INSTITUTE OF ECONOMICS

Scuola Superiore Sant'Anna

LEM | Laboratory of Economics and Management

Institute of Economics
Scuola Superiore Sant'Anna

Piazza Martiri della Libertà, 33 - 56127 Pisa, Italy
ph. +39 050 88.33.43
institute.economics@sssup.it

LEM

WORKING PAPER SERIES

Three green financial policies to address climate risks

Francesco Lamperti [a,d]
Valentina Bosetti [b,d]
Andrea Roventini [a,e]
Massimo Tavoni [c,d]
Tania Treibich [f,a]

[a] Institute of Economics and EMbeDS, Scuola Superiore Sant'Anna, Pisa, Italy.
[b] Bocconi University, Milan, Italy.
[c] Politecnico di Milano, School of Management, Italy.
[d] RFF-CMCC European Institute on Economics and the Environment, Milan, Italy.
[e] OFCE Sciences-Po, Sophia Antipolis, France.
[f] School of Business and Economics, Maastricht University, The Netherlands.

This paper is forthcoming in the Journal of Financial Stability.

2021/05 February 2021

ISSN(ONLINE) 2284-0400

Three green financial policies to address climate risks

Francesco LAMPERTI[*] Valentina BOSETTI[†] Andrea ROVENTINI[‡] Massimo TAVONI[§] Tania TREIBICH[¶]

February 3, 2021

Abstract

Which policies can increase the resilience of the financial system to climate risks? Recent evidence on the significant impacts of climate change and natural disasters on firms, banks and other financial institutions call for a prompt policy response. In this paper, we employ a macro-financial agent-based model to study the interaction between climate change, credit and economic dynamics and test a mix of policy interventions. We first show that financial constraints exacerbate the impact of climate shocks on the economy while, at the same time, climate damages to firms make the banking sector more prone to crises. We find that credit provision can both increase firms' productivity and their financial fragility, with such a trade-off being exacerbated by the effects of climate change. We then test a set of "green" finance policies addressing these risks, while fostering climate change mitigation: i) *green Basel-type* capital requirements, ii) *green public guarantees* to credit, and iii) *carbon-risk adjustment* in credit ratings. All the three policies reduce carbon emissions and the resulting climate impacts, though moderately. However, their effects on financial and real dynamics is not straightforwardly positive. Some combinations of policies fuel credit booms, exacerbating financial instability and increasing public debt. We show that the combination of all three policies leads to a virtuous cycle of (mild) emission reductions, stable financial sector and high economic growth. Additional tools would be needed to fully adapt to climate change. Hence, our results point to the need to complement financial policies cooling down climate-related risks with mitigation policies curbing emissions from real economic activities.

Keywords: Climate change; endogenous growth; financial stability; macroprudential policy; agent-based model.

JEL classification: C63; E5; O44; Q5.

[*]Corresponding author - Institute of Economics and EMbeDS, Scuola Superiore Sant'Anna, piazza Martiri della Libertà 33, 56127 Pisa (Italy) and RFF-CMCC European Institute on Economics and the Environment, via Bergognone 34, 20144 Milano (Italy); f.lamperti[at]santannapisa.it

[†]Bocconi University and RFF-CMCC European Institute on Economics and the Environment

[‡]Institute of Economics and EMbeDS, Scuola Superiore Sant'Anna and OFCE-Sciences Po

[§]Politecnico di Milano and RFF-CMCC European Institute on Economics and the Environment

[¶]School of Business and Economics, Maastricht University, Institute of Economics and EMbeDS, Scuola Superiore Sant'Anna and OFCE-Sciences Po

1 Introduction

An increasing body of literature shows that unmitigated climate change will significantly impact a number of economic variables, ranging from agricultural yields and electricity production to labor and capital productivity, with ineluctable ripple effects on multiple sectors, including the financial one. Following the first calls for attention (Dietz et al., 2016; Battiston et al., 2017), scholars and policy-makers have recently envisaged an active role of financial institutions and financial regulators in shaping both (i) climate risk-management (Campiglio et al., 2018; Battiston and Monasterolo, 2020a; Monasterolo, 2020), and (ii) the transition to low-carbon technologies and production (Campiglio, 2016; D'Orazio and Popoyan, 2019; Monasterolo and Raberto, 2018; Lamperti et al., 2019). Indeed, the financial and banking systems have a key role in the inter-relation between climate risks and the real economy. On the one side, banks can be more or less vulnerable to increases in volatility and bankruptcies stemming from climate shocks hitting borrowing firms. On the other side, via credit selection, they can channel resources either to "green" or "brown" projects, thus affecting the likelihood of transition to sustainable growth. From a policy perspective, different interventions can be designed to mitigate climate risk, encompassing information disclosure, macro-prudential adjustments and additional stress-testing. However, to the best of the authors' knowledge, the available evidence on how green financial regulations might help mitigate emissions and preserve banking-sector stability in the face of climate risks is rather scant.

For this reason, we build on a climate-economy macroeconomic agent-based model to study the co-evolution of climate change, financial (in)stability and the real economy, and assess the effects of a set of three green financial policy tools fostering carbon emission mitigation, as well as long-run financial and economic stability.[1] In particular, this paper tackles the relationship between credit provision mechanisms towards green businesses, the ensuing risks for banking sector stability and the impact of potentially unmitigated climate damages.

Our model allows for a realistic representation of the interactions between firms and the banking system on the one hand, and of climate damages at the micro-level on the other. While relevant for the analysis of a low-carbon transition and for impact assessment, these aspects usually lacks both in the ecological macroeconomic literature (see Rezai and Stagl, 2016 for a review) and in the stream of contributions rooted in dynamic general equilibrium models (DSGEs; see Golosov et al., 2014; Hassler and Krusell, 2018); Differently, the literature on computable general equilibrium integrated assessment models (IAMs) (Weyant, 2017) has made large progresses in describing mitigation pathways and the

[1]On macroeconomic agent-based models see Fagiolo and Roventini (2017a) and Dawid and Delli Gatti (2018). See also Dosi and Roventini (2019) for a discussion of ABMs from the perspective of macroeconomic history.

effects of climate change, but it almost completely overlooks the role of - and the risks for - financial institutions. Notably, Battiston et al. (2017) and Battiston and Monasterolo (2020a) combines IAMs' projections and economic data from relevant sectors to estimate the climate-related risks borne by various financial actors. Several agent-based macroeconomic models have been recently developed to uncover the links between climate change, the evolution of the energy sector, the banking system and different levels of economic performance (see Gerst et al., 2013; Hasselmann and Kovalevsky, 2013; Wolf et al., 2013; Safarzyńska and van den Bergh, 2016; Ponta et al., 2018 and the survey by Balint et al., 2017). While sticking to aggregate modelling, also scholars form the stock-flow consistent (SFC) tradition have contributed to the analysis of low-carbon transitions (Dafermos et al., 2017; Monasterolo and Raberto, 2018; Naqvi and Stockhammer, 2018; Carnevali et al., 2020), enhancing our understanding of the macro-financial consequences of resource use, environmental depletion and movements in labour productivity and energy intensity (Rezai and Stagl, 2016). Notwithstanding fundamental differences in the modelling philosophy, it is worth stressing that both the agent-based and ecological macroeconomic literatures have historically adopted a dis-equilibrium interpretation of economic dynamics, with large emphasis on the role of innovation, investment and credit provision as destabilising yet fundamental ingredients of economic change. These similarities often led complementary policy conclusions (see the discussion in Mercure et al., 2016 and Monasterolo et al., 2019), while DSGEs typically suggested opposite implications rooted in the internalisation of climate-related externalities. Moving from such different angles, the analysis of financial regulation for climate risks seems still in its infancy, with a variety mechanisms to be uncovered (Krogstrup and Oman, 2019).

The present paper offers, to the best of the authors' knowledge, a novel perspective on three green financial policies: i) *green Basel-type* capital requirements, ii) *green credit guarantees*, and iii) *carbon-emission adjustment* in credit ratings. These mechanisms are introduced in the context of an established model (labelled as *DSK*) of climate-economy-finance interactions (Lamperti et al., 2018b, 2019) to modify the allocation of financial resources across agents and production activities. While the model has been previously employed for the study of climate impacts on the economy, its use for policy analysis is a novelty. In contrast to the majority of climate policy designs, which construct sets of taxes and subsidies, we focus on regulation-based mechanisms that alter banks' balance sheets in terms of composition, size and risk exposure (more in section 2). The core of the model couples a Schumpeterian endogenous innovation engine with a Keynesian demand-generation process in line with the K+S family of models (Dosi et al., 2010, 2013, 2015).[2] Firms in the economic system strive to improve their production techniques through

[2] We invite the interested reader to look at Dosi et al. (2017) and Dosi et al. (2018) for two recent applications of the model to labor market issues.

innovation and imitation activities as well investments in novel capital goods. Climate change adversely impacts the productivity of labor and the capital stock of firms. To model climate-induced losses we employ a stochastic formulation of the loss function employed in a recent version of Nordhaus' DICE model (Nordhaus, 2017). Such function expresses a percentage loss in either labor productivity or capital stock for every temperature variation with respect to pre-industrial levels and has been extended to account for heterogeneity. Notwithstanding they offer a widely used benchmark, we acknowledge a series of limitations of DICE-type damage functions (e.g. they are estimated on cross-sectional data; they just depend on the mean surface temperature; they ignore heterogeneity of adaptation responses). The debate on damage modelling is currently lively but unsolved (Diaz and Moore, 2017). Global warming linearly depends on cumulative carbon emissions that, in turn, follow from firms' choices regarding production and investment in green technologies, as well as the development and diffusion of green energy plants. Our modeling of the carbon-climate-damage relationship follows a similar approach to small-scale macro models of the economy and the climate (e.g. Nordhaus, 2017; Golosov et al., 2014). In such a context, an element of novelty is provided by heterogeneous banks that supply credit to firms, thus conditioning the level of economic activity and the diffusion of green capital goods. By leveraging on the credit channel, we study how financial regulation can affect emission mitigation as well as banking stability, where the latter is threatened by both credit and climate-related risks.

