative externality in the long run, thus leading to the tragedy of the horizon (Carney, 2015). Nevertheless, central banks themselves have started to recognize the possibility of assuming a more active role (Carney, 2015; Coeure, 2018; ECB, 2019; NGFS, 2019). A climate-oriented monetary policy can accompany existing measures that target the innovation and adoption of clean technologies. Such a monetary policy would, independent of its actual design, aim at improving the financing conditions for low-carbon sectors (Aglietta et al., 2015; Schoenmaker, 2019). Hence, dirty production activities become less attractive, resulting in more resources shifted to clean production and more incentives for polluting firms to adopt cleaner technologies.

The integration of climate objectives into monetary policy can take various forms. Rozenberg et al. (2013) propose the introduction of carbon certificates distributed to low-carbon projects, that can be accepted as part of banks legal reserves and thus reduce the capital costs for sustainable activities. Campiglio (2016) discusses green reserve requirements, which take the carbon footprint of the asset portfolio held by the individual financial institution into account. Such differentiated reserve requirements based on the composition of a bank's asset holdings are also discussed by Volz (2017) and Fender et al. (2019).[4] Monnin (2018a) and Fisher and Alexander (2019), in turn, propose an overall update of central banks' collateral framework by incorporating sustainability criteria. Green quantitative easing, namely asset purchases by the central bank directed towards low-carbon financial assets, such as green bonds, represents another alternative for a climate-oriented monetary policy (Volz, 2017; Monnin, 2018a). This paper, in turn, focuses on a yet unexplored approach, according to which the central bank adopts an interest rate policy for reserve loans to banks, that depends on the emission intensity of the asset portfolio held by the individual institution. All the proposed measures, including our approach, make it necessary to amend central bank mandates by integrating climate goals. Admittedly, this represents a major change in the way monetary policy is conducted and may face resistance across the society. However, current climate policies suffer from political uncertainty, so that delegating climate actions to an independent authority, such as the central bank, might represent a reasonable strategy to achieve the overall climate targets.

[4] In addition, Volz (2017) proposes a climate-oriented bank regulation in the form of differentiated capital requirements depending on the type of lending conducted by the individual bank, as for example, higher risk weights for loans to emission-intensive and carbon-dependent sectors.

The implications of a climate-oriented monetary policy are, however, still unclear and require further in-depth investigation. To the best of our knowledge, there exists no theoretical model analyzing the integration of climate objectives into monetary policy. We aim to contribute to this gap in the literature by assessing the impact of an emission-based interest rate policy adopted by the central bank on the transition to a low-carbon economy. For our analysis, we attempt to reproduce the current monetary system as closely as possible. In this endeavor, we rely on Faure and Gersbach (2017), who emphasize the hierarchical structure of our monetary system by pointing out various stylized elements: first, the money stock available to the public takes mainly the form of deposits and only to a minor extent the form of cash. Second, deposits are created by commercial banks when granting loans or purchasing assets.[5] Third, the central bank issues reserves to commercial banks that use them to settle claims between each other, which can, for example, arise from interbank deposits flows. Fourth, the central bank issues cash to commercial banks that use them to settle withdrawals of deposits.[6] Our framework accounts for the generation of carbon emissions in the course of production activities, which may lead to increases in temperature and, ultimately, climate damage. We impose a linear relation between carbon emissions and temperature as estimated by Matthews et al. (2009). Climate damage, in turn, takes the form of final output reductions and is modeled as in Nordhaus and Sztorc (2013). Finally, we account for sectoral emission intensities of production and allow for their reduction through the adoption of cleaner technologies.

In our framework, commercial banks finance firms with loans and thereby create deposits, which serve as the only medium-of-exchange. Moreover, a central bank provides liquidity in terms of reserves to commercial banks, while applying an emission-based interest rate policy. Reserve loans are priced depending on the emission intensity of the asset portfolio held by the individual bank. Due to perfect competition in the banking sector, the liquidity costs of banks are passed on to the real economy. The financing costs of firms thus decrease with the emission intensity of the applied technology, so that the central bank policy affects the choice of clean technology adoption by firms. In our setting, the latter requires physical capital and, ultimately, reduces the input available for production. When maximizing profits, firms therefore face a trade-off between lowering financing costs through the adoption of a cleaner technology and reducing their production capacity.

We show that an emission-based interest rate policy adopted by the central bank can represent a valid instrument to promote the transition to a low-carbon economy: first, firms in low emission-intensive sectors are directly favored by lower financing costs, so that more resources are allocated to sustainable production activities. Second, the carbon-based pricing incentivizes all firms to adopt cleaner technologies. As we focus on a perfectly competitive banking sector, banks themselves do not face any direct costs from such a climate-oriented monetary policy.

[5] A comprehensive summary of money creation processes is, for instance, provided by McLeay et al. (2014) and by the Bundesbank (2017).

[6] In what follows, we refer to cash and reserves as central bank money or, more generally, liquidity.

However, depending on the risk characteristics and emission intensities of sectoral production, such a policy may affect the loan demand of firms and, hence, shape the composition of loan portfolios held by banks. We illustrate these effects by calibrating our model to data for the Euro Area.

The remainder of the paper is organized as follows: in Section 2, we briefly discuss other proposals for a climate-oriented monetary policy. Section 3 outlines our model, capturing the main characteristics of our current monetary system, introducing the emission-based interest rate policy applied by the central bank and highlighting firms' trade-off between technology adoption and production. Section 4 provides the theoretical model analysis. In Section 5, we outline the adopted numerical solution method, while Section 6 discusses the choice of parameters used for calibration and provides the results of our simulation exercise. In Section 7 we provide our conclusions and discuss policy implications.

2 Climate-oriented monetary policies

We can identify two main arguments in favor of integrating climate objectives into monetary policymaking: first, the financial sector itself is impacted by climate change and environmental policies, potentially leading to financial instability due to their impact on the risk-return structure of financial assets (Schoenmaker and Van Tilburg, 2016). Second, the financial sector can play a central role in financing the enormous investments required for the transition to a low-carbon economy, thus facilitating the transition itself. In the following, both arguments are outlined in greater detail.

Climate change and the consequent introduction of climate policies could impact the financial sector through physical risks, transition risks and liability risks (Carney, 2015; TCFD, 2017; Volz, 2017; Campiglio et al., 2018). The physical risks arise from climate-related events, such as droughts, floods, storms and sea-level rise. As illustrated in Dietz et al. (2016), Batten et al. (2016), Dafermos et al. (2017), Dafermos et al. (2018) and Bovari et al. (2018), such events can significantly endanger the value of financial assets in the economy. For example, Dietz et al. (2016) estimate the global climate value at risk at approximately USD 24 trillion. The transition risks arise from the shift towards less emission-generating technologies and changes in demand patterns. The transition entails costs due to investment and conversion activities, which can impair the ongoing production processes and thereby expose owners of financial assets to a higher risk of low returns (Monnin, 2018b). For example, Battiston et al. (2017) discuss that, as a result of climate policies favoring green firms and discouraging brown firms, a large portion of financial assets can be subject to substantial reevaluation. Stolbova et al. (2018), in turn, show that climate policies targeting the financial sector or non-financial firms can result in a significant amplification of shocks to the economy, thus, increasing gains and losses for the financial system. Finally, the liability risks arising from the potential impact of legal actions by parties suffering from climate change against those held responsible is widely discussed among policymakers and practitioners (Carney, 2015).

The transition to a low-carbon economy requires significant investments, often characterized by high upfront capital costs and high investment risks (Schmidt, 2014). The International Energy Agency (IEA) estimates that the green investment gap, that is, the additional amount of annual investments needed to decarbonize the global economy, is USD 900 billion (IEA, 2012); McKinsey (2010) estimates around USD 650 billion, whereas the World Economic Forum reports an intermediate value of USD 700 billion (WEF, 2013). Financial policies can help to reduce the green investment gap by mobilizing private funds for sustainable projects, thereby promoting the switch from dirty to clean technologies (Sachs et al., 2014; OECD, 2017).

With the adoption of a climate-oriented monetary policy the central bank can align its own investment decisions as well as those of financial institutions with the overall climate targets. Since the financial crisis 2007–08, the policies adopted by central banks have been represented by both unconventional measures, such as quantitative easing in the form of large-scale asset purchases at financial markets, and traditional measures, such as liquidity provisions in the form of loans to banks. With regard to the latter, central banks have several instruments available to control the liquidity costs for financial intermediaries, which indirectly affect their investment behavior. These instruments primarily comprise the reserve requirement, the collateral framework and the interest rate policy. By integrating climate objectives in the design of these instruments, central banks can use the existing framework to condition banks' liquidity costs on the sustainability of their investments. Specifically, the costs imposed by central banks should lead commercial banks to favor low-carbon assets, so that the corresponding sectors benefit from better financing conditions (Schoenmaker, 2019). Finally, as banks finance a large share of the economy, there is reason to believe that a shift in banks' investment behavior can have a signaling effect on other financial market participants.[7]

2.1 Green quantitative easing

After the financial crisis 2007–08, many central banks adopted unconventional policy measures. Most notably, central banks started to purchase assets at financial markets on a large scale in order to improve the mid- to long-term financing conditions in the real economy. Focusing on the European Central Bank (ECB), Matikainen et al. (2017) and Jourdan and Kalinowski (2019) stress that its portfolio resulting from such asset purchases is currently skewed towards emission-intensive assets. Such a bias might be detrimental for the achievement of the overall climate targets. Monetary policy could instead support long-term sustainability goals. For example, the central bank could engage in the purchase of green bonds issued by development banks, such as the European Investment Bank (Matikainen et al., 2017). Currently, the market

[7] For instance, De Fiore and Uhlig (2011) show that for corporations in the Euro Area bank finance is significantly more important than market finance for the acquisition of external funds.

for green bonds shows remarkable growth. However, as of 2016 they made up only one percent of the global bond market as reported by the Climate Bonds Initiative.[8] A climate-oriented monetary policy may help to develop this market further and, ultimately, ensure that sufficient resources are channeled to sustainable activities. Green quantitative easing requires investment guidelines, which account for the sustainability of financial assets. As any other climate-oriented monetary policy, the latter necessitates information disclosure about the carbon footprint of production activities at the firm level and the firms' decarbonization strategies. This issue has been recognized by major stakeholders, as shown by the foundation of the Task Force on Climate-Related Financial Disclosure in 2015.[9]

2.2 Green reserve requirements

In general, financial institutions issuing deposits have a demand for central bank money, as they require cash to meet withdrawals of deposits and reserves to settle interbank claims at the central bank. In order to reduce the illiquidity risk of these institutions, the central bank imposes a reserve requirement. Specifically, banks must hold reserves according to a predetermined share of deposits. These reserves are borrowed from the central bank and are therefore generally costly, so that the reserve requirement, if binding, influences the liquidity costs of banks. As commercial banks fund a large share of their investments with deposits, the liquidity costs impact their incentives to engage into lending activities to the real economy or asset purchases at financial markets. Following this reasoning, central banks can regulate the creation and allocation of credit through a differentiated reserve requirement based on the environmental impact of the financing activities conducted by the individual bank (Volz, 2017). Thus, imposing a lower reserve requirement on banks financing sustainable activities would theoretically favor green over conventional investments (Rozenberg et al., 2013; Campiglio, 2016). However, unconventional monetary policies applied in the aftermath of the financial crisis 2007–08 led to a tremendous increase in reserve holdings by commercial banks, so that in recent years reserve requirements imposed by central banks are rarely binding. Hence, conditioning reserve requirements on the carbon footprint of banks' asset portfolio must be combined with a significant increase of reserve requirements in order to render such a climate-oriented monetary policy effective.

2.3 Green collateral framework

Reserve loans granted by the central bank are generally collateralized. In other words, banks have to pledge assets during the borrowing period in order to secure their loans. The central bank defines the assets eligible as collateral and the collateral value of these assets through the

[8] Available at https://www.climatebonds.net/resources/publications/bonds-climate-change-2016, accessed on 23/11/2019.

[9] Available at https://www.unepfi.org/climate-change/tcfd/, accessed on 23/11/2019.

use of haircuts. Both the choice of eligible assets and the choice of haircuts safeguard the central bank from the risk inherent in its lending activities. Nyborg (2017) argues that the collateral framework can distort financial markets as well as the real economy. This is due to the fact that securities which can be used as collateral in the interaction with the central bank become more liquid and, thus, the financing costs for the issuer of the security decrease (Nagel, 2016; Nyborg, 2017). Similarly, a lower haircut increases the liquidity of the security and therefore reduces the financing costs (Ashcraft et al., 2011). Since the issuers of eligible assets generally enjoy better financing conditions, the collateral framework may represent a tool for central banks to steer funds towards low-carbon projects. Specifically, integrating sustainability criteria into the collateral framework represents an advantage for the issuers of low-carbon assets. This may be particularly relevant as under the current collateral framework, assets from companies which employ new, sustainable technologies may face barriers to eligibility (Matikainen et al., 2017), for example, due to the lower credit ratings obtained by such companies.