Model validation is performed via a simple calibration and stylized fact replication procedure. Simulation results show that the DSK model is able to jointly reproduce a large ensemble micro and macro regularities concerning credit and real dynamics. Moreover, in a business-as-usual (BAU) scenario, the model projects temperature anomalies consistent with a SSP 5 - RCP 8.5 scenario (Riahi et al., 2011, 2017), where climate-related impacts considerably worsen the growth performance of the economy, while spurring volatility and unemployment (similarly to the dynamics already observed in Lamperti et al., 2019).[3]

The main contribution of the present work is a careful inspection of the three green credit policies mentioned above, both in isolation and in a policy mix. As a concept proof of model functioning, we first investigate the finance-climate nexus by exogenously changing credit conditions, that is, by altering the Basel-like macroprudential limit to credit creation. In that, we single out the two main mechanisms

[3]RCP stands for Representative Concentration Pathway and represents a greenhouse gases concentration trajectory throughout the 21st century. Four RCPs have been developed to characterize different possible climatic futures; more information at http://www.iiasa.ac.at/web-apps/tnt/RcpDb. SSPs stand for Shared-Socio Economic Pathways and represents scenarios coupling climate and socio-economic information. The framework is built around a conceptual matrix that combines climate forcing on one axis (as represented by the Representative Concentration Pathways) and socio-economic conditions on the other. Together, these two axes describe situations in which mitigation, adaptation and residual climate damage can be evaluated. More information at https://tntcat.iiasa.ac.at/SspDb.

induced by credit provision in our model: a *productivity-enhancing* effect linked to investment in more productive and greener capital goods, and a *fragility-enhancing* effect due to increased leverage. We find that financial constraints exacerbate the impact of climate shocks on the economy, while at the same time climate damages to firms make the banking sector more prone to crises. Secondly, we study how green financial policies alter these mechanisms and, hence, the aggregate dynamics. Results show that each of these policies - taken alone - is self-defeating (it either hampers growth, financial stability or raises emissions growth). However, a policy mix comprising all of them solves the trade-off allowing the economy to enter a win-win-win virtuous cycle. In short, while green Basel-type requirements exacerbate the productivity-enhancing effect and spur growth, carbon risk adjustment and green (public) credit guarantee aggregate emissions cuts, with the latter instrument also cushioning the fragility-enhancing effect. In that, green financial policies can contribute to achieve sustainable and resilient growth patterns.

The paper is organized as follows. Section 2 provides a brief review of the relevant literature; Section 3 describes the model employed for the simulation experiments; Section 4 provides evidence of the main relationships between climate change, economic and financial dynamics; Section 5 tests and discusses green financial policies. Finally, Section 6 concludes the paper.

2 Review of a nascent literature

This section offers a brief overview of the nascent literature on the financial impacts of climate change and the role of financial regulators and governments in addressing climate risks.

As emphasized in Dell et al. (2014), the idea that rising temperatures and other weather events could adversely affect economic activities is an old one, featured prominently in the writings of the Ancient Greeks, Romans and - later - during the Enlightenment, when Montesquieu reported in The Spirit of Laws (1748)[4] that an "excess of heat" made men "slothful and dispirited". Strong and robust evidence on the detrimental effect of climate change (and related extreme events) on labor productivity, aggregate output, energy requirements, agricultural yields, crime, or fertility has been reported (see the surveys in Dell et al., 2012, 2014; Carleton and Hsiang, 2016). Yet, despite the strong and increasing connections between real and financial activities, the possible impacts of climate change on financial institutions and financial markets have only been studied very recently.

In 2015, the Governor of the Bank of England, Mark Carney, acknowledged in a speech[5] the presence of three types of climate-related risks that might affect the financial system. First, *physical risks*, i.e.

[4]The book is currently edited as Montesquieu (1748).

[5]Speech from September 2015 to the insurance market Lloyd's of London.

the direct impact (today) of climate change on insurance liabilities and the value of financial assets that arise from climate- and weather-related events, such as floods and storms that damage property or disrupt trade. Second, *liability risks*, i.e. the impacts that could arise tomorrow if parties who have suffered loss or damage from the effects of climate change seek compensation and, finally, *transition risks*, which encompass the financial risks which could result from the process of adjustment towards a lower-carbon economy. This includes for example, changes in policy, technology and physical risks which could prompt a reassessment of the value of a large range of assets as costs and opportunities become apparent.

The last category is probably the one that has received the most attention - both across the scientific literature and the media - because of the so-called *stranded assets*, i.e. assets that are at risk of losing value due to climate change mitigation objectives (Leaton, 2012). Recent estimates find that potential large losses may occur. Following McGlade and Ekins (2015), emission trajectories consistent with a two degrees target requites a large portion of oil, gas and coal reserves to remain in the ground. The Carbon Tracker Initiative reported that the stranded assets already present in the fossil fuel sector alone amount to $1300bn, and $25,000bn of fossil fuels' built assets will be stranded by 2100 (CTI, 2018). Notwithstanding such risks, there are claims that the current pipeline of power plant investments is not compatible with the targets of the Paris agreement (Pfeiffer et al., 2018). The macroeconomic impacts of carbon assets' stranding will likely be substantial. In a preliminary evaluation Mercure et al. (2018) report that a discounted global wealth loss of 1 to 4 trillion dollars may emerge. In addition, there would be important distributional impacts, with winner and looser countries. Finally, the systemic interconnections of financial institutions holding stranded assets in their balance-sheets could exacerbate losses and induce financial contagion dynamics (Battiston et al., 2017; Safarzyńska and van den Bergh, 2017; Stolbova et al., 2018; Battiston and Monasterolo, 2020b).

The other two categories of climate risks refer to direct losses in the value of financial assets due to climate- and weather-related events (i.e. physical risks), and the impacts that could subsequently arise if parties suffering losses or damages ask for some form of compensation (i.e. liability risks). A battery of recent studies have highlighted the financial system's exposure to such risks, yet none of them examines the public costs of the ensuing instability. Dietz et al. (2016) document a skewed distribution of climate-induced losses in the value of financial assets along with a business-as-usual emissions path, with the 99^{th} percentile amounting to a 18.9% write-down of the value of global financial assets. Under a mild mitigation scenario, Dafermos et al. (2018) find that climate damages seriously harm the solvency and leverage of financial institutions, sharply reducing GDP growth from 2.5% to about 1.5% at the end of the century.[6] In a previous paper, some of the authors of this study evaluated a forward-looking scenario

[6]The analysis of Dafermos and co-authors builds on the DEFINE model, which has been previously established in Dafermos

of high climate change and estimated the potential financial stability impact of climate damages together with the ensuing public costs to be borne by governments. We found that up to 20% of aggregate climate impacts (i.e. impacts on GDP growth) are caused by climate-induced financial distress (Lamperti et al., 2019).

Based on these preliminary studies, strong attention is emerging on how central banks and financial regulation authorities may manage climate-related risks to financial stability (HLEG, 2017; Campiglio et al., 2018; D'Orazio and Popoyan, 2019). Indeed, a variety of measures have been proposed and, in broad sense, they all foster the ability of private firms to adopt greener technologies (Goldstein et al., 2018). First of all, such regulations would enhance the disclosure of information related to climate-related risks borne by firms, banks and other institutional investors (McFarland, 2008; Kolk et al., 2008; Monasterolo et al., 2017; HLEG, 2017; Dietz et al., 2017; Goldstein et al., 2018). Second, they would modify bank capital and reserve requirements to protect them against losses (possibly from physical risks) and to increase the quality of assets on banks' balance-sheets (Spencer and Stevenson, 2013; D'Orazio and Popoyan, 2019). For example, some emerging market central banks have used prudential policies to mitigate environment-related risks or have encouraged lending to low-carbon activities (Dikau and Ryan-Collins, 2017).[7] Finally, central banks might re-design their collateral frameworks. The collateral framework defines assets that financial institutions can pledge to borrow from the central bank. Central banks could therefore consider incorporating climate-related risks explicitly in determining the list of eligible collateral and the size of the haircut (Campiglio, 2016).[8] This paper is a first attempt to model the mechanisms behind these policy initiatives, and to evaluate their effectiveness both on climate change mitigation and on financial resilience.