3 Model

We consider a variation of the neoclassical growth model in discrete time, which features households, firms, banks and a central bank. As in standard classical theory, households are utility-maximizing and are endowed with physical capital and labor. Firms can use physical capital and labor to produce a unique output good or to adopt new technologies. The output good is then consumed or invested by households. Production generates emissions which entail increases in temperature. Higher temperature, in turn, leads to climate damage, which reduces final output. Firms can lower emissions by adopting new technologies, which are cleaner than the old ones. Firms finance their activities with loans from banks. While granting loans, banks issue deposits, which, as a result of trades, may circulate between banks and, hence, give rise to interbank claims. Liabilities among banks are settled with reserves, which the central bank issues in its lending facilities. The central bank pursues a climate-oriented monetary policy, so that reserve loans are priced according to the emission intensity of the loan portfolio held by the individual bank. In our economy, trades are settled instantaneously, with deposits at banks as the only medium-of-exchange. Households own firms and banks with unlimited liability, so that they receive all available profits and must cover all incurred losses. The government, which in our setting only comprises of the central bank, operates with a balanced budget, so that generated profits or losses are distributed to or compensated by households.

In each period, there is uncertainty about the state of the economy, which may affect the productivity of firms and the monetary policy conducted by the central bank. We model a monetary economy in which trades and the related payment processes follow a predetermined order. Accordingly, we divide each period into four stages (I)—(IV), which are described below.

In stage (I), the state of the economy realizes, so that the productivity of firms and the monetary policy of the central bank are determined. Banks grant loans to firms in different production sectors and thereby create deposits. All assets held by banks are funded with deposits; a circumstance which we capture by the so-called "money creation constraint". To settle future deposit outflows resulting from trades between households and firms, banks demand reserve loans from the central bank.[10] In stage (II), households rent physical capital and labor to firms for the production of the output good. Firms finance the rental costs of the input factors with the previously acquired deposits from banks. Trading activities between firms and households lead to interbank deposit flows, which result in claims among banks, which are settled at the central bank by using reserves. In stage (III), firms use the acquired capital and labor to produce the output good and to adopt a cleaner technology. Banks credit deposits held by households with interest, whereas the central bank pays interest on reserve deposits held by banks. The profits (losses) of firms, banks and the central bank are distributed to (compensated by) households. In stage (IV), households purchase the output good from firms using all available funds. As households and firms trade, deposits circulate among banks resulting in interbank claims, which are settled at the central bank using reserves. Firms use the revenues from sales of the production output to repay their outstanding loans to banks. In the same manner, banks repay the reserve loans to the central bank.

Uncertainty enters our model in the following way: each period $t \in \mathbb{N}_0$ an economic state $z_t \in \mathcal{Z} = \{1, \ldots, Z\}$, with $Z \in \mathbb{N}$ denoting the number of states, is realized. The states are independent and identically distributed across time, with probabilities $\pi(z) > 0$, for all $z \in \mathcal{Z}$. Thus, given the initial state $z_0 \in \mathcal{Z}$, any variable X_t is a function of the history of states $z^t = (z_0, \ldots, z_t) \in \mathcal{Z}^{t+1}$, that is, $X_t : \mathcal{Z}^{t+1} \to \mathbb{R}$, if not defined otherwise. The expectation conditional on the information set available at the end of time period t is denoted by $\mathbb{E}_t[\cdot]$.

3.1 Households

There is a continuum of identical and infinitely-lived households with unit mass, so that we can focus on a representative agent. The household consists of $N_t = N(z^{t-1}) > 0$ identical individuals and is endowed with aggregate capital $K_t = K(z^{t-1}) > 0$. Each individual can supply one unit of labor. We abstract from disutility of labor, so that, in period t, the household provides the total endowment of physical capital K_t and labor N_t to firms in $S \in \mathbb{N}$ different sectors for the production of the single output good. The nominal rental rate of physical capital is given by $Q_t > 0$, whereas the nominal wage rate for labor provided to sector $s \in \mathcal{S} = \{1, \ldots, S\}$ is given by $W_{s,t} > 0$. In what follows, we assume that the size of the household grows each period by η_t percent, that is, $N_t = (1 + \eta_t)N_{t-1}$, for all $t \in \mathbb{N}$. The individual supplies each period a share $n_s \in [0, 1]$ of its labor endowment inelastically to sector s. Thus, the total nominal wage received by the household is given by $W_t N_t = \sum_{s \in \mathcal{S}} W_{s,t} n_s N_t$. As the

[10] Note that we abstract from the possibility of deposit withdrawals, which would further increase the liquidity demand of banks.

household rents physical capital and labor to firms, it receives deposits $Q_tK_t + W_tN_t$. These deposits are credited by banks with a nominal gross interest rate $R_t^D > 0$. The household owns banks and firms, so that it receives all available profits and must compensate all incurred losses. Moreover, the central bank generates profits (seigniorage) through its liquidity provisions to banks. The household is exposed to profits or losses of firms Π_t^F, banks Π_t^B and the central bank Π_t^{CB} before the purchase of the output good. The household uses all available funds to purchase the production output of firms reduced by climate damage $\tilde{Y}_t$ at the nominal price $P_t > 0$. Hence, the household faces the budget constraint

$$P_t\tilde{Y}_t \leq R_t^D(Q_tK_t + W_tN_t) + \Pi_t^F + \Pi_t^B + \Pi_t^{CB}.$$

The output good can be used for consumption C_t and investment I_t into the capital stock, as captured by the resource constraint $\tilde{Y}_t \geq C_t + I_t$. Physical capital depreciates each period by a share $\delta \in [0, 1]$ and evolves according to the standard law of motion $K_{t+1} = (1-\delta)K_t + I_t$. The household maximizes the expected discounted utility from consumption of all individuals across the infinite horizon. The utility of the individuals is weighted equally, that is, the household maximizes the utilitarian welfare given by

$$\mathbb{E}_0\left[\sum_{t=0}^{\infty} \beta^t N_t \frac{c_t^{1-\sigma} - 1}{1-\sigma}\right],$$

where c_t represents the consumption per capita and $\sigma \geq 0$ captures the constant relative risk aversion of the instantaneous utility function of each individual. The parameter $\beta = 1/(1+\rho)$ denotes the discount factor, where $\rho > 0$ represents the discount rate. Given our assumptions on the utility function, the resource constraint and the budget constraint are binding. Hence, when maximizing utility, the household faces a single constraint, that is,

$$P_t(C_t + K_{t+1}) = R_t^D(Q_tK_t + W_tN_t) + P_t(1-\delta)K_t + \Pi_t^F + \Pi_t^B + \Pi_t^{CB},$$

where we made use of the law of motion for physical capital.

3.2 Firms

Each of the S different production sectors in the economy is described by a continuum of identical firms with unit mass. Thus, we can focus on a representative agent for each of the sectors. Firms are assumed to be penniless, so that they rely on external financing in the form of bank loans to cover the rental service of capital and the costs of labor employment. Therefore, in period t, the loans $L_{s,t}$ demanded by the representative firm in sector s are given by

$$L_{s,t} = Q_tK_{s,t} + W_{s,t}N_{s,t},$$

where $K_{s,t}$ and $N_{s,t}$ denote the physical capital and labor employed by the firm. Production generates carbon emissions, which may entail an increase in temperature and ultimately climate damage, as we outline at a later stage. Specifically, one unit of production output in sector s leads to $\Gamma_{s,t} \geq 0$ units of emissions. We can therefore interpret $\Gamma_{s,t}$ as the emission intensity of production in sector s. Each firm can reduce the emission intensity by devoting a share of the acquired capital to the adoption of a cleaner technology. However, this constitutes a trade-off for the firm, as devoting capital to the adoption of a cleaner technology reduces its production capacities. In our model, cleaner technologies are not superior to the old ones in terms of productivity; this extreme view serves our purpose of highlighting the effects of a climate-oriented monetary policy on the adoption of clean technologies, but can generally be relaxed. In what follows, we denote the share of capital devoted to the adoption of a cleaner technology by $\gamma_{s,t} \in [0, 1]$. The firm in sector s produces the output good according to a Cobb-Douglas aggregation, so that production $Y_{s,t}$ in sector s is given by

$$Y_{s,t} = A_{s,t}(\bar{\gamma}_{s,t} K_{s,t})^{\alpha} N_{s,t}^{1-\alpha},$$

where $\bar{\gamma}_{s,t} = 1 - \gamma_{s,t}$ is the share of capital devoted to production, $A_{s,t}$ is the state-dependent and sector-specific total factor productivity, and α is the capital intensity, which we assume to be homogeneous across sectors. The total factor productivity consists of a deterministic part $\hat{A}_t$ which grows each period by a_t percent, that is, $\hat{A}_t = (1 + a_t)\hat{A}_{t-1}$ for all $t \in \mathbb{N}$, and is subject to a stochastic productivity shock $A_s(z_t)$. Hence, the total factor productivity is given by $A_{s,t} = \hat{A}_t A_s(z_t)$. Adoption of a new technology lowers the emission intensity $\Gamma_{s,t}$ according to $\Gamma_{s,t} = (1 - \iota_s \gamma_{s,t})\Gamma_{s,t-1}$. The parameter ι_s is referred to as the innovation impact factor and captures the possibilities for the adoption of a cleaner technology in sector s.[11]

Production generates emissions, which entail temperature increases and climate damage. Emissions depend on the level of production before climate damage and on the emission intensities across sectors, so that they take the form

$$E_t = \sum_{s \in \mathcal{S}} \Gamma_{s,t} Y_{s,t},$$

where emissions are potentially stochastic due to the sectoral productivity shocks. Following Matthews et al. (2009), we impose a linear relationship between carbon emissions and temperature increases. Hence, in our model, the temperature above the preindustrial level T_t evolves

[11] Note that we abstract from energy as an input factor for production, although energy generation contributes to a large part of global greenhouse gas emissions (IEA, 2012). This clearly represents a limitation of our framework, as the shift from fossil fuels to renewable sources exhibits some distinctive traits, which we may be unable to capture by focusing solely on the adoption of clean technologies across sectors. While this assumption serves the purpose of keeping our model tractable, it will be relaxed in future work.

according to

$$T_{t+1} = T_t + \tau E_t,$$

where $\tau \geq 0$ represents the carbon-climate response as described by Matthews et al. (2009). Temperature increase leads to higher climate damage, which is modeled as in Nordhaus and Sztorc (2013), so that it is given by

$$\Omega(T_t) = \frac{1}{1 + \pi_1 T_t + \pi_2 T_t^2},$$

where the coefficients $\pi_1 \geq 0$ and $\pi_2 \geq 0$ capture the convexity of the non-linear damage function. Accounting for climate damage, the final production in sector s is given by $\tilde{Y}_{s,t} = \Omega(T_t) Y_{s,t}$. The loans, which the firm obtains from banks, are subject to repayment costs determined by the nominal gross loan rate $R^L_{s,t} > 0$. As discussed in Section 4, the emission-based interest rate policy adopted by the central bank leads to liquidity costs for banks, which are passed on to the real economy, so that the financing costs of firms decrease with the sectoral emission intensity. Thus, the loan rate $R^L_{s,t}$ ultimately depends on the emission intensity $\Gamma_{s,t}$ of the applied technology. As the adoption of a new technology requires physical capital, the firm faces a trade-off between lower financing costs and higher production. As the firm is owned with unlimited liability and distributes each period all available profits to the household, we can focus on a static optimization problem. Given the prevailing emission intensity $\Gamma_{s,t-1}$ in sector s and the current temperature T_t, the firm maximizes each period nominal profits with decisions about technology adoption, $\gamma_{s,t}$, and production input factors, $K_{s,t}$ and $N_{s,t}$, that is,

$$\max_{\gamma_{s,t}, K_{s,t}, N_{s,t}} \quad \Pi^F_{s,t} = P_t \tilde{Y}_{s,t} - R^L_{s,t} L_{s,t}.$$

3.3 Banks

Banks are identical and exist in a continuum with unit mass, so that we focus on a representative agent.[12] The loans granted to sector s are denoted by $L_{s,t}$, whereas the total loans are given by $L_t = \sum_{s \in \mathcal{S}} L_{s,t}$. The bank creates deposits D_t when providing loan financing, so that all bank assets are funded with deposits; a circumstance that we capture by the money creation constraint $L_t = D_t$. The repayment costs charged by the bank on the loans provided to sector s are determined by the nominal gross loan rate $R^L_{s,t} > 0$. Deposits are credited with interest according to the nominal gross deposit rate $R^D_t > 0$. Deposits are used by firms to settle the rental costs for physical capital and labor, and are used by the household to finance the purchase of the output good. Both transactions may lead to outflows and inflows of deposits at banks.

[12] Faure and Gersbach (2017) provide conditions, when the representative agent approach can be adopted in the presence of money creation.