Policies originated within the financial system might foster the transition to clean capital, channelling investments and spotting opportunities for sustainable and inclusive development. The usual way of thinking about climate mitigation policy is to impose additional costs on activities producing emissions to compensate for the expected future costs of a changing climate. As a matter of fact, the majority of dynamic climate-economy models restricts attention to policies expressed as monetary incentives (Clarke et al., 2009; Acemoglu et al., 2012; Golosov et al., 2014; Weyant, 2017).[9] Such perspective implicitly assumes that investment and research would migrate from emission-intensive to low-carbon

et al. (2017).

[7]To be precise, Banque Du Liban differentiates reserve requirement ratios — that is, the required ratio of central bank reserves held by private banks to their stock of deposits — according to the amount of bank lending flowing to renewable energy and energy-efficient projects. Banco Central do Brasil requires commercial banks to incorporate environmental risk factors into their governance framework and demonstrate how these risks are evaluated when calculating their capital needs.

[8]A haircut refers to a reduction applied to the face value of an asset, expressed in percentage terms.

[9]A recent notable exception is offered in Rozenberg et al. (2014), where the authors compare mandates, feebates, performance standards, and carbon pricing in producing stranded assets during a transition to green capital.

technologies as soon as the latter become relatively more profitable. However, this might not happen because of lack of adequate information, need of patient capital, technological uncertainty and path-dependent investment behavior (Geels, 2013; Mazzucato and Semieniuk, 2018; Lamperti et al., 2019). In addition, the banking sector's climate sentiments (i.e. banks' anticipation of the impact of climate policies) and their consequent revision of lending conditions for green/brown firms, play a main role in the success of climate policies' implementation, as shown in Dunz et al. (2020). Therefore, policies and practices in the financial system might help - not just hedge - a transition (Raberto et al., 2018). One of the innovations of this paper is to focus on regulation-based policy mechanisms altering the credit allocation process.

Indeed, we contribute to such literature by exploring the effects of three stylized yet relevant climate-related macroprudential and credit policy designs on banks' balance-sheet, financial stability and, ultimately, long run growth in a model embedding climate-related costs (Lamperti et al., 2018a,b). The DSK model is an evolutionary climate-economy model model, where heterogeneous agents, firms and banks co-evolve and react to climate shocks caused by rising emissions concentrations in the atmosphere (see the full description of the model in Section 3). In that, we also contribute to the macro-financial literature grounded in complex systems (i.e. agent-based, system dynamics and network-based models). Such strand of contributions has recently devoted a large attention to the analysis of climate impacts, energy transitions and green finance (Balint et al., 2017; Lamperti et al., 2018, 2019). However, despite the various calls for interest, there are very few modeling efforts aimed at testing financial-based interventions to manage climate risks along specified climate and socio-economic scenarios.[10]

3 Banking and credit allocation mechanisms in the model

The *Dystopian Schumpeter meeting Keynes* (DSK) model is an agent-based model featuring an economy with heterogeneous agents and a simple climate module (Lamperti et al., 2018b). It belongs to the so-called "Schumpeter meeting Keynes" (or K+S) family of models, which provides flexible simulation environments for policy analysis across various fields (from fiscal to monetary and labor market policies) and couples features of Keynesian demand management, Schumpeterian theories of firms' interaction and competition and Minskian credit dynamics (see the survey in Dosi et al., 2017). We employ the same baseline structure of Lamperti et al. (2018b) but adding heterogeneous banks, a novel set of policies and a different calibration. Indeed, we now employ stricter empirical targets and attempt at improving the

[10]Interestingly, this holds true for the mainstream finance literature (Diaz-Rainey et al., 2017), which makes it even more relevant to start modelling these mechanisms.

representation of climate damages by jointly matching emissions dynamics and temperature projections (see Section 3.5 for additional details).[11]

The model is composed of four sectors and a government body (which implements fiscal, monetary and macroprudential policies). First, in the upstream sector, capital-good firms produce heterogeneous machines and carry out R&D activities. They are vertically linked to consumption-good firms, which employ such production technologies to manufacture a homogeneous final good that is sold to consumers/workers. The financial system is represented by a banking sector in which heterogeneous banks gather deposits and provide credit to consumption-good firms in need of external funds for investment and production activities. Finally, in the energy sector, a variety of energy plants rely either on low-carbon (green) or fossil-fuel (brown) resources to supply energy inputs to capital and consumption-good firms. An important feature of the model is the climate module, which creates a feedback loop between economic activity and climate damages. Indeed, the use of fossil fuels entails the emission of CO_2, which increases the atmospheric temperature. In turn, such variations produce stochastic physical impacts on the economic activity of the agents, in the form of negative shocks to labor productivity and capital. The aggregate damage of climate change on macroeconomic and financial outcomes emerges then indirectly from the boundedly-rational interactions of such ecology of actors. More precisely, firms are hit with negative micro shocks to their labor productivity and/or capital, which alter their relative performance and therefore reduces their market shares and their probability to be funded by banks.

The microeconomic foundations of the model are "behavioural" (Akerlof, 2002). Heterogeneous agents (firms, banks, etc.) behave in a "realistic" way — i.e. in line with the micro-empirical evidence — and they interact without resorting to any ex-ante commitment to the reciprocal consistency of their actions, thus implicitly addressing the plea by Solow (2005) for genuine micro-heterogeneity. Finally, the aggregate dynamics emerge indirectly from the interactions of these agents.

In what follows we sketch the functioning of the various sectors that compose the model, but we devote particular attention to the banking system and the mechanisms of credit allocation, which are the key ingredients for the analysis that will follow. Further details on the backbone of the model can be found in the Appendix.

[11] In Lamperti et al. (2018b) the model was calibrated to emissions growth, but not to temperature. However, the climate module was different and inspired to Sterman et al. (2013).

3.1 The capital and consumption good sectors

Firms in the capital-good industry (identified with the subscript i) produce machines by employing labor and energy. These machines are then sold to consumption-good firms (identified with the subscript j). Capital-good firms invest in R&D a fraction of their past sales in order to discover new machines or imitate those of their competitors. New machines can be more productive, energy efficient, or “greener” (i.e. as indicated by the level of CO_2 emissions they entail). Indeed, machines and production technologies induce CO_2 emissions, as defined by a technical coefficient proxying their heterogeneous emission intensities, i.e. the amount of carbon dioxide emitted for each unit of energy employed throughout the production process. Therefore the amount of CO_2 emissions depends on technical change in the upstream sector (the characteristics of machines produced and sold) as well as on investment decisions in the downstream sector (defining the choice of new machines and their diffusion in the economy).

Consumption-good firms produce a homogeneous good using their stock of machines, energy and labor under constant returns to scale. If the current capital, $K_j(t)$, is not sufficient to satisfy the desired level of production, they can invest in new machines. Firms may also want to replace their current stock of machines with more productive (and environmental-friendly) ones. Firms’ gross investment is simply the sum of expansion and replacement investments. Such level of *desired* investment however can be limited by financial constraints. Consumption-good firms finance their investments as well as their production relying on imperfect capital markets (Stiglitz and Weiss, 1981; Greenwald and Stiglitz, 1993). Firms first use their stock of liquid assets, and if not sufficient, then ask for bank credit. The borrowing capacity of firms is limited by their ratio between debt and sales. Banks provide loans to consumption-good firms on a pecking order basis, ranking their clients according to their net worth-to-sales ratio and then allocating credit until it is entirely exhausted. If credit supply is lower than demand, some firms end up being credit-rationed (see Section 3.3 below).

At the end of the period, firms receive sales revenues, compute their profits (see eq. 24 in the Appendix) and pay taxes on positive profits. Firms with negative stocks of liquid assets or (approximately) zero market shares exit the market and are replaced by new ones.

3.2 The energy sector

Energy production is performed by a set of heterogeneous power plants featuring green (renewable) or brown (carbon-intensive) technologies. Such plants compete to produce homogeneous energy inputs that are demanded from firms. Endogenous technological change occurs along both the green and brown technological trajectories. Investments in new energy plants are decided by a central authority on the basis of the lifetime costs of energy plants from alternative energy technologies.[12] The central authority is also assumed to compute profits in the industry and levy taxes.

Plants differ by their technical coefficients, reflecting cost structures, thermal efficiencies and environmental impacts. While burning fossil fuels yields emissions, the carbon footprint of green plants is assumed to be zero. Brown and green plants exhibit opposite cost outlines: marginal production costs are relatively larger for dirty energies, while fixed and instalment costs are higher for clean energies. The levelised cost of energy reflects an initial cost-advantage of brown plants.[13]

The energy market is competitive. Plants submit production orders at their marginal production cost; then, the central authority ranks all orders and allow production on a merit-order basis (the cheapest plant is activated first). The price of energy is fixed in every period according to an additive markup over the marginal cost of the last activated plant (see eq. 28).