These interbank deposit flows lead to claims among banks, which must be settled at the central bank by using reserves. Hence, the bank must obtain in advance sufficient reserves from the central bank. Reserve loans are denoted by $L_{CB,t}$, which at origination equal reserve deposits $D_{CB,t}$. In what follows, we assume that due to trading activities on the capital and labor market as well as on the output good market, each time a constant share $\phi_t = \phi(z^{t-1}) \in [0, 1]$ of deposits is subject to outflows. We focus on a gross settlement procedure, which does not account for inflows of deposits, so that each time the bank requires reserves in the amount $\phi_t D_t$. In our subsequent analysis, inflows and outflows of deposits match. Thus, after trades have been settled the bank holds the reserves it originally borrowed from the central bank. In addition, the central bank may require the bank to comply with a reserve requirement, that is, the bank must hold reserves at least in the amount of $\varphi_t D_t$. We assume that the reserve requirement $\varphi_t = \varphi(z^{t-1}) \in [0, 1]$ does not depend on the current economic state. Reserve deposits are credited with interest according to the nominal gross interest rate $R^D_{CB,t} > 0$, while reserve loans lead to repayment costs that are determined by the nominal gross loan rate $R^L_{CB,t} > 0$. Reserves are generally costly for the bank, that is, $R^L_{CB,t} \geq R^D_{CB,t}$, so that we can, without loss of generality, state $D_{CB,t} = \psi_t D_t$, where we use the notation $\psi_t = \max\{\phi_t, \varphi_t\}$. As banks are owned with unlimited liability and distribute each period all available profits to households, we can focus on a static optimization problem. The bank maximizes each period nominal profits by choosing its lending plans $\{L_{s,t}\}_{s\in\mathcal{S}}$, that is,

$$\max_{\{L_{s,t}\}_{s\in\mathcal{S}}} \Pi^B_t = \sum_{s\in\mathcal{S}} [R^L_{s,t} - R^D_t - \psi_t(R^L_{CB,t} - R^D_{CB,t})] L_{s,t},$$

where we already incorporated the money creation constraint $L_t = D_t$ and used the fact that at origination reserve loans $L_{CB,t}$ and reserve deposits $D_{CB,t}$ equal.

3.4 Central bank

The central bank uses its lending facilities to provide liquidity in terms of reserves to banks. In general, the central bank can use three instruments to steer liquidity costs, which in turn affect the investment behavior of banks: the loan and deposit rates for reserves, the reserve requirement and the collateral framework, which defines the assets eligible as collateral for central bank loans and the applicable haircuts on these assets. We abstract from the collateral framework and focus solely on the interest rates for reserves and the reserve requirement; hence, the central bank provides unsecured loans to banks. In our framework, monetary policy is assumed to be climate oriented, so that the liquidity costs depend on the emission intensity of the financial assets held by the bank. Specifically, we assume that reserve loans $L_{CB,t}$ demanded by the bank are subject to repayment costs determined by the nominal gross loan rate $R^L_{CB,t} = R^L_{CB}(\mathbf{l}_t, \mathbf{\Gamma}_t, z^t) > 0$, where $\mathbf{l} = \{l_{s,t}\}_{s\in\mathcal{S}}$ represents the set of sectoral weights in the loan portfolio of the bank, that is, $l_{s,t} = L_{s,t}/L_t$, and $\mathbf{\Gamma}_t = \{\Gamma_{s,t}\}_{s\in\mathcal{S}}$ denotes the set of sectoral emission intensities. The reserve deposits $D_{CB,t}$ held by the bank are credited by the central bank with interest according to the nominal gross deposit rate $R^D_{CB,t} > 0$. In what follows, we assume that the loan rate on reserves satisfies the following additive form

$$R^L_{CB,t} = R^D_{CB,t} \sum_{s\in\mathcal{S}} \kappa_t(\Gamma_{s,t}) l_{s,t},$$

where $\kappa_t(\Gamma_{s,t}) = \exp(\kappa_{1,t}\Gamma_{s,t})$, with $\kappa_1 \geq 0$, representing the cost factor for loans provided by the bank to sector s. Since the cost factor weakly exceeds unity, reserves are generally costly for the bank. Moreover, the cost factor increases with the sectoral emission intensity, that is, $\partial\kappa(\Gamma_{s,t})/\partial\Gamma_{s,t} \geq 0$. In period t, the realized profits of the central bank are then given by

$$\Pi^{CB}_t = (R^L_{CB,t} - R^D_{CB,t}) L_{CB,t},$$

where we used the fact that reserve loans and reserve deposits are equal at origination, that is, $L_{CB,t} = D_{CB,t}$. The latter can also be interpreted as the money creation constraint on the side of the central bank. The central bank credits the accounts of the household at commercial banks with the generated seigniorage, before the household purchases the production output from firms.

Banks can lend to other banks and deposit at other banks, which is commonly referred to as the interbank market. From the perspective of the bank, interbank loans provide an alternative to central bank loans. Hence, a climate-oriented monetary policy can be undermined, if banks with a relatively low emission-intensive loan portfolio demand reserves at the central bank and channel them further to banks with a higher emission-intensive loan portfolio. Such a situation is ruled out in our model, as we assume that the central bank perfectly observes lending activities between banks and applies a look-through approach, so that the liquidity costs for interbank loans account for the emission intensity of the assets held by the financed bank. Thus, the equivalence of liquidity provisions from the central bank and other banks is guaranteed. As a consequence, we disregard interbank deposit and lending activities.

As outlined above, the central bank also sets a reserve requirement for banks, that is, the bank must hold at least a share $\varphi_t = \varphi(z^{t-1}) \in [0, 1]$ of deposits D_t in reserves.

In our model, we integrate climate targets into the objective function of the central bank. Specifically, the central bank is interested in reducing the emission intensity of banks' loan portfolio, ultimately enforcing the decarbonization of the entire economy. It pursues the latter by targeting a reduction of the expected emission intensity of banks' loan portfolio by a constant share $\xi \in [0, 1]$ until the threshold value $\hat{\Gamma}$ is reached. The instruments available to the central bank to achieve its goal are the state-contingent deposit rates on reserves, the emission-based cost factor, which determines the repayment costs on reserve loans, and the reserve requirement.

Thus, in period t, the optimization problem of the central bank is given by

$$\min_{R^D_{CB,t}, \kappa_{1,t}, \varphi_t} \quad d\left(\mathbb{E}_{t-1}[\bar{\Gamma}_t], \xi \mathbb{E}_{t-2}[\bar{\Gamma}_{t-1}]\right),$$

where $\bar{\Gamma}_t = E_t/Y_t$, with $Y_t = \sum_{s\in\mathcal{S}} Y_{s,t}$, denotes the emission intensity of banks' loan portfolio and $d(\cdot,\cdot)$ represents a metric defined on $\mathbb{R}_+$.

4 Model analysis

We first outline the equilibrium notion applied in our analysis and then discuss the equilibrium properties.

4.1 Competitive equilibrium

In our model analysis, we focus on competitive equilibria, as defined hereafter. For their decisions, households, firms and banks take the monetary policy as given. Hence, we introduce the notion of a monetary framework $\mathcal{M}$, which consists, for all periods $t \in \mathbb{N}_0$, of the the state-contingent deposit rates $R^D_{CB,t}$, the emission-based pricing factor $\kappa_{1,t}$ for loans, the reserve requirement φ_t and the share ϕ_t of deposits circulating among banks.

Definition 1 (Competitive equilibrium)**.** *Given a monetary framework $\mathcal{M}$ and an initial temperature T_0, a competitive equilibrium is described by prices $\{P_t, Q_t, \{W_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$, interest rates $\{R^D_t, R^L_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$ and allocations $\{C_t, K_{t+1}, \{\gamma_{s,t}, K_{s,t}, N_{s,t}\}_{s\in\mathcal{S}}, \{L_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$, so that*

(1) given prices $\{P_t, Q_t, \{W_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$ and interest rates $\{R^D_t\}_{t\in\mathbb{N}_0}$, the choices $\{C_t, K_{t+1}\}_{t\in\mathbb{N}_0}$ maximize the utility of the household,

(2) given prices $\{P_t, Q_t, W_{s,t}\}_{t\in\mathbb{N}_0}$ and interest rates $\{R^L_{s,t}\}_{t\in\mathbb{N}_0}$, the choices $\{\gamma_{s,t}, K_{s,t}, N_{s,t}\}_{t\in\mathbb{N}_0}$ maximize the expected profits of the firm in sector $s \in \mathcal{S}$,

(3) given interest rates $\{R^D_t, \{R^L_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$, the choices $\{\{L_{s,t}\}_{s\in\mathcal{S}}\}_{t\in\mathbb{N}_0}$ maximize the expected profits of the bank, and

(4) each period capital, labor and output good markets clear, that is, $K_t = \sum_{s\in\mathcal{S}} K_{s,t}$, $N_t = \sum_{s\in\mathcal{S}} N_{s,t}$ and $\tilde{Y}_t = \sum_{s\in\mathcal{S}} \tilde{Y}_{s,t}$.

In our model, all agents are aware of climate damage due to carbon emissions generated in the course production activities. However, the individual agent is atomistic and, hence, does not internalize the externality, when making its decisions. Rather than analyzing the first-best allocation emerging from a socially optimal equilibrium, we study second-best outcomes resulting from the decentralized equilibrium, assuming that the central bank pursues a climate-oriented monetary policy. Thus, we are interested in the central bank's optimal choice to achieve its targets and the consequent allocations emerging in the economy.

4.2 Equilibrium Properties

For our subsequent analysis of the competitive equilibrium, we take the monetary framework $\mathcal{M}$ as given. We analyze the optimization problem of banks, firms and households, in this order, to illustrate how the emission-based interest rate policy adopted by the central bank affects first the financial sector and then the real economy. Using the structure of loan and deposit rates for reserves, as set by the central bank, the necessary and sufficient optimality conditions for the optimization problem of the bank are given by

$$R^L_{s,t} = R^D_t + \psi_t R^D_{CB,t}[\kappa_t(\Gamma_{s,t}) - 1], \qquad \text{for} \quad s \in \mathcal{S},$$

showing that the loan rate charged by the bank must be sufficient to cover the interest promised to depositors and the liquidity costs imposed by the central bank. We assume that banks cannot discriminate between deposits held by the household and firms, and deposits held by other banks. It then follows from a no-arbitrage argument that the interest rate on bank deposits equals the deposit rate for reserves, that is,

$$R^D_t = R^D_{CB,t}. \tag{1}$$

From the perspective of an individual bank, it is not optimal to promise a higher interest rate on deposits than the deposit rate on reserves set by the central bank. This is due to the fact that deposit and reserve flows match. Thus, when the bank receives deposits from other banks, it also receives the same amount of reserves, which, however, are credited with less interest than promised to depositors. In turn, if banks promise an interest rate on deposits which is lower than the deposit rate on reserves, banks themselves deposit only at the central bank. Regarding the deposits of households and firms, the individual bank always has an incentive to promise a slightly higher deposit rate, which is still below the deposit rate on reserves, and thus attracts all available deposits in the economy, resulting in riskless profits for that particular bank. In a competitive banking sector such arbitrage is eliminated, resulting in an interest rate on bank deposits that equals the deposit rate on reserves. Thus, using the equality of deposit rates, the optimality conditions for the bank simplify to

$$R^L_{s,t} = R^D_{CB,t}[1 + \psi_t\kappa_t(\Gamma_{s,t}) - \psi_t], \qquad \text{for} \quad s \in \mathcal{S}. \tag{2}$$

Banks operate in a perfectly competitive market, so that they pass the liquidity costs, as determined by the central bank, completely on to the real economy. Firms with a higher emission intensity face higher loan rates. A more detailed analysis of the bank's optimization problem is given in Appendix A. Firms have full knowledge about the structure of loan rates charged by banks. Hence, accounting for the dependency of the loan rates on the emission intensity, the first-order conditions for the optimization problem of the firm in sector s, with respect to $\gamma_{s,t}$, $K_{s,t}$ and $N_{s,t}$, are given by

$$-\alpha \tilde{A}_{s,t} \bar{\gamma}_{s,t}^{\alpha-1} K_{s,t}^{\alpha} N_{s,t}^{1-\alpha} = q_t K_{s,t} \frac{\partial R_{s,t}^L}{\partial \gamma_{s,t}} - \mu_{s,t}, \tag{3}$$

$$\alpha \tilde{A}_{s,t} \bar{\gamma}_{s,t}^{\alpha} K_{s,t}^{\alpha-1} N_{s,t}^{1-\alpha} = R_{s,t}^L q_t, \tag{4}$$

$$(1-\alpha) \tilde{A}_{s,t} \bar{\gamma}_{s,t}^{\alpha} K_{s,t}^{\alpha} N_{s,t}^{-\alpha} = R_{s,t}^L w_{s,t}, \tag{5}$$

and the complementary slackness condition $\mu_{s,t}\gamma_{s,t} = 0$, where $\mu_{s,t} \geq 0$ represents the Karush-Kuhn-Tucker multiplier for the non-negativity constraint on $\gamma_{s,t}$ and $\tilde{A}_{s,t} = \Omega(T_t)A_{s,t}$ denotes the total factor productivity taking climate damage into account. The variables q_t and $w_{s,t}$, in turn, denote the real rental price of physical capital in term of the output good, that is, Q_t/P_t and the real wage rate in sector s in terms of the final output good, that is, $W_{s,t}/P_t$, respectively. In what follows, we briefly characterize the optimal behavior of firms; a more comprehensive analysis is provided in Appendix A. Note that as the Cobb-Douglas production function satisfies the Inada conditions, firms never decide to devote all their capital to the adoption of a new technology, that is, $\gamma_{s,t} < 1$. Firms face competitive markets, so that they operate efficiently if and only if marginal returns equal marginal costs. Using the first-order condition (4) and the market clearing condition for physical capital, we can derive the share $\zeta_{s,t} \in [0, 1]$ of aggregate capital K_t allocated to sector s in period t, that is,

$$\zeta_{s,t} = \left(\sum_{\bar{s} \in \mathcal{S}} \left[\frac{A_s(z_t)}{A_{\bar{s}}(z_t)} \frac{\bar{\gamma}_{s,t}^{\alpha}}{\bar{\gamma}_{\bar{s},t}^{\alpha}} \frac{N_{s,t}^{1-\alpha}}{N_{\bar{s},t}^{1-\alpha}} \frac{1 + \psi_t \kappa_t(\Gamma_{\bar{s},t}) - \psi_t}{1 + \psi_t \kappa_t(\Gamma_{s,t}) - \psi_t} \right]^{\frac{1}{\alpha-1}} \right)^{-1}. \tag{6}$$