Investment in the energy sector can be associated to i) the replacement of old and obsolete plants or ii) capacity expansion. Replacement is due to the fact that all (brown and green) plants have a constant life-time, while expansionary investments are needed to face an eventually increasing energy demand. In each period, investments are made of green or brown plants according to the relative levelized cost of energy.

3.3 The banking sector

The structure of the banking sector is akin to Dosi et al. (2015), which provided one of the first contributions matching an agent-based model of endogenous growth with an articulated financial system (see Raberto et al., 2012; Assenza et al., 2015; Caiani et al., 2016; Popoyan et al., 2017; van der Hoog and Dawid, 2017 for some alternatives). It is composed of B heterogeneous commercial banks gathering deposits and providing credit to firms and a central bank running monetary and macro-prudential policies. The number of commercial banks is constant (no entry) and is proportional to the number of firms in the consumption-good sector (F_2): $B = \frac{F_2}{\alpha_b}$.[14] Heterogeneity is crucial to study the emergence of banking crises and their effects on the real side through the credit channel. For example, insolvencies of some banks might have an impact on specific production activities and the public budget, thereby altering the

[12] This implies that investments might dynamically lead to lock-ins in certain energy technologies, which would reflect an history of R&D activities and innovations along a prevailing technological trajectory.

[13] See the various Annual Energy Outlook publications by the International Energy Association and the US Energy Information Administration.

[14] α_b is a parameter controlling for the competitiveness of the banking industry.

dynamics of competition among firms. If the banking sector was aggregate, the effects of instability would - to the contrary - cut equally across firms. On the opposite side, a change in the risk profile of firms can have a different effect on some banks with respect to others (e.g. small vs. large; more or less leveraged) with aggregate implications that are difficult to derive ex-ante. [15] At the beginning of the simulation, firms are randomly assigned to a bank, so that the distribution of clients per bank follows a Pareto distribution (Janicki and Prescott, 2006).[16] The relative sizes of banks' balance-sheet, and as a consequence, credit supply, then evolves endogenously depending on micro positive (profits) and negative (bad loans) shocks. Indeed, credit supply is limited by the bank's equity NW_b through a simplified Basel-II capital adequacy rule:

$$TC_b(t) = \frac{NW_b(t-1)}{\kappa} \tag{1}$$

where TC_b indicates total credit supplied by bank b and $\kappa > 0$ expresses the capital requirement fixed by the regulatory authority (the central bank in our case).[17] Then, banks evaluate applicants in terms of their perceived creditworthiness as expressed by the ratio between past net worth, $NW_j(t-1)$, and past sales, $S_j(t-1)$. Let $A_b(t)$ be the set of applicants at bank b in period t

$$Creditworthiness_j(t) = \frac{NW_j(t-1)}{S_j(t-1)} \quad \forall j \in A_b(t). \tag{2}$$

Firms applying for a loan are then ranked as follows

$$Rank_j(t) < Rank_k(t) \iff Creditworthiness_j(t) > Creditworthiness_k(t) \quad \forall j,k \in A_b(t) \tag{3}$$

where $Rank_{j,k} \in \mathbb{N}$. Banks provide loans following the ranking and until maximum credit supply is reached. While in the baseline configuration credit provision is just affected by the creditworthiness of the applicant, we will study the effects of including climate-related risks in Section 5.

Banks earn profits from the loans they allocate as well as the government bonds they buy. All banks apply a homogenous mark-up black μ_b on the central bank interest rate (r, see eq. 7): $r_{deb}(t) = (1+\mu_b)r(t)$. Then, they fix a risk premium on the basis of clients' position in the credit ranking. In every period, four

[15] The interested reader might also want to look at Haldane and Turrell (2018) for a discussion on the role of heterogeneity and interactions in models of the financial system.

[16] In particular, we account for the presence of a "fat" right tail of the distribution. This is obtained setting the shape parameter to 0.8, and is tested for robustness in the range from 0.6 to 1. While we acknowledge that small samples might not adequately reflect the tail of the distribution and vary considerably from run to run, the relatively low standard errors in our Monte Carlo exercises suggest robustness of our results.

[17] We assume here that banks always set their credit amount at the limit and keep the minimum capital requirements allowed by the regulation (see both equations 1 and 8). This feature allows policy experiments on capital adequacy ratios to unambiguously affect the ability of banks to lend. Differently, in Dosi et al. (2015) and Lamperti et al. (2019) banks also maintain a counter-cyclical buffer in order to reduce their exposure in bad times.

credit classes are created by the banks, corresponding to the quartiles in their ranking of clients. Given the base loan rate r_{deb}, each firm pays:

$$r_{deb,j}(t) = (1 + (q_j - 1)k_{scale})r_{deb}(t), \tag{4}$$

where q_j is the quartile of firm j' ranking and k_{scale} is a scaling parameter. Firms' deposits are provided an interest rate r_D, banks' reserves at the central bank yield the reserve rate r_{res} and government bonds pay a constant return such that $r_D \leq r_{res} \leq r_{bonds} \leq r \leq r_{deb}$.

Hence, the profits of a bank can be expressed as follows:

$$\Pi_b(t) = \sum_{\text{clients}} r_{deb,j}(t)Deb_j(t) + r_{res}(t)Cash_b(t) + r_{bonds}(t)Bonds_b(t) - r_D Dep_b(t) - BD_b(t), \tag{5}$$

where, for each bank b, Deb_j represents clients' debt, $Cash_b$ are the liquidities, $Bond_b$ is the stock of government bonds, and BD_b indicates non-performing loans. Loan losses occur whenever a borrower goes bankrupt and exits the market with a positive debt, which may lead to negative profits. Profits are taxed and added to the net worth of the bank:

$$NW_b(t) = Loans_b(t) + Cash_b(t) + Bonds_b(t) - Dep_b(t) + \Pi^*_b(t), \tag{6}$$

where $Loans_b$ represents the sum of existing loans provided by the bank b to its clients and Π^*_b the after-tax value of bank profits.

A bank goes bankrupt when its net worth becomes negative (due to the accumulation of loan losses), and it is then bailed-out by the government. Since this is the only mechanism of financial instability that we consider, which has been proven large under rapid climate change in Lamperti et al. (2019), we can single out how altering credit allocation to firms may alleviate or exacerbate risks for the banking system.

The cost of the public bail out (GB) is the difference between the failing bank's net worth before and after the public intervention. Specifically, we assume that the bank's equity after the bailout is a fraction of the equity value of the smallest incumbent, provided it satisfies the capital adequacy ratio. Mirroring the entry rule of firms in the real sector, this fraction is a random draw from a Uniform distribution between ϕ_1 and ϕ_2. The bail-outs thus represent part of the public costs of climate-induced financial losses. Such assumption finds in line with the historical evidence of large government spending in rescuing banking institutions during financial crises (Laeven and Valencia, 2012).

3.4 The central bank and the government

The central bank runs monetary and macroprudential policies. In that, it fixes the policy rate according to a Taylor rule (Taylor, 1993; Howitt, 1992) of the following type:

$$r(t) = r^T(t) + \gamma_\pi(\pi(t) - \pi^T) + \gamma_U(U^T - U(t)), \tag{7}$$

where $\gamma_\pi, \gamma_U > 1$, π^T indicates the target level of inflation, U^T the target level of unemployment and r^T the target interest rate. Further, the central bank implements a stylized Basel-II type capital requirements scheme that determines the capital adequacy ratio κ:

$$\kappa = \frac{NW_b(t-1)}{RWA_b(t)} = \frac{NW_b(t-1)}{\theta_1 Loans_b(t) + \theta_2 Bonds_b(t)} \tag{8}$$

where RWA_b represents the risk-weighted assets of bank b and $\theta_{1,2}$ are the weights. According to the prevailing practices, we assume that bonds are risk-free ($\theta_1 = 0$) and commercial loans are full weight ($\theta_1 = 1$). Hence, the risk-weighted assets coincide with the total amount of loans to firms, and equation (1) can be retrieved from (8). In short, given the net worth of a bank at the beginning of each period, the macro-prudential framework limits the risks it can expose to when lending to firms. While the baseline prudential policy in the model assume $\kappa = 9\%$ and equal weights for loan, section 5 introduces different requirements for green and brown assets, as the latter entail climate-related physical risks while former does not.

Taxes and subsidies are the fiscal instruments that contribute to the aggregate demand management. Our setup includes automatic stabilizers which help the economic system to recover from recessions. Taxes paid by firms and banks on their profits are gathered by the government at the fixed tax rate tax_p. Workers' income is taxed at the rate tax_i,[18] which is also fixed. Total government revenues are indicated as $Taxes$. Direct government expenses G are composed of subsidies to unemployed workers, who receive a fraction (w^U) of the current market wage;[19] the costs of bank bailouts and the costs of any additional climate policy involving public spending (see Section 5.1 for further details). In addition to these primary expenses, the government pays interests on its stock of sovereign bonds (SB) owned by banks and the central bank. The cost of public debt on government's deficit is then equal to $CD(t) = r_{bonds}(t)SB(t-1)$.