In this regard, equation (6) shows that a sector with a greater marginal return due to a higher total factor productivity, innovating less, employing more labor or operating with a cleaner technology, attracts more physical capital. Note that climate damage does not play a role in the allocation of capital across sectors, as each sector is impacted with the same intensity. The labor employment $N_{s,t}$ by sector s in period t follows from the clearing condition for the labor market, the household's total labor endowment and the assumption of inelastic supply to each sector, that is, $N_{s,t} = n_s N_t$. The financing costs of firms decrease with the emission intensity $\Gamma_{s,t}$, so that already clean firms (that is, low $\Gamma_{s,t-1}$) and firms adopting cleaner technologies (that is, positive $\gamma_{s,t}$) benefit from relatively lower loan rates. Given that firms have full knowledge, the latter generally devote some capital to the adoption of a cleaner technology. Using the first-order conditions (3) and (4) of firms, we can obtain the following equation which determines the share $\gamma_{s,t}$, that is, in period t the firm in sector s devotes a fraction

$$\gamma_{s,t} = \max\left\{\frac{\psi_t[1 + (\kappa_{1,t}\iota_s\Gamma_{s,t-1} - 1)\kappa_t(\Gamma_{s,t})] - 1}{\psi_t\kappa_{1,t}\iota_s\Gamma_{s,t-1}\kappa_t(\Gamma_{s,t})}, 0\right\} \tag{7}$$

of physical capital to the adoption of a cleaner technology. The share $\gamma_{s,t}$ is weakly increasing in the convexity of the cost schedule $\kappa_{1,t}$, the prevailing emission intensity $\Gamma_{s,t-1}$ and the reserve to deposit ratio ψ_t. To derive the profits of firms, we first use the first-order conditions (4) and (5) to express the real rental rate of physical capital q_t and the real wage rate $w_{s,t}$ as

$$q_t = \frac{\alpha\tilde{Y}_{s,t}}{R^L_{s,t}K_{s,t}} \qquad \text{and} \qquad w_{s,t} = \frac{(1-\alpha)\tilde{Y}_{s,t}}{R^L_{s,t}N_{s,t}}. \tag{8}$$

Due to our Cobb-Douglas specification, the capital rental service is rewarded with a share α of production and labor supply with the residual share $1-\alpha$. The technologies applied by firms exhibit constant returns to scale, so that firms make zero profits. Moreover, banks make zero profits, while the central bank generates seignorage due to its liquidity provisions to banks, namely

$$\Pi^{CB}_t = \psi_t R^D_{CB,t}\sum_{s\in\mathcal{S}}[\kappa_t(\Gamma_{s,t}) - 1]L_{s,t}.$$

Using the fact that firms and banks make zero profits and the structure of the central bank seigniorage, we can show that any nominal output good price is compatible with market clearing and the budget constraint of households (see Appendix A). The household makes its consumption and capital accumulation decision taking prices as given. From our assumption of exogenous population growth and the inelastic labor supply to each of the sectors, it follows that the necessary first-order conditions of the household's optimization problem are then given by the Euler equations, that is for all $t \in \mathbb{N}_0$

$$c_t^{-\sigma} = \beta\mathbb{E}_t\left[c_{t+1}^{-\sigma}(R^D_{CB,t+1}q_{t+1} + 1 - \delta)\right].$$

The Euler equations and the transversality condition $\lim_{t\to\infty}\beta^t c_t^{-\sigma}k_{t+1} = 0$ are jointly sufficient for the optimization problem of the household. The characterization of the competitive equilibrium follows then from our previous observations.

Proposition 1 (Competitive equilibrium)**.** *Given a monetary framework $\mathcal{M}$, initial emission intensities $\Gamma_{s,-1} \geq 0$, with $s \in \mathcal{S}$, an initial capital stock $K_0 > 0$ and an initial temperature $T_0 \geq 0$, the competitive equilibrium is characterized by*

(1) prices q_t and $w_{s,t}$, with $s \in \mathcal{S}$, satisfying (8),

(2) interest rates R_t^D and $R_{s,t}^L$, with $s \in \mathcal{S}$, satisfying (1) and (2), and

(3) allocations described by $K_{s,t} = \zeta_{s,t} K_t$, where $\zeta_{s,t}$ follows from (6), $N_{s,t} = n_s N_t$. Additionally, the loans provided to sector s are given by $L_{s,t} = Q_t K_{s,t} + W_{s,t} N_{s,t}$ and the share $\gamma_{s,t}$ of capital devoted to the adoption of a cleaner technology follows from (7), so that the new emission intensity is given by $\Gamma_{s,t} = (1 - \iota_s \gamma_{s,t}) \Gamma_{s,t-1}$. Finally, the aggregate capital stock is given by $K_{t+1} = \tilde{Y}_t + (1-\delta) K_t - C_t$ and consumption c_t satisfies $\lim_{t \to \infty} \beta^t c_t^{-\sigma} k_{t+1} = 0$ and follows, for all $t \in \mathbb{N}_0$, as a solution from

$$c_t^{-\sigma} = \beta \mathbb{E}_t \left[c_{t+1}^{-\sigma} (R_{CB,t+1}^D q_{t+1} + 1 - \delta) \right].$$

5 Solution method

To obtain a solution of our model, we need to determine the optimal climate-oriented monetary policy and the consumption and capital accumulation decisions of households. The two corresponding optimization problems can be solved sequentially, as the central bank policy does not depend on the capital stock available in the economy. Thus, we first solve for the optimal monetary policy and then for the decisions of households.

Given the initial emission intensities across sectors, for each period we derive the optimal emission-based cost factor chosen by the central bank to achieve a reduction of the expected emission intensity of banks' loan portfolio. Moreover, note that deposit rates do not enter firms' decision about the adoption of a new technology. Thus, we disregard deposit rates in the optimization problem of the central bank and leave them unspecified. For simplicity, we set the reserves to deposits ratio to its current level and keep it constant across the infinite horizon. The optimal monetary policy allows us to determine the share of capital that firms in each sector devote to the adoption of a new technology and the resulting new emission intensities.

Given the optimal monetary policy, the innovation shares and the emission intensities, we use the Euler equations and the budget constraint to derive the decisions of the household with regard to consumption and capital accumulation, that is, for all $t \in \mathbb{N}_0$ it must hold

$$\begin{aligned} c_t^{-\sigma} &= \beta \mathbb{E}_t [c_{t+1}^{-\sigma} (R_{CB,t+1}^D q_{t+1} + 1 - \delta)], \\ C_t + K_{t+1} &= \tilde{Y}_t + (1-\delta) K_t. \end{aligned}$$

Note that the choice of consumption C_t and of capital next period K_{t+1} can be described by a policy function which, in our context, depends on sectoral capital $K_{s,t}$, labor employment $N_{s,t}$, total factor productivity $A_{s,t}$, innovation $\gamma_{s,t}$ and the temperature level T_t. We denote these state variables using the vector X_t. The decisions of households can then be obtained from the consumption function $C_t = C(X_t)$, the capital function $K_{t+1} = K(X_t)$ or from the expectation about next period marginal utility, that is,

$$G(X_t) = \beta \mathbb{E}_t[c_{t+1}^{-\sigma}(R_{CB,t+1}^D q_{t+1} + 1 - \delta)].$$

Our model does not allow for an analytical solution, so that we rely on numerical methods to approximate one of these functions. Specifically, we use the parametrized expectations algorithm outlined in Den Haan and Marcet (1990) and Maliar et al. (2001) to approximate the expectation function. The standard algorithm is based on functional approximation using parametrization, for example with polynomial functions, and on an iterative procedure to generate new data, which is then used to update the parameters of the functional approximation. Starting from an initial guess for the parameters of the approximating function and initial values for the state variables, a path of states and controls—in our context represented by consumption—is derived from the Euler equations and the budget constraint. The generated data is then used in a regression analysis to derive new estimates of the parameters of the approximating function. In this respect, note that $G(X_t)$ represents the conditional mean of the realizations $\beta c_{t+1}^{-\sigma}(R_{CB,t+1}^D q_{t+1} + 1 - \delta)$, so that a regression analysis is well suited to estimate the function $G(\cdot)$. The generation of new data and the updating of parameters is repeated, with the same initial values for the state variables, until the parameters of the approximating function converge. To the best of our knowledge, there exist no results proving the convergence of this algorithm. Nevertheless, it has been used to solve stochastic dynamic general equilibrium models and has been proven to work well in stationary environments.

Our model is however non stationary due to the time dependence of the innovation shares, total factor productivities, population growth and temperature. Models with constant growth, for example due to technology improvement or population growth, can generally be rewritten as stationary models by using growth-adjusted state variables. However, such an approach is not feasible in our setting as the growth rates of the state variables change over time. We circumvent this issue by generating several paths of states and controls in each updating step in order to approximate the distribution of state variables at each point in time. Our regression analysis uses Bayesian optimization. Specifically, we model our function $G(\cdot)$ as a Gaussian process denoted by

$$G(\cdot) \sim \mathcal{GP}(m(\cdot), \sigma(\cdot, \cdot)),$$

where $m : \mathbb{R}^d \to \mathbb{R}$ represents the mean function and $\sigma : \mathbb{R}^d \times \mathbb{R}^d \to \mathbb{R}$ denotes the covariance function, with $d \in \mathbb{N}$ being the dimension of any input data point X_t. A Gaussian process is a set of random variables with the specific characteristic that any finite sample of it is jointly Gaussian distributed. In the following, we outline the Gaussian process regression used in our simulations. Suppose that we are given a set of data points $\{(X_i, y_i), \quad i = 1, \ldots, n\}$, so that

$y_i = g(X_i) + \epsilon_i$, where ϵ_i is independent and identically distributed according to a Gaussian distribution with mean zero and variance $\sigma_\epsilon^2 > 0$. We define the input data $\mathbf{X} = [X_1, \dots, X_n]$ and the output data $\mathbf{y} = [y_1, \dots, y_n]$. The prior on the unknown function $G(\cdot)$ is Gaussian, so that $G(\mathbf{X})|\mathbf{X} \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$, where $\boldsymbol{\mu} = [\mu(X_1), \dots, \mu(X_n)]^T$ and $\boldsymbol{\Sigma} = [\sigma(X_i, X_j)]_{1\leq i,j\leq n}$. The likelihood function of our observed output data is then given by $\mathbf{y}|\mathbf{X}, \sigma_\epsilon \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma} + \sigma_\epsilon^2 I_n)$, with I_n denoting the identity matrix of dimension n. Thus, for any input data point $\tilde{X}$ we can derive the posterior distribution

$$G(\tilde{X})|\mathbf{X}, \mathbf{y}, \sigma_\epsilon \sim \mathcal{N}(\tilde{\mu}(\tilde{X}), \tilde{\sigma}(\tilde{X}, \cdot)),$$

where the updated mean function and covariance function are given by

$$\begin{aligned}\tilde{\mu}(\tilde{X}) &= \mu(\tilde{X}) + \boldsymbol{\Sigma}_{\tilde{X}}(\boldsymbol{\Sigma} + \sigma_\epsilon^2 I_n)^{-1}(\mathbf{y} - \boldsymbol{\mu})\\ \tilde{\sigma}(\tilde{X}, \cdot) &= \sigma(\tilde{X}, \cdot) - \boldsymbol{\Sigma}_{\tilde{X}}(\boldsymbol{\Sigma} + \sigma_\epsilon^2 I_n)^{-1}\boldsymbol{\Sigma}_{\tilde{X}}^T,\end{aligned}$$

where $\boldsymbol{\Sigma}_{\tilde{X}} = [\sigma(\tilde{X}, X_i)]_{1\leq i\leq n}$ represents the covariance of the new data point $\tilde{X}$ with the previously observed input data $\mathbf{X}$. In our analysis, we use the mean $\tilde{\mu}(\cdot)$ of the posterior distribution as the predictor for the unknown function $G(\cdot)$. Throughout our analysis, we use the Matérn kernel as covariance function, that is,

$$\sigma(X_i, X_j) = \frac{2^{1-\nu}}{\Gamma(\nu)}\left(\sqrt{2\nu}\|\hat{X}_i - \hat{X}_j\|_2\right)^\nu K_\nu\left(\sqrt{2\nu}\|\hat{X}_i - \hat{X}_j\|_2\right),$$

where $\|\cdot\|2$ denotes the Euclidean distance, $\Gamma(\cdot)$ denotes the Gamma function and $K_\nu(\cdot)$ is the modified Bessel function of the second kind. We use the notation $\hat{X} = [X(1)/l_1, \dots, X(d)/l_d]^T$, where $X(k)$ represents the value of X in dimension k and $l_k > 0$ being the scaling parameter in dimension $k = 1, \dots, d$. In general, $\mathbf{l} = [l_1, \dots, l_d]$ are also referred to as hyper-parameters. The variance σ_ϵ^2 of the noise as well as the hyper-parameters $\mathbf{l}$ are estimated using maximum-likelihood. In our application, we set $\nu = 1.5$. We use a maximum of 100 iterations in the parametrized expectations algorithm. We then use the estimated posterior distribution to simulate 1'000 paths of our model for a time horizon of 300 periods.