Then, the public deficit corresponds to:

$$Def(t) = G(t) - Taxes(t) + CD(t), \tag{9}$$

[18] This excludes unemployed workers.

[19] The dynamics of the market wage are described in the Appendix, eq. 35.

If the deficit is positive the government issues new sovereign bonds, which are bought by banks according to their share in the total supply of credit (and by the central bank as an eventual lender of last resort); when the deficit is negative, the government uses its surplus to repay its stock of debt.

3.5 Model calibration and validation

As in every ABM, the properties of the model are analyzed via extensive computer simulations. We first calibrate and empirically validate the "baseline" or "business-as-usual" model, in absence of climate impacts and green financial policies. We do so by performing a Monte Carlo analysis of 300 independent model replications in order to assess whether the statistical properties of artificially-generated microeconomic and macroeconomic data are similar to their empirically-observed counterparts (for a critical review of the validation techniques for ABMs see Fagiolo et al., 2019).

We configure the baseline model in a high growth, high emissions scenario without considering climate impacts. It is intended to proxy a SSP 5 cum RCP 8.5 future (van Vuuren et al., 2014), characterized by high output growth (O'Neill et al., 2014), sustained energy demand (Riahi et al., 2017) and soaring emission concentrations until the end of the century (Riahi et al., 2011). To obtain such configuration we rely on an indirect calibration approach (Fagiolo et al., 2007). We first search the parameter space to identify a set of calibration candidates that allow matching as closely as possible the target empirical features reported in Table 1; then we retain the candidate that is closest to the parameter sets tested and employed in earlier versions of the model (Dosi et al., 2015; Lamperti et al., 2018b); hence, we check whether the selected configuration allows to replicate a long list of micro- and macro-level stylized facts.[20] The main parameters obtained through such a procedure are listed in Table 2, while the complete list in the Appendix, which also contains a discussion and a list of the stylized facts that the model successfully replicates.

4 Credit provision, banking and the climate

Figure 1 shows the behavior of main macroeconomic variables (output, unemployment, emissions) and the temperature anomaly simulated by the model in the baseline configuration, i.e. without climate impacts and green financial policies. Endogenous growth emerges together with business cycles. The sustained growth of output spurs emissions leading to temperature increases, all consistent with a SSP5

[20] Please notice that our calibration differs from the one in Lamperti et al. (2019) as it focuses more to past empirically observed features of modern economies, rather than future projections, in line with the prevailing practice in the macro ABM literature.

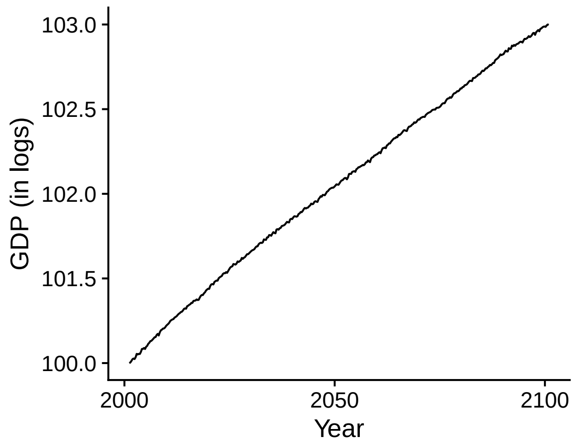
Table 1: Main socio-economic features of the high growth, high emission scenario and the simulated counterparts obtained from the baseline model runs. The behaviour of targeted macroeconomic series is expressed through historical averages corresponding to the business-as-usual.

Scenario setting – without climate impacts				
	Target (historical average)	Data source	Model average	St. dev.
Yearly GDP growth	0.044	WDI	0.032	0.010
Unemployment rate	0.061	WDI	0.092	0.026
Energy demand growth	0.023	WDI	0.025	0.009
Emissions growth	0.018	CDIAC	0.016	0.001
Volatility of output	0.018	FRED	0.261	0.013
Temperature at 2100	-	-	4.57	0.590

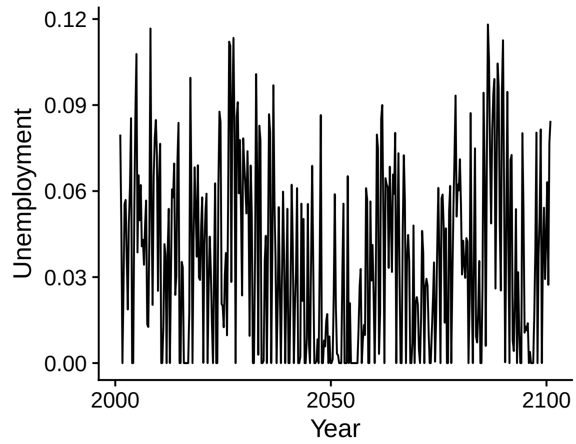
Note: All values refer to a Monte Carlo of size 300. Temperature is expressed in Celsius degrees above the preindustrial level, which is assumed to be 14 Celsius degrees. WDI stands for World Development Indicators, provided by the World Bank. Empirical counterparts are computed over large time spans, but are subject to data availability: World real GDP, unemployment and CO_2 emissions data refer to the period from 1980 to 2010; employed energy consumption data go from 1991 to 2013; quarterly data for volatility analysis are from 1970 to 2007 and refer to the US economy, but the reported features are quite robust across countries, see also Stock and Watson (1999); Napoletano et al. (2006). Volatility of output is expressed as standard deviations of bandpass filtered series. Growth rates computed as $(y_{\text{final}} - y_{\text{initial}})/(y_{\text{initial}} * T)$.

Table 2: Main parameters and their values upon model calibration to the high growth, high emissions scenario. The values of other parameters can be found in the Appendix.

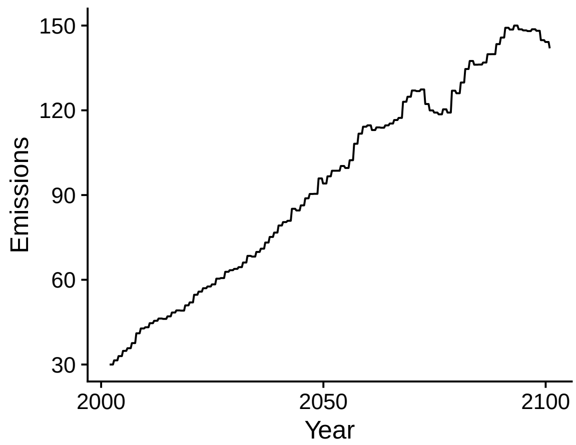
Description	**Symbol (if any)**	**Value**
Number of firms in capital-good industry	F_1	50
Number of firms in consumption-good industry	F_2	200
Number of banks	B	10
Basel II capital requirement	κ	0.09
Profit tax rate	tax_p	0.15
Unemployment subsidy rate	w^U	0.35
Carbon-climate sensitivity	λ_{CCR}	1.8
First order damage response to temperature	c_1	0
Second order damage response to temperature	c_2	0.0022



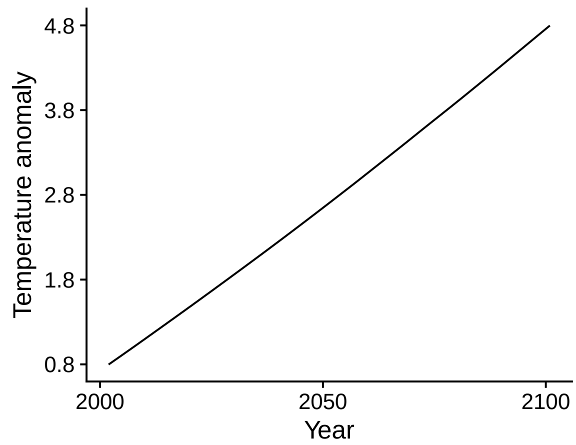
(a) GDP



(b) Unemployment rate



(c) CO_2 Emissions



(d) Temperature

Figure 1: Main macroeconomic and climate-related variables in the baseline scenario. A single run is showed. GDP is expressed in logs and normalized to its initial values. Emissions are measured in $GtCO_2eq$. Temperature is expressed in Celsius degrees above the pre-industrial level.

scenario. Table 1 compares the statistics in the simulated and historical data. The emerging dynamics are qualitatively comparable to the baseline scenario analysed in Lamperti et al. (2019), as the structure of the configuration (no policy, no impacts) is identical. The use of a different calibration obviously alters the quantitative figures, but we interpret the slight difference as a signal of robustness.

Although banks exhibit a relatively balanced financial structure and obtain a positive average net profit rate, banking crises endogenously emerge triggering deep downturns (cf. Figure 2; see also Dosi et al., 2015). Nonetheless, in this setup without climate damages, bank bailouts appear fairly distributed across time, even though clusters indicates occasional periods of particular distress. In turn, public debt fluctuate around 80% of GDP.

Table 3: Main features of the banking system in the baseline scenario. Monte Carlo averages and standard deviations are reported.

Banking system statistics – without climate impacts		
Variable	MC average	MC std. dev.
Public debt over GDP	0.82	0.09
Banks' debt over equity	1.55	0.14
Banks' (net) profits over deposits	0.04	0.01
Number of bailouts/10y	5.4	1.9
Average cost of bailout (% of GDP)	8.3	2.1

Note: All values refer to a Monte Carlo of size 300. Bank variables refer to an average across all banks in the model.

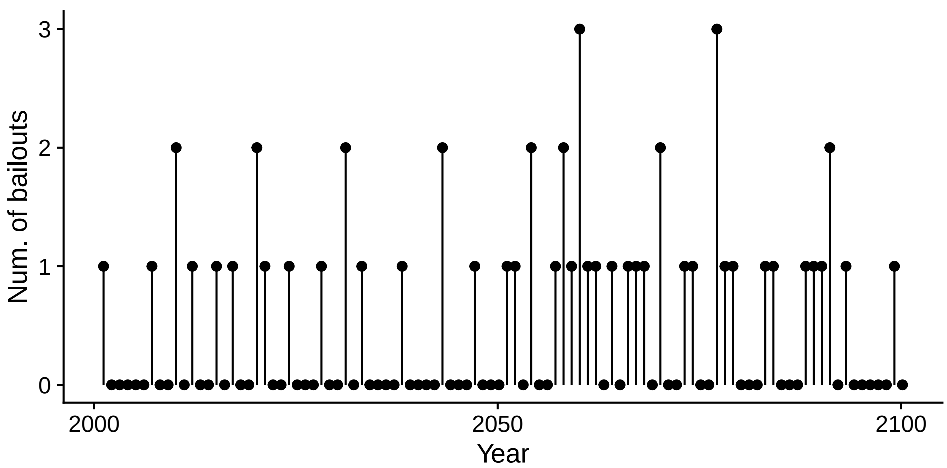


Figure 2: Number of bank bailouts carried out by the government in the baseline (high growth, high emissions) scenario without climate impacts. A single run is showed.

The view that the level and composition of lending activities is crucial in influencing the growth rate and business cycle properties of modern economies has long-standing roots (Gurley and Shaw, 1955; Kindleberger, 1978). From a Keynesian perspective, credit-fueled investments can foster aggregate demand, increase productivity and wage growth without dampening the financial conditions of firms. At the same time, credit booms can nurture firms' financial fragility possibly leading to banking crises à la Minsky (1977, 1986). Naturally, the foregoing dynamics are intimately intertwined with government and central bank policies and macroprudential regulation.

In the DSK model, Basel II macroprudential regulation constrains banks' lending capacity, which is proportional to their equities (cf. Section 3). In Figure 3 we show the average growth rate of the economy for different values of the Basel capital adequacy ratio κ in presence (right) and absence (left) of climate impacts on the real economy. In particular, we let k vary around its baseline value ($k = 0.09$), which is representative of the Basel II regulation. To facilitate interpretation, we report on the horizontal axis the inverse of the capital requirement $\frac{1}{\kappa}$ (with $1/k = 11.11$ in the baseline); therefore as values on the horizontal axis increase, credit supply enlarges and firms' financial constraints are loosened. In the scenario without climate impacts, the relation between average GDP growth and maximum credit supply is non-linear (Figure 3, left). We find that lessening macroprudential regulation constraints has a positive impact on GDP growth up to an upper threshold, then its effect becomes negligible (in line with the results in Dosi et al., 2013).

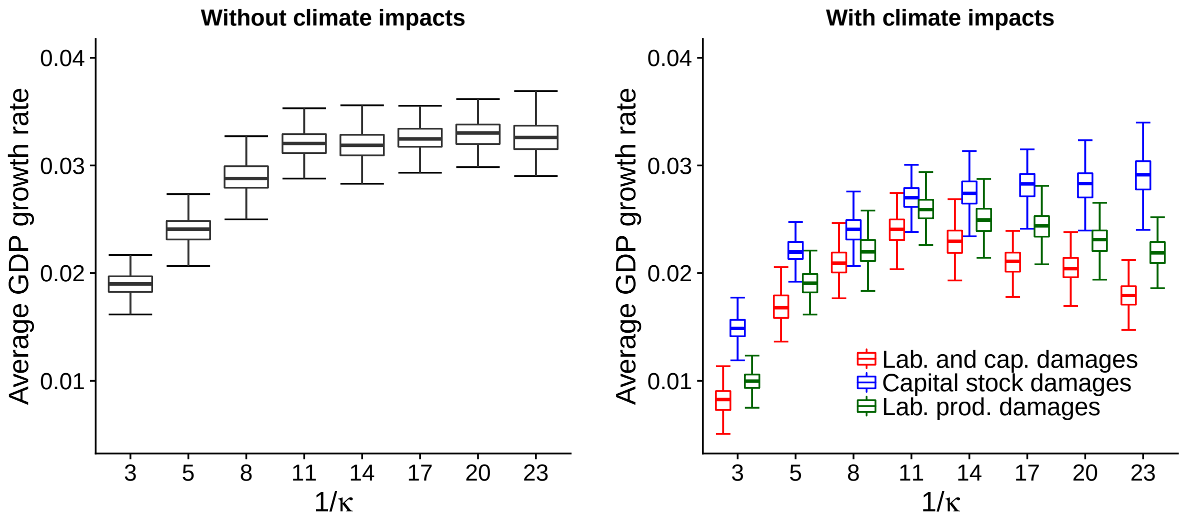


Figure 3: Credit supply and growth of the economy in absence (left) and presence (right) of climate impacts. Box-plots based on 300 independent model runs. $1/\kappa$ indicates the ability of banks to provide credit above their equities according to the Basel II regulation.

These aggregate impacts reflect the role of credit provision to firms. Intuitively, firms that request loans to banks need to either expand or renew their capital stock (see Section 3). In both cases, they are likely to substitute relatively lower productive machines with novel and more productive ones. Indeed, larger credit supply stimulates the ability of firms to invest in capital goods (Figure 4, top-left panel. Such investments obviously absorb liquid assets and increase the stock of debt, thereby augmenting firms' leverage, which prompts larger bankruptcy rates when credit conditions are excessively loose (i.e. for high levels of $1/\kappa$; crf. Figure 4, middle-left panel). To better inspect the firm-level consequences of credit provision we run a simulation experiment whose results are summarised in Figure 5. In particular, the figure depicts how the access to external financing affects the productivity and creditworthiness of firms (measured as the ratio between past net worth $NW_j(t-1)$ and past sales $S_j(t-1)$, see Section 3): it compares these variable one and five years ahead of receiving credit to the average firm in the sector (black dotted line), and to a counterfactual firm which would be denied credit (displayed in blue). We recognize two effects of credit provision.

First, a *productivity-enhancing effect*. Access to credit allows improving productivity both with respect to the counterfactual of being credit-rationed and to the average in the consumption-good sector. Further, such effect is quite persistent over time, as median productivity differentials remains significantly different not only 1 but also 5 years after receiving credit.[21]

Second, a *fragility-enhancing effect*. Access to external financing reduces firms' creditworthiness in the aftermath of credit provision with respect to a counter-factual where the same firms did not receive the requested loan. Even though such negative effect reverts over time for the median firm, the distribution of firms' creditworthiness enlarges considerably and skews the distribution to the left, suggesting that while beneficial in aggregate, the balance-sheet of many business becomes de-facto more fragile in the years after credit provision.

The prevalence of either one or another effect in shaping the macroeconomic outcome is uncertain and depends on the regulatory context. When the constraints on total credit are loosened, the increase in GDP growth identified above (Figure 3, left) are driven by the labor-productivity enhancing effect of credit. Figure 4 (middle and bottom left panels) shows that such stimulus is mirrored by a decrease in banks' and firms' failure rates, which shrink by few percentage points when restrictions to credit provision are gradually relaxed (i.e. $1/\kappa$ moves from 3 to around 11). However, as credit supply is further expanded ($1/\kappa > 11$), the fragility-enhancing effect bites back leading to higher banks and firms failures. Hence, the stability of the banking system is also non-linearly affected by the size of the credit supply, giving rise to a U-shaped relationship between the inverse of the capital adequacy ratio and the

[21] Recall that 1 year corresponds to 4 simulation periods in the model.

bankruptcy rates of banks and firms (see Figure 4 and Dosi et al., 2013). Intuitively, stringent macro-prudential regulation reduces the availability of loans, forcing firms to rely more heavily on their highly volatile net profits and - de facto - limiting their ability to invest. At the opposite end, relaxing capital requirements fuels credit booms, eventually leading to overproduction and over-investment episodes (see the top and middle panel in Figure 4). The potentially destabilizing effect of excessive credit supply is also visible from its positive association with the cost of banks' bailouts (Figure 6).