6 Simulation

In this section, we illustrate the role of a climate-oriented monetary policy in terms of emission-based interest rates for the Euro Area (EA). We provide empirical support for some fundamental assumptions of our model and discuss the choice of parameters used in our calibration. Finally, we provide the simulation results and discuss policy implications.

6.1 Descriptive Statistics

In our model, the loan volume matches at any time the outstanding amount of deposits. Although this represents a strong assumption on the structure of asset markets and banks' balance sheets, it is not at odds with the observed data. The left panel of Figure 1 depicts the loan to deposit ratio for the EA, where we distinguish between total outstanding loans and deposits, and loans and deposits of private agents and of governments, excluding monetary financial institutions (MFIs). Since the foundation of the EA, both ratios have never recorded values higher than 1.2 or lower than 0.9. Another crucial assumption of our model is that firms completely rely on external financing in the form of bank loans. Thus, loans are used to cover all production expenses, which consist of capital service and labor income. As we focus on a closed economy, the latter coincide with the gross domestic product (GDP). The right panel of Figure 1 shows that, in the EA, this assumption is generally in line with the empirical observation. A rationale for this pattern may be the strong reliance of private corporations within the EA on bank loans in the acquisition of external financing (De Fiore and Uhlig, 2011).

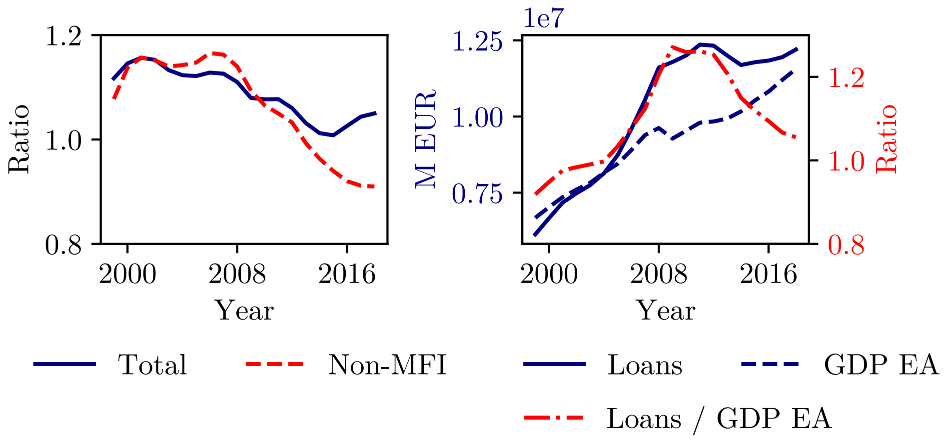

Figure 1: Loans to deposits ratio for the EA (left panel); loans, GDP and loans to GDP ratio for the EA (right panel). *Source:* European Central Bank, accessed on 09/11/2019.

In our framework, banks demand reserves at the central bank either to comply with a reserve requirement or to settle claims among banks, which arise from interbank deposit flows. Figure 2 depicts the excess reserves held by MFIs in the EA as well as the reserves to deposits ratio. It shows that until 2014 credit institutions in the EA were holding no reserves in excess of the amount required by the central bank. Accordingly, the ratio of reserves to deposits was stable during this period. With the launch of the quantitative easing by the European Central Bank (ECB) in March 2015, MFIs are holding more reserves than necessary under the imposed reserve requirement. This led to an increase in the reserves to deposits ratio, leveling at 0.08 in 2018.

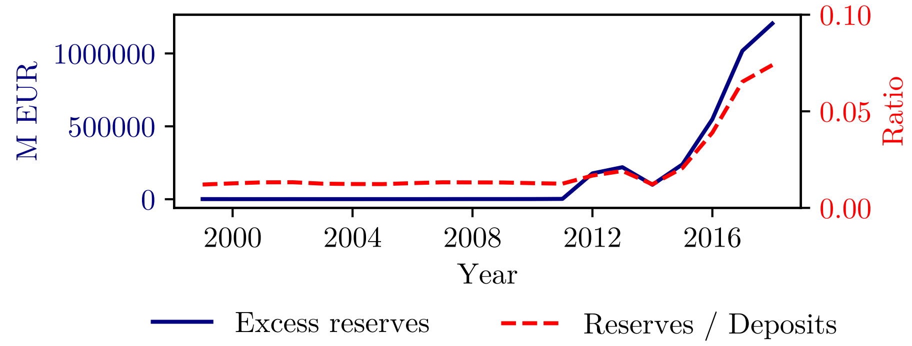

Figure 2: Excess reserves and reserves to deposits ratio in the EA. *Source:* European Central Bank, accessed on 09/11/2019.

6.2 Parameters

In our simulations, we take 2018 as our initial period and assume that the EA population decreases from 2018 to 2100 by 0.2 percent per year and is constant after this period. That is, $\eta_t = -0.02$ for $t \in \{0, \ldots, 81\}$ and $\eta_t = 0$ otherwise. We justify this assumption based on the projections of the United Nations according to which the EA population will grow from 340 million in 2018 to its peak of 341 million in 2022 and then will steadily decline to 287 million in 2100. Following Nordhaus and Sztorc (2013) in their specification of the 2013R version of the DICE model, we set the relative risk aversion parameter σ to 1.45. We also use their discount rate $\rho = 0.015$, so that the discount factor $\beta \approx 0.985$. We add up the capital stocks for all EA countries as provided by the Penn World Table, so that the initial capital stock is given by USD 66.1 trillion (at constant 2011 national prices).

On the side of firms, we set the capital intensity α to 0.42. We derive this value by computing the share of labor income in the EA GDP as an average from the country-specific labor share estimates provided by Penn World Table, weighting each country by its relative population size. Following this procedure, we obtain a labor income share of 0.58. Physical capital depreciates each period by a share 0.04. We obtain this value by using the country-specific estimates for the average capital depreciation as provided by the Penn World Table and derive the EA depreciation rate by weighting each country according to its capital stock. We use Eurostat data on the sectoral emission intensities for all EA countries as of 2016 to derive estimates of the sectoral emission intensities at the EA level. For the identification of the sectors, we rely on the NACE economic activities classification.[13] We weight the sectoral emission intensity, measured in kilogram of carbon dioxide per Euro at current prices, by the sectoral gross value added of each country at current prices. We model two sectors only, a clean and a dirty one, indexed by c and d, respectively. We use the median sectoral emission intensity in the EA to allocate the

[13] See `https://ec.europa.eu/eurostat/documents/3859598/5902521/KS-RA-07-015-EN.PDF`, for a detailed description of the economic activities.

different production activities between the two aggregate sectors.[14] By weighting each included sector according to its gross value added, we obtain that the emission intensity of the clean and dirty sector are 0.02 and 0.5, respectively. Next, we derive the shares of labor employed by each of the NACE sectors, which are then aggregated according to our clean and dirty classification. As we find that labor is equally allocated across the clean and dirty sectors, we set $n_s = 0.5$. We assume that both sectors face the same initial expected total factor productivity $\hat{A}_0$, but are subject to productivity shocks, which cause the realized productivity to deviate in each state by approximately 5 percent from its expectation. There are only two possible states of the economy, which occur each period with equal probability, that is, $\pi(z) = 0.5$. Thus, we denote the set of states by $\mathcal{Z} = \{1, 2\}$. The sectoral productivities exhibit a perfect negative correlation. Thus, if the clean sector incurs a positive productivity shock, the dirty sector experiences a negative shock of the same magnitude, and vice versa. In our analysis, the clean sector experiences a positive productivity shock in the first state, that is, $A_c(1) = 1.05$ and $A_c(2) = 0.95$, while the dirty sector does so in the second state, that is, $A_d(1) = 0.95$ and $A_d(2) = 1.05$. We can obtain the expected total factor productivity by matching the expected production output under the previous assumptions on the capital intensity, the labor share, the productivity shocks, the initial capital stock and the initial population size with the EA GDP.[15] As of 2018, the latter is given by USD 13.7 trillion (in 2011 USD international prices), so that we obtain an initial expected total factor productivity of $\hat{A}_0 = 0.08$. We assume that the expected productivity grows each period by 0.3 percent, that is, $a_t = 0.003$.

Based on IPCC estimates, the initial temperature is set to 0.87°C above the preindustrial level, as defined by the benchmark period 1850-1900.[16] Temperature depends linearly on the generated carbon emissions. For our calibration we rely on Matthews et al. (2009), who find that temperature increases in the range of 1.0-2.1°C (representing the 5th and the 95th percentile) per teraton of carbon. In our specification, we use their best estimate of 1.5°C per teraton of carbon, so that, taking into account that one teraton of carbon represents approximately 3.67 teratons of carbon dioxide, we set $\tau = 0.00041$.[17] In describing the evolution of emissions and temperature, we take the emissions of non-EA countries as given. Specifically, we use the emission path compatible with the 1.5°C target, as estimated by the Climate Action Tracker.[18] Since these projections are computed at the global level, we need to exclude EA emissions,

[14] See Appendix B, for a more detailed description of the NACE classification and our grouping of sectors into clean and dirty.

[15] Note that the assumption of identical expected total factor productivities, identical labor shares and identical risk across sectors does, in the absence of a climate-oriented monetary policy, lead to identical capital allocation across sectors.

[16] Available at https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf, accessed on 20/10/2019.

[17] Note that carbon has an atomic mass of 12, while oxygen has an atomic mass of 16. Thus, the atomic mass of carbon dioxide is given by 44, so that one kilogram of carbon is equivalent to $44/12 \approx 3.67$ kilograms of carbon dioxide.

[18] Available at https://climateactiontracker.org/methodology/global-pathways/, accessed on 29/11/2020.

which are, in turn, modeled within our framework. Accordingly, we subtract from the global emissions the share caused by EA countries, that is obtained through own computations based on data from the World Bank.[19] In our analysis, we set the reserves to deposits ratio to its current value, that is, $\psi_t = 0.08$.

6.3 Results

We first discuss the optimal climate-oriented monetary policy and then proceed to the optimal decisions of households. The optimal monetary policy aims at reducing the expected emission intensity of banks' loan portfolio and, ultimately, of the economy as a whole, by a predetermined share until the desired target is achieved. In what follows, we provide an illustration for the case of a 5 and 10 percent annual reduction, that is, $\xi = 0.95$ and $\xi = 0.9$, and a target value of $\hat{\Gamma} = 0.001$. Note that deposit rates do not influence the decision of firms to adopt a cleaner technology. Thus, we leave them unspecified in our analysis. We then solve for the optimal emission-based cost schedule which is needed to achieve the postulated goals, assuming innovation impact factors of $\iota_s = 0.5$ and $\iota_s = 1$. For simplification, the latter are assumed to be homogeneous across sectors. Figure 3 and 4 show for the cases of a 5 and 10 percent reduction target, the optimal climate-oriented monetary policy in the form of the emission-based cost factor, the expected emission intensity of banks' loan portfolio, the resulting innovation shares and the emission intensities for the clean and dirty sector, as well as the capital allocations in both states. In the case of a 5 and 10 percent annual reduction target, the cost factor $\kappa_{1,t}$ chosen by the central bank steadily increases until the year 2127 and 2071, respectively. After this point, the expected emission intensity of banks' loan portfolio is lower than the target value $\hat{\Gamma} = 0.001$, so that no climate-oriented monetary policy is adopted. As long as the target is not achieved, the central bank continuously increases the cost factor over time in order to maintain the incentives of banks to favor low-carbon assets, while the economy is getting cleaner. Thus, the central bank also indirectly preserves the incentives of firms to adopt cleaner technologies. The path of the expected emission intensity of banks' asset portfolio shows that starting from an initial value of 0.26 kilograms of carbon dioxide per USD (in constant 2011 national prices) in 2018, the adopted policies would achieve the target level of 0.001 in the year 2127 (2071) if a 5 (10) percent emission reduction target is applied. For all the different targets ξ and innovation impact factors ι_s, the reduction of the expected emission intensity in the earlier periods is achieved solely by shifting capital from the dirty to the clean sector, without inducing innovation. After this initial phase, the cost parameter chosen by the central bank is such that it leads to innovation of firms. The latter initially takes place only in the dirty sector, as this is sufficient to achieve the desired emission reduction. However, as soon as dirty firms operate with the same emission intensity as clean firms, both sectors start to innovate

[19] We use the most recent data on emissions of carbon dioxide available at https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?locations=XC, accessed on 05/11/2019.

and devote a share $(1-\xi)/\iota_s$ of their capital to the adoption of a cleaner technology. With a 5 percent emission target and an innovation impact factor of 0.5 (1), innovation by clean firms starts in the year 2068 (2069). With a 10 percent target, in turn, clean firms start innovating in 2042, for an innovation impact factor of 0.5 and in 2043, for an innovation impact factor of 1. Note that for clean and dirty firms the incentives to innovate are not only determined by the monetary policy, but also by their possibilities to adopt cleaner technologies as captured by the innovation impact factor ι_s. As the climate-oriented monetary policy leads to the adoption of new technologies and, thus, affects the sectoral emission intensities over time, the allocation of capital across production sectors is impacted. Specifically, the clean sector benefits from the adoption of cleaner technologies in the dirty sector, by receiving more capital. This effect reduces with the innovation impact factor in the dirty sector and vanishes when the clean sector starts to innovate as well.

In Figures 5 and 6, we depict the expected capital accumulation, consumption, temperature and climate damage, for a 5 and 10 percent reduction target and considering different values of the innovation impact factor. The vertical lines indexed by the numbers 1-4 indicate different structural breaks of our model: "1" represents the time period in which dirty firms start to innovate, "2" indicates the start of innovation by clean firms, "3" is the time period when both types of firms stop innovating and "4" denotes the time period after which the population size remains constant. For a given emission reduction target, the evolution of temperature and climate damage is independent of the innovation impact factor. However, the possibilities for adopting new technologies, as captured by the innovation impact factor, influence the decisions of the household with regard to consumption and capital accumulation. With a lower innovation impact factor more resources are needed to achieve the same reduction target. Thus, for $\iota_s = 1$ the consumption and the accumulated capital exceed their counterparts for the case of $\iota_s = 0.5$, at least during the period in which a climate-oriented monetary policy is adopted. If the central bank pursues the target of reducing the expected emission intensity of banks' loan portfolio by 5 (10) percent per year, temperature increases until a level of 1.45° (1.43°C) above the preindustrial level in the year 2127 (2071) and then remains approximately constant. Temperature still increases slightly as the emission intensities of the clean and dirty sector have not been driven to zero, but are only lower than the postulated target of 0.001. Following a 5 (10) percent reduction target, climate damage increases until the year 2127 (2071), but remains roughly constant after this period at a level of 0.49 (0.48) percent of GDP. Again, climate damage slightly increases over time, as temperature increases, which is a result of the adopted climate-oriented monetary policy, which does not drive emissions to zero. The small difference in temperature and climate damage between the case of a 5 and 10 percent reduction target is due to the fact that, in our analysis, the emissions from the EA represent only 6 percent of global emissions, so that the impact of EA emissions on global temperature is generally small and further reduced by innovation, as induced by the climate-oriented monetary policy. We find

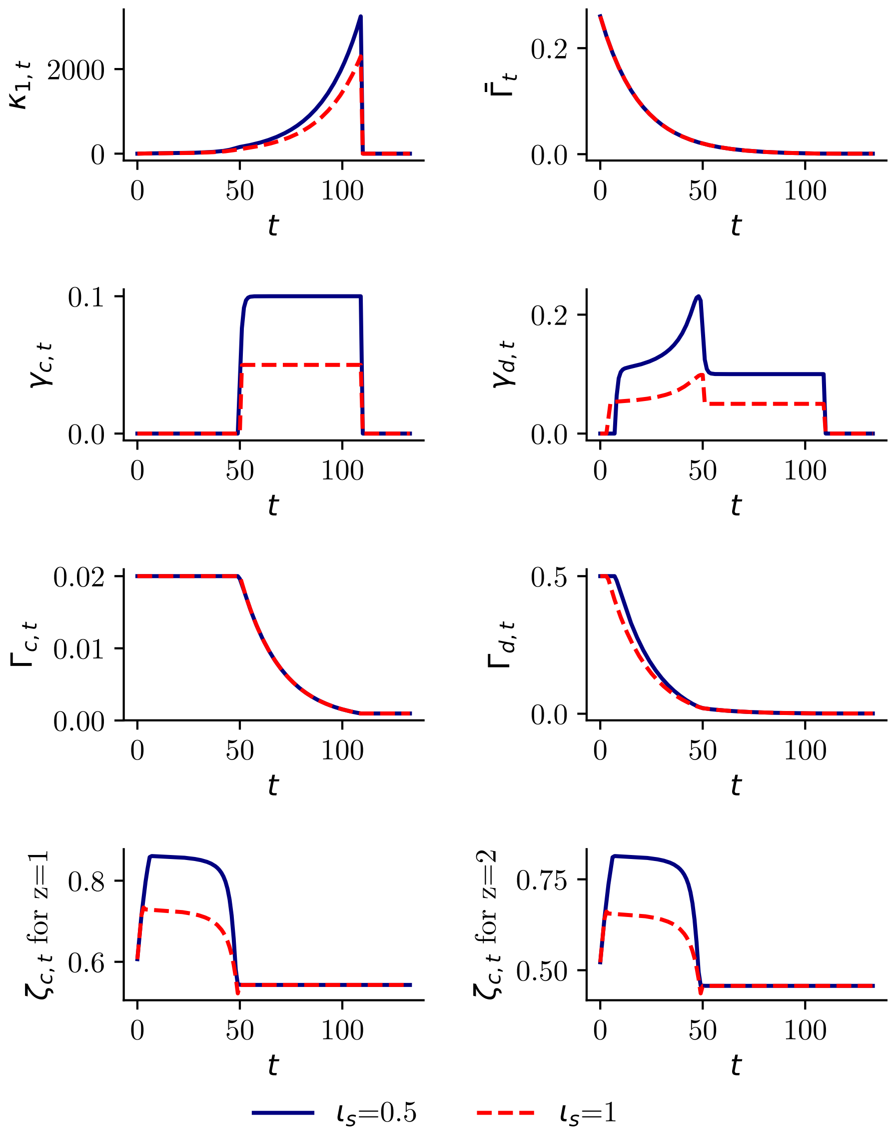

Figure 3: Optimal monetary policy and resulting allocations, for a 5 percent emission reduction target and an innovation impact factor of $\iota_s = 0.5$ and $\iota_s = 1$: the cost factor (upper left panel), the expected emission intensity (upper right panel), the sectoral innovation shares (upper center panels), the sectoral emission intensities (bottom center panels) and the capital share allocated to the clean sector in the two states (bottom panels).

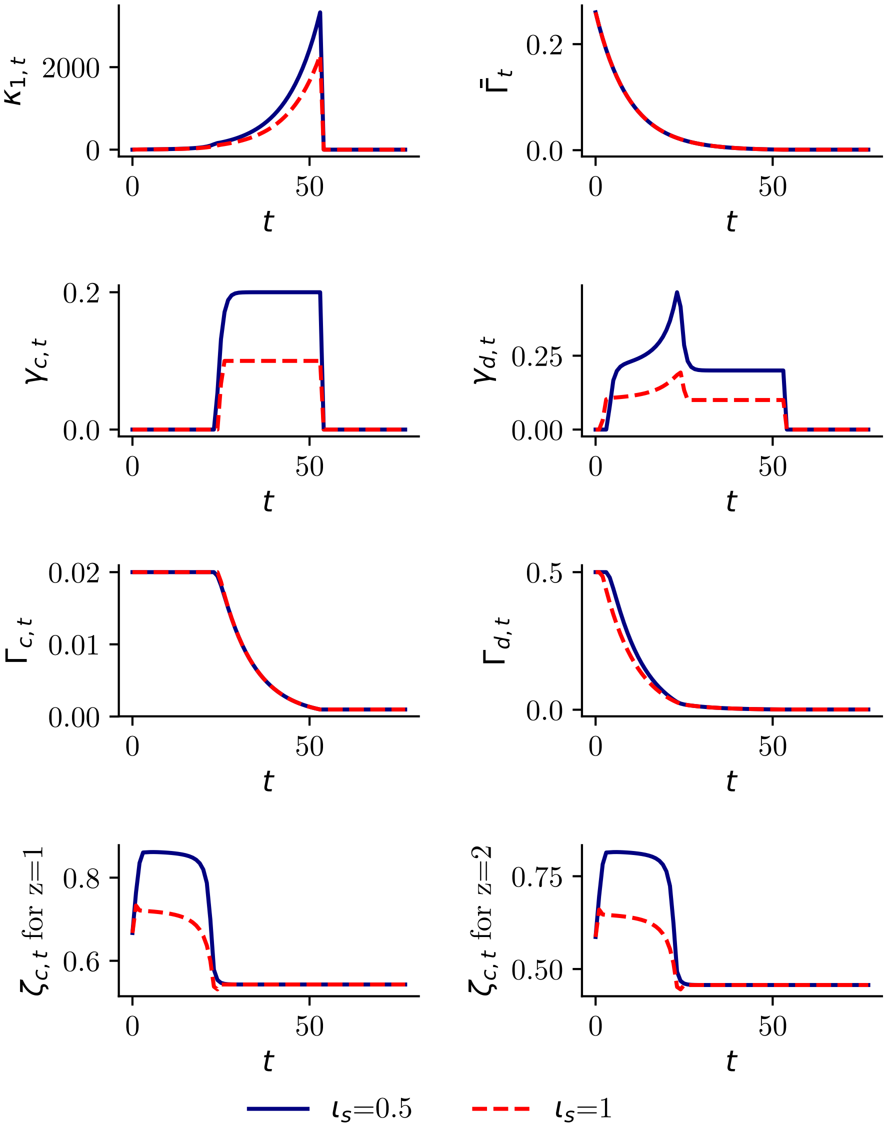

Figure 4: Optimal monetary policy and resulting allocations, for a 10 percent emission reduction target and an innovation impact factor of $\iota_s = 0.5$ and $\iota_s = 1$: the cost factor (upper left panel), the expected emission intensity (upper right panel), the sectoral innovation shares (upper center panels), the sectoral emission intensities (bottom center panels) and the capital share allocated to the clean sector in the two states (bottom panels).

that with a 5 (10) percent reduction target, temperature is 8 (9) percent lower in the year 2100 compared to the case in which no climate-oriented monetary policy is adopted. In the year, 2200 we find that temperature is reduced by 24 (25) percent compared to the case with no climate policies. Similarly, climate damage is reduced by 16 (17) percent in the year 2100 compared to the no policy case, if an emission reduction target of 5 (10) percent is applied. Finally, in the year 2200, climate damage is 42 (43) percent lower if the emission-based interest rate policy is adopted with a 5 (10) percent reduction target. Across the illustrated cases of different emission reduction targets and innovation impact factors, we find that the climate-oriented monetary policy is welfare decreasing. This might however be due to the fact that in our analysis the EA emissions constitute only a small fraction of global emissions and our welfare analysis excludes other countries, which may benefit from the climate-oriented monetary policy adopted within the EA. Our analysis should therefore be considered as an illustration of the mechanisms embedded in our framework, but is not suited to provide a reliable assessment of the welfare impact of the climate-oriented monetary policy. We aim to integrate a more comprehensive welfare analysis with a particular focus on the optimal climate-oriented monetary policy in future work.

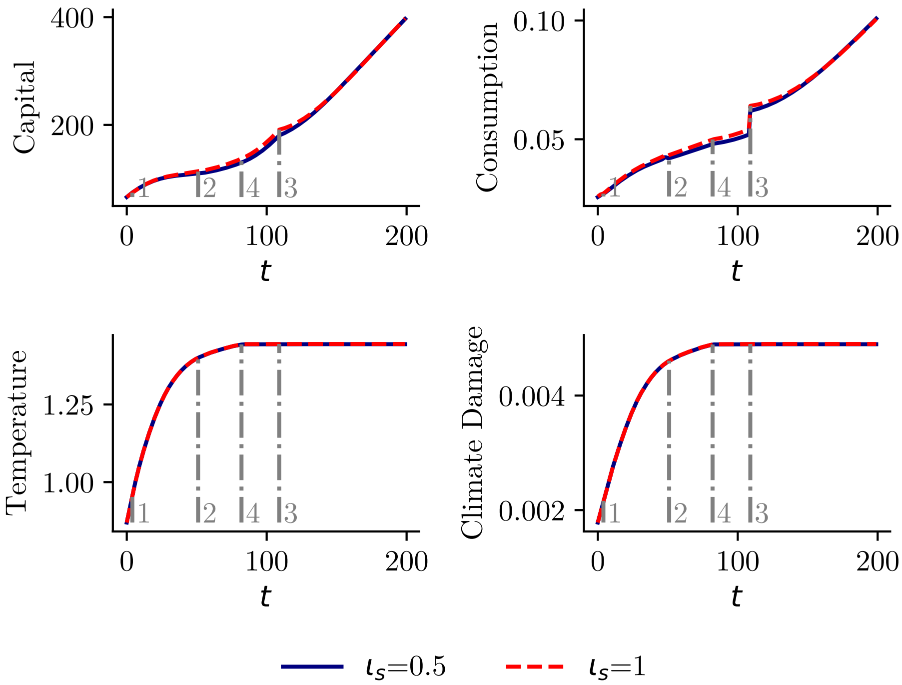

Figure 5: Expected capital accumulation, consumption, temperature and climate damage evolutions for a 5 percent emission reduction target and an innovation impact factor of $\iota_s = 0.5$ and $\iota_s = 1$.