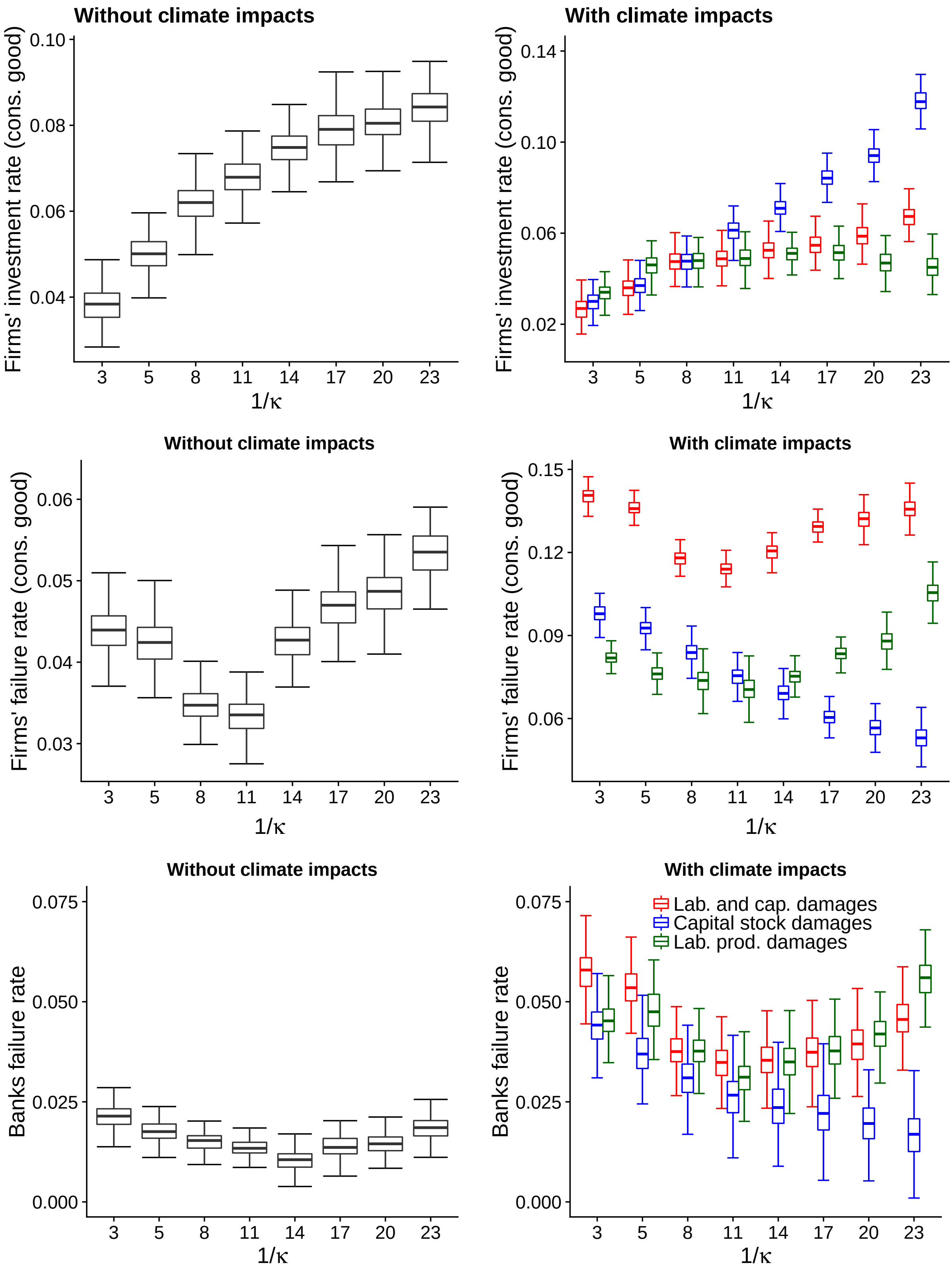


Figure 4: Credit supply and the investment rate of firms (top), the failure rate of firms (middle) and the failure of banks (bottom) in absence (left) and presence (right) of climate impacts. Box-plots based on 300 independent model runs. Investment rate is measured through the investments to capital stock ratio. $1/\kappa$ indicates the ability of banks to provide credit above their equities according to the Basel II regulation.

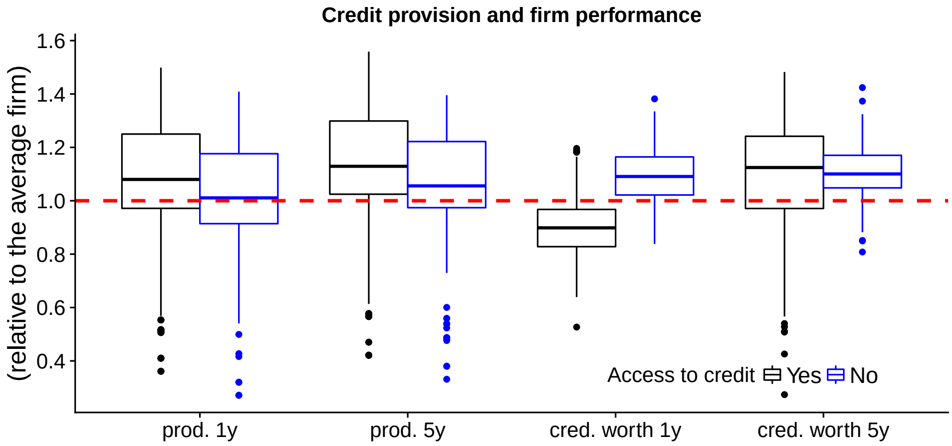


Figure 5: The firm-level effects of credit provision, 1 and 5 years ahead. Box-plots represent the distribution of firm characteristics (productivity and creditworthiness) relative to credit-provision events that are constrained to happen (access to credit) or not (no access to credit). To ease comparisons and the evaluation of the effects, results are expressed in relative terms with respect to the "average firm" in the sector, i.e. the firm possessing the average characteristics, as illustrated with the black dotted line.

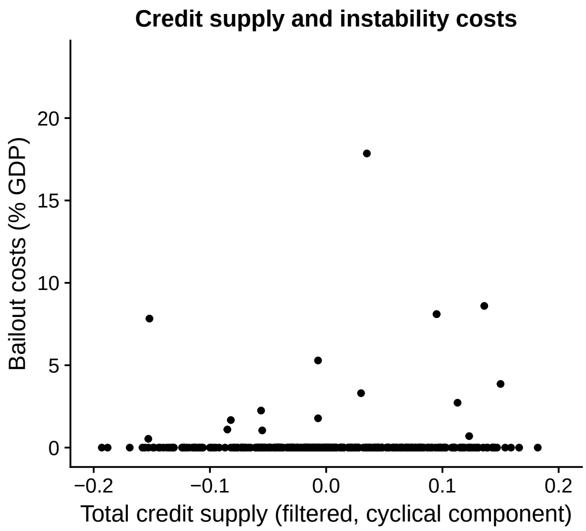


Figure 6: The aggregate risks of excessive credit supply. The scatterplot shows the positive association between total credit supply (detrended using a bandpass-filtered (6,32,12)) and the costs of banks' bailouts as a share of GDP. The plot refers to one exemplifying simulation run.

Let us now move to the inclusion of climate change impacts, which may alter the aggregate effects of credit-provision (cf. right panel of Figure 3). We account for the feedback of climate change on the economy following a robust and increasing empirical evidence (Dell et al., 2009; Hsiang et al., 2017), and considering three different types of climate-impacts: damages to labor productivity, damages to the capital stock of firms and a combination of these two effects.[22]

[22]To be more precise, A_i^{LP} and B_i^{LP} are reduced when climate change affects labor productivity; K_i is cut when shocks target

First, climate change shocks exerts a negative effect on the long-run performance of the economy, independently of the macroprudential framework (in line with Lamperti et al., 2018b): GDP growth is systematically lower in the right panel compared to the left one. Second, the type of climate impact damages affects the response of credit and economic dynamics. More specifically, when climate shocks hit firms' labor productivity, a reverse U-shaped relation between credit availability and output growth emerges (cf. green and black box-plots). Climate change harms firms' profitability, which reduces the ability of firm to invest in new machines and - hence - to spur technological advances (see Figure 4, top panel). Under these conditions, low credit supply exacerbates the negative effect on growth, while excessive lending induces over-investment, which increases the financial fragility of firms, making them more vulnerable to negative productivity impacts. Indeed, we also observe more frequent and longer crises (this is also reflected in a higher number of bank failures, see Figure 4) that contract the GDP growth rate with respect to the baseline. Overall, climate damages affecting labor productivity exacerbate the trade-off between the productivity-enhancing and the fragility-enhancing effects of credit provision.