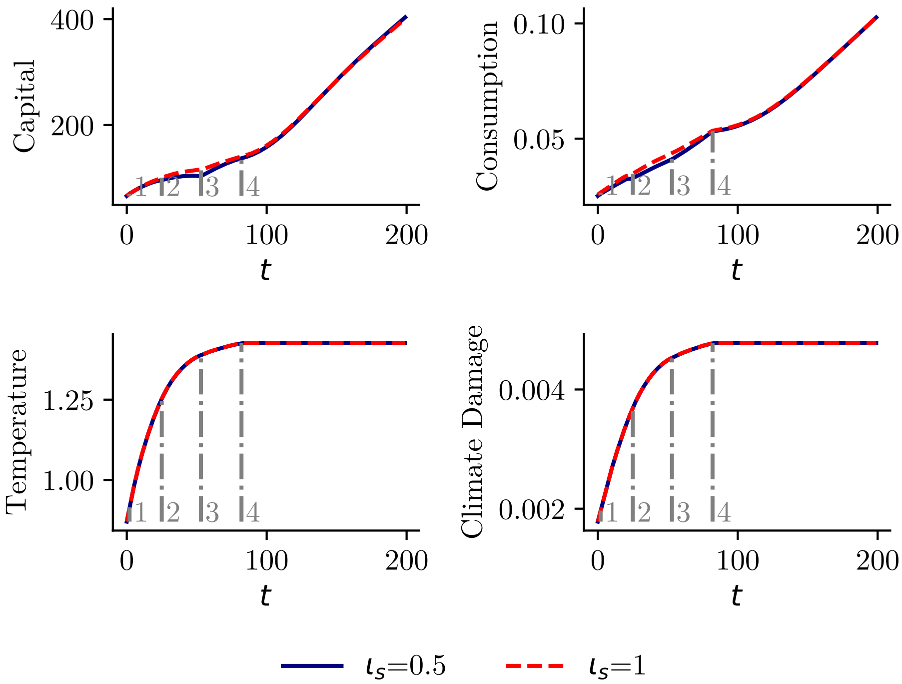

Figure 6: Expected capital accumulation, consumption, temperature and climate damage evolutions for a 10 percent emission reduction target and an innovation impact factor of $\iota_s = 0.5$ and $\iota_s = 1$.

7 Conclusion

Policies aiming at fostering the adoption of clean technologies and thus reducing the negative impact of carbon emissions have so far mostly taken the form of fiscal instruments, such as carbon taxes and cap-and-trade system for emission certificates. Although these instruments have been shown to be effective in reducing carbon emissions and promoting clean innovation, their viability has been questioned, mostly due to lack of political acceptability and distributive effects. This paves the way for the introduction of new instruments, which ensure that sufficient resources are allocated to sustainable projects. On this account, a more active role of the financial sector and specifically of central banks has been advocated by politicians, academics and central bankers themselves, as pioneered by the speech on "The Tragedy of the Horizon" held by the governor of the Bank of England in 2015. Through their impact on banks' investment decisions, central banks can indeed steer liquidity towards low-carbon activities and discourage production in more polluting sectors. Moreover, by adjusting their own investment guidelines central banks can have an even larger impact with regard to the decarbonization of the economy, as their portfolios currently overweight emission-intensive compared to low-carbon assets. There is no unique solution for a climate-oriented monetary policy and several options have been proposed. These range from green quantitative easing, in the form of purchases of low-carbon assets by central banks, to green reserve requirements, namely minimum reserve holdings of banks depending on the carbon footprint of the assets held by the individual institution, and to the integration of sustainability criteria into the collateral framework of central banks.

In the present paper, we focus on an alternative, yet unexplored approach. Specifically, we study the introduction of an emission-based interest policy adopted by the central bank, which aims at increasing the financing costs for dirty production activities. Indeed, such a monetary policy leads to higher liquidity costs for banks holding more emission-intensive asset portfolios, so that banks have an incentive to favor low-carbon assets. The adoption of the climate-oriented monetary policy is justified by the presence of damage on output caused by temperature increases, which, in turn, are due to carbon emissions generated in the course of production activities. Firms can devote a share of their inputs to the adoption of a cleaner technology reducing the emission intensity of the sector. This gives rise to a trade-off for the individual firm between lowering its financing costs and reducing its production capacity. The central bank aims at reducing the expected emission intensity of banks' loan portfolio. We calibrate our model using data from the Euro Area. Our findings show that the applied monetary policy is able to induce the adoption of cleaner technologies across the entire economy and reduces the expected emission intensity of the economy from 0.26 kilogram carbon dioxide per USD in 2018 to 0.001 in 2127 (2071), when applying a 5 (10) percent target for the annual reduction of the expected emission intensity of banks' loan portfolio.

To the best of our knowledge, this work represents the first attempt to integrate a climate-oriented monetary policy in a theoretical model. Accordingly, many extensions of the current framework can and need to be pursued. A key priority is to derive the optimal second-best policy adopted by the central bank. The integration of a more sophisticated climate module, as, for example, described in Nordhaus and Sztorc (2013), and the adoption of alternative damage function specifications, as shown in Bretschger and Karydas (2019) is also desirable. Moreover, the diffusion process of clean technologies should be improved. On this account, the heterogeneous innovation possibilities across sectors should be taken into account. In addition, alternative climate policies must be embedded in the current framework to provide a realistic assessment of the actual impact of a climate-oriented monetary policy. Finally, we aim to integrate the traditional goals of monetary policy, represented by price and economic stability, as objectives of the central bank.

References

Acemoglu, D., Aghion, P., Bursztyn, L., and Hemous, D. (2012). The environment and directed technical change. *American Economic Review*, 102(1):131–166.

Acemoglu, D., Akcigit, U., Hanley, D., and Kerr, W. (2016). Transition to clean technology. *Journal of Political Economy*, 124(1):52–104.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., and Van Reenen, J. (2016). Carbon taxes, path dependency, and directed technical change: evidence from the auto industry. *Journal of Political Economy*, 124(1):1–51.

Aglietta, M., Espagne, E., and Perrissin-Fabert, B. (2015). A proposal to finance low carbon investment in Europe. *France Stratégie: Paris*.

Ashcraft, A., Garleanu, N., and Pedersen, L. H. (2011). Two monetary tools: interest rates and haircuts. *NBER Macroeconomics Annual*, 25(1):143–180.

Baranzini, A., Van den Bergh, J. C., Carattini, S., Howarth, R. B., Padilla, E., and Roca, J. (2017). Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations. *Wiley Interdisciplinary Reviews: Climate Change*, 8(4):e462.

Batten, S., Sowerbutts, R., and Tanaka, M. (2016). Let's talk about the weather: the impact of climate change on central banks. *Bank of England Working Paper*.

Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., and Visentin, G. (2017). A climate stress test of the financial system. *Nature Climate Change*, 7(4):283–288.

Borissov, K., Brausmann, A., and Bretschger, L. (2019). Carbon pricing, technology transition, and skill-based development. *European Economic Review*.

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

Bretschger, L. and Karydas, C. (2019). Economics of climate change: introducing the basic climate economic (bce) model. *Environment and Development Economics*, pages 1–23.

Bundesbank, D. (2017). The role of banks, non-banks and the central bank in the money creation process. *Deutsche Bundesbank Monthly Report, April 2017,*, 69(4):13–33.

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

Campiglio, E., Dafermos, Y., Monnin, P., Ryan-Collins, J., Schotten, G., and Tanaka, M. (2018). Climate change challenges for central banks and financial regulators. *Nature Climate Change*, 8(6):462.

Carney, M. (2015). Breaking the tragedy of the horizon–climate change and financial stability. *Speech given at Lloyd's of London*, 29:220–230.

Coeure, B. (2018). Climate change and financial stability.

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

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

De Fiore, F. and Uhlig, H. (2011). Bank finance versus bond finance. *Journal of Money, Credit and Banking*, 43(7):1399–1421.

Den Haan, W. J. and Marcet, A. (1990). Solving the Stochastic Growth Model by Parameterizing Expectations. *Journal of Business & Economic Statistics*, 8(1):31–34.

Dietz, S., Bowen, A., Dixon, C., and Gradwell, P. (2016). Climate value at risk of global financial assets. *Nature Climate Change*, 6(7):676–679.

ECB (2019). Climate change and financial stability. *Financial Stability Review.*

Faure, S. and Gersbach, H. (2017). Money creation and destruction. *Working Paper.*

Fay, M., Hallegatte, S., Vogt-Schilb, A., Rozenberg, J., Narloch, U., and Kerr, T. (2015). *Decarbonizing development: Three steps to a zero-carbon future.* The World Bank.

Fender, I., McMorrow, M., Sahakyan, V., and Zulaica, O. (2019). Green bonds: the reserve management perspective. *BIS Quarterly Review, September.*

Fisher, P. and Alexander, K. (2019). Climate change: the role for central banks. *Working paper No. 2019/6.*

Gerlagh, R., van den Bijgaart, I., and Nijland, Hansand Michielsen, T. (2018). Fiscal policy and CO2 emissions of new passenger cars in the EU. *Environmental and Resource Economics*, 69(1):103–134.

Gersbach, H. and Winkler, R. (2011). International emission permit markets with refunding. *European Economic Review*, 55(6):759–773.

Goulder, L. H. and Schein, A. R. (2013). Carbon taxes versus cap and trade: a critical review. *Climate Change Economics*, 4(03):1350010.

Greaker, M. and Hagem, C. (2014). Strategic investment in climate friendly technologies: the impact of global emissions trading. *Environmental and Resource Economics*, 59(1):65–85.

Greaker, M., Heggedal, T.-R., and Rosendahl, K. E. (2018). Environmental policy and the direction of technical change. *The Scandinavian Journal of Economics*, 120(4):1100–1138.

IEA (2012). Energy technologies perspective 2012. https://www.iea.org/etp/publications/etp2012/.

IMF (2019). Fiscal policies for Paris climate strategies–From principle to practice. https://www.imf.org/en/Publications/Policy-Papers/Issues/2019/05/01/Fiscal-Policies-for-Paris-Climate-Strategies-from-Principle-to-Practice-46826.

IPCC (2018). Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Technical report, IPCC.

Jourdan, S. and Kalinowski, W. (2019). Aligning monetary policy with the EU's climate targets. *Working Paper*.

Krogstrup, S. and Oman, W. (2019). *Macroeconomic and Financial Policies for Climate Change Mitigation: A Review of the Literature*. International Monetary Fund.

Maestre-Andrés, S., Drews, S., and van den Bergh, J. (2019). Perceived fairness and public acceptability of carbon pricing: a review of the literature. *Climate Policy*, 19(9):1186–1204.

Maliar, L., Maliar, S., et al. (2001). *Parametrized Expectations Algorithm and the Moving Bounds*. Instituto Valenciano de Investigaciones Económicas.

Matikainen, S., Campiglio, E., and Zenghelis, D. (2017). The climate impact of quantitative easing. *Policy Paper, Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science*.

Matthews, H. D., Gillett, N. P., Stott, P. A., and Zickfeld, K. (2009). The proportionality of global warming to cumulative carbon emissions. *Nature*, 459(7248):829.

McKinsey (2010). Impact of the financial crisis on carbon economics. https://www.mckinsey.com/business-functions/sustainability/our-insights/impact-of-the-financial-crisis-on-carbon-economics-version-21.

McLeay, M., Radia, A., and Thomas, R. (2014). Money creation in the modern economy. *Bank of England Quarterly Bulletin*, page Q1.

Monnin, P. (2018a). Central banks and the transition to a low-carbon economy. *Council On Economic Policies, Discussion Note*, 1.

Monnin, P. (2018b). Integrating climate risks into credit risk assessment. current methodologies and the case of central banks corporate bond purchases. *Discussion Note 2018/4*.

Nagel, S. (2016). The liquidity premium of near-money assets. *The Quarterly Journal of Economics*, 131(4):1927–1971.

NGFS (2019). A Call for Action: Climate Change as a Source of Financial Risk. *Network for Greening the Financial System*.

Nordhaus, W. and Sztorc, P. (2013). DICE 2013R: introduction and user's manual.

Nordhaus, W. D. (2013). *The climate casino: risk, uncertainty, and economics for a warming world*. Yale University Press.

Nyborg, K. G. (2017). Central bank collateral frameworks. *Journal of Banking & Finance*, 76:198–214.

OECD (2017). *Investing in Climate, Investing in Growth*.

Proença, S. and Aubyn, M. S. (2013). Hybrid modeling to support energy-climate policy: effects of feed-in tariffs to promote renewable energy in portugal. *Energy Economics*, 38:176–185.

Ramstein, C., Dominioni, G., Ettehad, S., Lam, L., Quant, M., Zhang, J., Mark, L., Nierop, S., Berg, T., Leuschner, P., et al. (2019). State and trends of carbon pricing 2019. *The World Bank*.

Rozenberg, J., Hallegatte, S., Perrissin-Fabert, B., and Hourcade, J.-C. (2013). Funding low-carbon investments in the absence of a carbon tax. *Climate Policy*, 13(1):134–141.

Sachs, J., Guerin, E., Mas, C., Schmidt-Traub, G., Tubiana, L., Waisman, H., Colombier, M., Bulger, C., Sulakshana, E., Zhang, K., et al. (2014). Pathways to deep decarbonization. *2014 Report*.

Schmidt, T. S. (2014). Low-carbon investment risks and de-risking. *Nature Climate Change*, 4(4):237.

Schoenmaker, D. (2019). Greening monetary policy. *CEPR Discussion Paper No. DP13576*.

Schoenmaker, D. and Van Tilburg, R. (2016). What role for financial supervisors in addressing environmental risks? *Comparative Economic Studies*, 58(3):317–334.

Stolbova, V., Monasterolo, I., and Battiston, S. (2018). A financial macro-network approach to climate policy evaluation. *Ecological Economics*, 149:239–253.

TCFD (2017). Recommendations of the Task Force on Climate-related Financial Disclosures. *Network for Greening the Financial System.*

Volz, U. (2017). On the role of central banks in enhancing green finance. *UN Environment Inquiry Working Paper 17/01.*

WEF (2013). The green investment report. http://reports.weforum.org/green-investing-2013/.

Weitzman, M. L. (2014). Can negotiating a uniform carbon price help to internalize the global warming externality? *Journal of the Association of Environmental and Resource Economists*, 1(1/2):29–49.

A Mathematical derivations

A.1 The optimization problem of firms

Note that the Cobb-Douglas production function of firms satisfies the Inada conditions, so that firms choose positive capital and labor inputs for production, ruling out the extreme case where they only devote capital to the adoption of a new technology, that is, $\gamma_{s,t} < 1$. Thus, when solving the optimization problem of firms, we only need to account for the non-negativity constraint on $\gamma_{s,t}$. The Karush-Kuhn-Tucker (KKT) conditions are then given by equations (3), (4), (5), the non-negativity constraint on the share $\gamma_{s,t}$ and on the KKT multiplier $\mu_{s,t}$, as well as the complementary slackness condition $\mu_{s,t}\gamma_{s,t} = 0$. Equating the first-order conditions with respect to capital (4) of two different sectors $s, \bar{s} \in \mathcal{S}$, we obtain

$$K_{\bar{s},t} = \left[\frac{A_s(z_t)}{A_{\bar{s}}(z_t)} \frac{\bar{\gamma}_{s,t}^{\alpha}}{\bar{\gamma}_{\bar{s},t}^{\alpha}} \frac{N_{s,t}^{1-\alpha}}{N_{\bar{s},t}^{1-\alpha}} \frac{R_{\bar{s},t}^{L}}{R_{s,t}^{L}} \right]^{\frac{1}{\alpha-1}} K_{s,t}.$$

Using $R_{s,t}^{L} = R_{CB,t}^{D}[1 + \psi_t \kappa_t(\Gamma_{s,t}) - \psi_t]$ and the notation $K_{s,t} = \zeta_{s,t} K_t$, we obtain

$$\zeta_{\bar{s},t} = \left[\frac{A_s(z_t)}{A_{\bar{s}}(z_t)} \frac{\bar{\gamma}_{s,t}^{\alpha}}{\bar{\gamma}_{\bar{s},t}^{\alpha}} \frac{N_{s,t}^{1-\alpha}}{N_{\bar{s},t}^{1-\alpha}} \frac{1 + \psi_t \kappa_t(\Gamma_{\bar{s},t}) - \psi_t}{1 + \psi_t \kappa_t(\Gamma_{s,t}) - \psi_t} \right]^{\frac{1}{\alpha-1}} \zeta_{s,t}.$$

Summing these equations over all $\bar{s} \in \mathcal{S}$, yields

$$1 = \left(\sum_{\bar{s} \in \mathcal{S}} \left[\frac{A_s(z_t)}{A_{\bar{s}}(z_t)} \frac{\bar{\gamma}_{s,t}^{\alpha}}{\bar{\gamma}_{\bar{s},t}^{\alpha}} \frac{N_{s,t}^{1-\alpha}}{N_{\bar{s},t}^{1-\alpha}} \frac{1 + \psi_t \kappa_t(\Gamma_{\bar{s},t}) - \psi_t}{1 + \psi_t \kappa_t(\Gamma_{s,t}) - \psi_t} \right]^{\frac{1}{\alpha-1}} \right) \zeta_{s,t},$$

as given by equation (6) in the text. We now turn to the decision of firms to adopt a cleaner technology. Given the loan rate $R_{s,t}^{L} = R_{CB,t}^{D}[1 + \psi_t \kappa_t(\Gamma_{s,t}) - \psi_t]$, we obtain

$$\begin{aligned} \frac{\partial R_{s,t}^{L}}{\partial \gamma_{s,t}} &= R_{CB,t}^{D} \psi_t \frac{\partial \kappa_t(\Gamma_{s,t})}{\partial \Gamma_{s,t}} \frac{\partial \Gamma_{s,t}}{\partial \gamma_{s,t}} \\ &= R_{CB,t}^{D} \psi_t \kappa_{1,t} \kappa_t(\Gamma_{s,t})(-\iota_s \Gamma_{s,t-1}). \end{aligned}$$

For any interior solution $\gamma_{s,t} \in (0,1)$, the first-order condition (3) reads as

$$\alpha \tilde{A}_{s,t} \bar{\gamma}_{s,t}^{\alpha-1} K_{s,t}^{\alpha-1} N_{s,t}^{1-\alpha} = q_t R_{CB,t}^{D} \psi_t \kappa_{1,t} \kappa_t(\Gamma_{s,t}) \iota_s \Gamma_{s,t-1},$$

as the KKT multiplier $\mu_{s,t} = 0$. Combining this equation with the first-order condition with respect to capital (4), we obtain the optimal adoption level chosen by firms. For $\gamma_{s,t} = 0$, the first-order conditions with respect to $\gamma_{s,t}$ and $K_{s,t}$ reduce to

$$\alpha \tilde{A}_{s,t} K_{s,t}^{\alpha} N_{s,t}^{1-\alpha} = q_t K_{s,t} R_{CB,t}^{D} \psi_t \kappa_{1,t} \kappa_t(\Gamma_{s,t-1}) \iota_s \Gamma_{s,t-1} + \mu_{s,t}$$

and

$$\alpha \tilde{A}_{s,t} K_{s,t}^{\alpha} N_{s,t}^{1-\alpha} = q_t K_{s,t} R_{CB,t}^{D} [1 + \psi_t \kappa_t(\Gamma_{s,t-1}) - \psi_t],$$

respectively, which together yield the KKT multiplier

$$\mu_{s,t} = q_t K_{s,t} R_{CB,t}^{D} \{1 - \psi_t [1 + (\kappa_{1,t} \iota_s \Gamma_{s,t-1} - 1) \kappa_t(\Gamma_{s,t-1})]\} > 0.$$

Thus, the choice of adopting a cleaner technology is generally described by

$$\gamma_{s,t} = \max \left\{ \frac{\psi_t [1 + (\kappa_{1,t} \iota_s \Gamma_{s,t-1} - 1) \kappa_t(\Gamma_{s,t})] - 1}{\psi_t \kappa_{1,t} \iota_s \Gamma_{s,t-1} \kappa_t(\Gamma_{s,t})}, 0 \right\},$$

and the KKT multiplier is given by

$$\mu_{s,t} = q_t K_{s,t} R_{CB,t}^{D} \max\{1 - \psi_t [1 + (\kappa_{1,t} \iota_s \Gamma_{s,t-1} - 1) \kappa_t(\Gamma_{s,t-1})], 0\}.$$

Note that

$$\alpha \bar{\gamma}_{s,t}^{\alpha} K_{s,t}^{\alpha-1} N_{s,t}^{1-\alpha} \tilde{A}_{s,t} = \frac{\alpha \tilde{Y}_{s,t}}{K_{s,t}} \quad \text{and} \quad (1-\alpha) \bar{\gamma}_{s,t}^{\alpha} K_{s,t}^{\alpha} N_{s,t}^{-\alpha} \tilde{A}_{s,t} = \frac{(1-\alpha) \tilde{Y}_{s,t}}{N_{s,t}}.$$

Using this fact, it is straightforward to derive equations (8) in the paper, from the first-order conditions with respect to capital and labor. The loans provided to sector s are therefore given by

$$L_{s,t} = Q_t K_{s,t} + W_{s,t} N_{s,t} = \frac{P_t \tilde{Y}_{s,t}}{R_{s,t}^{L}},$$

which leads to the conclusion that firms make zero profits.

A.2 The optimization problem of households

We show that any nominal output good price satisfies the budget constraint of the household, while imposing market clearing for the single output good. First, note that firms and banks make zero profits, that is, $\Pi_t^F = \Pi_t^B = 0$. The constraint faced by the household, when optimizing, is therefore given by

$$P_t (C_t + K_{t+1}) = R_{CB,t}^{D} (Q_t K_t + W_t N_t) + (1-\delta) P_t K_t + \Pi_t^{CB}.$$

With the central bank seigniorage given by

$$\Pi_t^{CB} = \psi_t R_{CB,t}^D \sum_{s\in\mathcal{S}} [\kappa_t(\Gamma_{s,t}) - 1] L_{s,t},$$

and given that the household's income can be rewritten as

$$Q_t K_t + W_t N_t = \sum_{s\in\mathcal{S}} (Q_t K_{s,t} + W_{s,t} N_{s,t}) = \sum_{s\in\mathcal{S}} L_{s,t},$$

the constraint faced by the household reads

$$P_t(C_t + K_{t+1}) = R_{CB,t}^D \sum_{s\in\mathcal{S}} [1 + \psi_t \kappa_t(\Gamma_{s,t}) - \psi_t] L_{s,t} + (1-\delta) P_t K_t.$$

Noting that, as before, loans in each sector can be rewritten as

$$L_{s,t} = \frac{P_t \tilde{Y}_{s,t}}{R_{s,t}^L},$$

where $R_{s,t}^L = R_{CB,t}^D [1 + \psi_t \kappa_t(\Gamma_{s,t}) - \psi_t]$, the constraint of the household is given by

$$C_t + K_{t+1} = \tilde{Y}_t + (1-\delta) K_t,$$

where we used the market clearing condition $\tilde{Y}_t = \sum_{s\in\mathcal{S}} \tilde{Y}_{s,t}$.

B Industrial classification system

We have used the statistical classification of economic activities in the European Community (NACE) as adopted by Eurostat, which represents the classification of economic activities adopted in the European Union.[20] The NACE code is subdivided in a hierarchical, four-level structure. The categories at the highest level are called sections. The first two digits of the code identify the division, the third digit identifies the group, and the fourth digit identifies the class. For the scope of our study, however, we only used the most aggregated 1-digit level, as reported below. Given our computations related to the median emission intensity across sectors in the EA, we aggregate in the clean sector the economic activities **M** to **S**, whereas the dirty sector comprises the activities **A** to **I**. The remaining economic activities were excluded from the analysis because of the lack of available data.

[20] The NACE Rev. 2, the mostly recently revised classification whose implementation began in 2007, is available at https://ec.europa.eu/eurostat/documents/3859598/5902521/KS-RA-07-015-EN.PDF.

Code	**Economic activities: 1-digit**
A	Agriculture, forestry and fishing
B	Mining and quarrying
C	Manufacturing
D	Electricity, gas, steam and air conditioning supply
E	Water supply; sewerage, waste management and remediation activities
F	Construction
G	Wholesale and retail trade; repair of motor vehicles and motorcycles
H	Transportation and storage
I	Accommodation and food service activities
J	Information and communication
K	Financial and insurance activities
L	Real estate activities
M	Professional, scientific and technical activities
N	Administrative and support service activities
O	Public administration and defense; compulsory social security
P	Education
Q	Human health and social work activities
R	Arts, entertainment and recreation
S	Other service activities
T	Activities of households as employers
U	Activities of extraterritorial organisations and bodies

Table 1: NACE classification.

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(PDF-files of the Working Papers can be downloaded at www.cer.ethz.ch/research/working-papers.html).

20/337 F. Böser, C. Colesanti Senni
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Corona Fatality Development and the Environment: Empirical Evidence for OECD Countries

20/335 M. Arvaniti, W. Habla
The Political Economy of Negotiating International Carbon Markets

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A model-based clustering approach for analyzing energy-related financial literacy and its determinants

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Buffering Volatility: Storage Investments and Technology-Specific Renewable Energy Support

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Negotiating with frictions

19/308 H. Gersbach and S. Papageorgiou
On Banking Regulation and Lobbying

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