Instead, climate damages to capital stock raise the desired level of investment in machines, as firms need to rebuild capacity. In presence of buoyant credit conditions, the investment rate lifts-up considerably, overcoming the counter-factual levels observed in absence of climate-relates effects. This boosts the performance of the economy thanks to the diffusion of novel vintages of capital, and reduces both the bankruptcy rate of firms and the instability of the banking sector (see the right panels of Figures 3 and 4).[23] Indeed, for the same level of total credit supply, capital damages make firms scoring high in banks' credit ranking exhausting a large share of available, as their investment needs are increased. This leave the other firms credit rationed. As a consequence, the bulk of credit goes to the relatively safer firms and banks can benefit via lower rates of default. In addition, contrarily to the case of damages to labour productivity, shocks to capital stocks do not substantially cut demand (crf. Figure 3, further preserving the stimulus to invest.

5 Financial policy tools to cope with climate risks

Despite a variety of discussions about the role of financial regulators and central bankers in the development of climate-related risks (Campiglio et al., 2018; Monasterolo, 2020), few mechanisms have been

the capital stock while both lessen in the third case. In those cases where we study a combination of labor productivity and capital shocks, the share of damage attached to the two dimensions is determined by the labor share of output: being $x\%$ the size of the shock suffered by firm i and s_L the labor share, the climate damage to the productivity of workers of firm i amounts to $s_L x\%$. Relevantly, there is ample and robust evidence that climate change affects both labor and capital inputs (Dell et al., 2009; Hsiang et al., 2017).

[23] Note, however, that climate shocks hitting capital stock considerably increase the volatility of growth. More on that in Lamperti et al. (2018b, 2019).

robustly tested in the literature. Part of the reason lies in the structure of many climate-economy models, which are not suited to study the interactions between the real and the financial sides of economies (Weyant, 2017). Further, those models often focus their analysis on policies characterized by monetary incentives, while the majority of current proposals concern financial regulation mechanisms D'Orazio and Popoyan (2019) that are difficult to implement into such aggregate frameworks. Krogstrup and Oman (2019) extensively mention credit allocation and financial regulation policies (e.g. differential liquidity and/or capital requirements) as tools to favour mitigation, but do not describe how they might be implemented in practice.

We employ the DSK model with heterogeneous banks described in Section 3 as a "policy laboratory" to study the impact of green financial regulations on economic dynamics and their interplay on both financial stability and climate mitigation objectives. In particular, we test and compare three "climate-finance" policy mechanisms that can influence the allocation of credit to firms, the level of risk borne by banking institutions and the stability and growth of the economy (cf. Section 5.1), under both high-climate-damage and no-climate-damage scenarios. Our ultimate goal is to study whether an appropriate financial regulation framework can stabilize the economy, while mitigating the impact of climate change by fostering investments in green businesses.[24]

5.1 Green financial policies

As shown in the previous section, the banking sector, the real economy and climate change are interrelated: climate change shocks negatively impact the economy and affect the bankruptcies of firms and banks, while the decisions of economic agents affect the intensity and speed of climate change. The banking sector can both increase the resilience of the system to climate-related risks (see also Section 2), and channel investments towards sustainable projects, thus helping emission mitigation. In the following we study three "green" financial policy tools pursuing either one or both these goals by altering the dynamics of credit provision (see Figure 7). These policies are shaped in the form of regulations altering the mechanisms of credit provision to firms (see Section 3), by leveraging on the distinction between green and brown firms. *Green firms* corresponds to the $\alpha_G\%$ least emitting consumption-good businesses in the economy. In particular, we set $\alpha_G = 0.25$, i.e. we focus on the quartile of consumption-good firms with the lowest level of emission intensity (A^{EI}). While we acknowledge an oversimplification in our definition of "green", there is a generalized difficulty at providing an adequate taxonomy, as highlighted in the final report of the High Level Expert Group on Sustainable Finance (HLEG, 2018). To test the robustness

[24] Punzi (2019) develops a DSGE to show that providing credit to green firms is essential to kick-start the transition, but overlooks the possible effects on credit quality, financial stability and the physical risks of climate change.

of our findings to alternative definitions, we run a battery of robustness exercises in the Appendix.

Carbon-risk adjustment. Recent studies have put forward the idea of disclosing information on the carbon footprint of businesses and also on their exposure to climate-related events - e.g. weather extremes (Monasterolo et al., 2017; HLEG, 2017; Goldstein et al., 2018). In economies exposed to climate impacts and to the effects of climate policy (see the discussion on stranded assets in Section 2), such information should complement the standard balance-sheet measures in assessing the expected solvency of firms. Here, we characterize a policy scheme that forces firms to disclose their level of emission intensity together with their balance-sheet information. We assume that such information is immediately observed by banks, which in turn use it in their credit ranking (see also Figure 7, bottom-right), where balance-sheet and emission information have the same weight for simplicity and higher emissions negatively affect the position in the ranking. In other words, we hypothesize that banks are susceptible to information (i.e. carbon emissions) revealing the exposure of firms to additional costs they would need to bear if a climate policy (e.g. a carbon tax) was introduced. In particular, if $Rank^{CW} = 1, ..., A_b$ and $Rank^{EI} = 1, ..., A_b$ indicate the position of firms applying for a loan at bank b in two rankings based on the sales-to-net-worth ratio (see equation 3) and on emission intensity (where $Rank^{EI}_j < Rank^{EI}_k$ if and only if $A^{EI}_j < A^{EI}_k$) respectively, then *carbon risk adjustment* implies that credit will be allocated to firms according to a pecking-order indexed by:

$$Rank_{CRA} = \frac{Rank^{CW} + Rank^{EI}}{2}. \tag{10}$$

The carbon-risk adjustment of the credit ranking then implies that green firms "climb" in the pecking-order, reducing their probability to be credit-constrained. Banks fix their total supply of credit according to the standard Basel II framework. However, as borrowers' financial health is no longer the unique criteria for credit allocation, the probability of defaults on loan increases, possibly amplifying the financial fragility of banks. The reason is that when credit is allocated using (also) emission intensity, the amount of credit supply – everything else being equal – does not vary, but it is allocated to riskier firms than if creditworthiness was the only used metric.

Green public guarantees (or green credit easing). This is a form of credit easing where the government "backs" loans to green firms, thereby favouring financing of green projects. More specifically, if a green firm applies for a loan, the government steps in and provides a guarantee on the total amount of the credit.[25] Hence, if a green firm is not able to pay its loan, it does not go bankrupt: the government steps in and repays the bank. Thus, government-backed green loans have the same default risk as sovereign

[25] Such type of initiatives already exist, even though they are far from being diffused. Here is an example from the EU.

bonds, and consequently green firms are placed at the top of banks' credit ranking. The effects of such policy scheme are summarized in the bottom-left panel of Figure 7. Note that this green financial policy does not expand credit supply beyond the limit set by the standard Basel II regulation. However, defaults of green firms, if important, could cause public debt to soar. However, banks' default rate is instead decreased due to the guarantee scheme, which in turn reduces fiscal costs of banking crises. The overall expected impact on public debt is therefore not easy to predict. Indeed, the public spending $G(t)$ takes now the following form:

$$G(t) = US(t) + Bail(t) + \sum_j GL_j^*(t) \tag{11}$$

where US indicates total unemployment subsidies, $Bail$ the total costs of banks' bailouts and GL^* non-performing green loans.

green Basel II capital requirements. Both Basel II and III capital requirements attribute different weights to diverse types of assets in banks' balance sheets to account for their degree of risk. Along this vein, a *green Basel II* policy scheme excludes loans to green firms from banks' capital requirements regulation, thus relaxing the credit constraints of the former. More precisely, the macroprudential framework defines the total supply of credit, which is allocated to both green and brown firms on a pecking-order basis. As loans to green firms are excluded from the regulation, this expands the credit supply which can be allocated to those green firms that would be credit rationed otherwise. In particular, the policy allows banks to expand their supply of credit above the regulation limit (cf. eq. 1) by an amount that equals the total size of green loans they concede. Hence, total credit granted by a bank b becomes:

$$TC_b(t) = \underbrace{\kappa NW_b(t-1)}_{\text{to brown firms}} + \underbrace{\sum_j GL_j(t)}_{\text{to green firms}} \tag{12}$$

where GL_j indicates a loan to a green firm j such that its position in the pecking-order of bank b is lower than that of the last brown firm receiving a loan.

Figure 7 shows the conceptual effects of such policy on credit allocation in the top-right panel, compared to the benchmark setup. Note that as *green Basel II* allows banks to provide extra loans to green firms, it enlarges their balance sheets, possibly increasing their solvency risk and the likelihood of banking crises (see also Safarzyńska and van den Bergh, 2017).[26]

[26]Green capital requirements have been discussed in Campiglio (2016); EBP (2018) and D'Orazio and Popoyan (2019). There are generally two forms that have been proposed: "de-risking" of green assets or "risk-augmenting" of brown assets in the evaluation of the risk adjusted asset-side of banks' balance-sheet. While the effects on the supply of credit might be - in some cases - similar to the policy tested in the present paper, both instruments do not guarantee that funds are channeled to green projects (see also Van Lerven and Ryan-Collins, 2018).

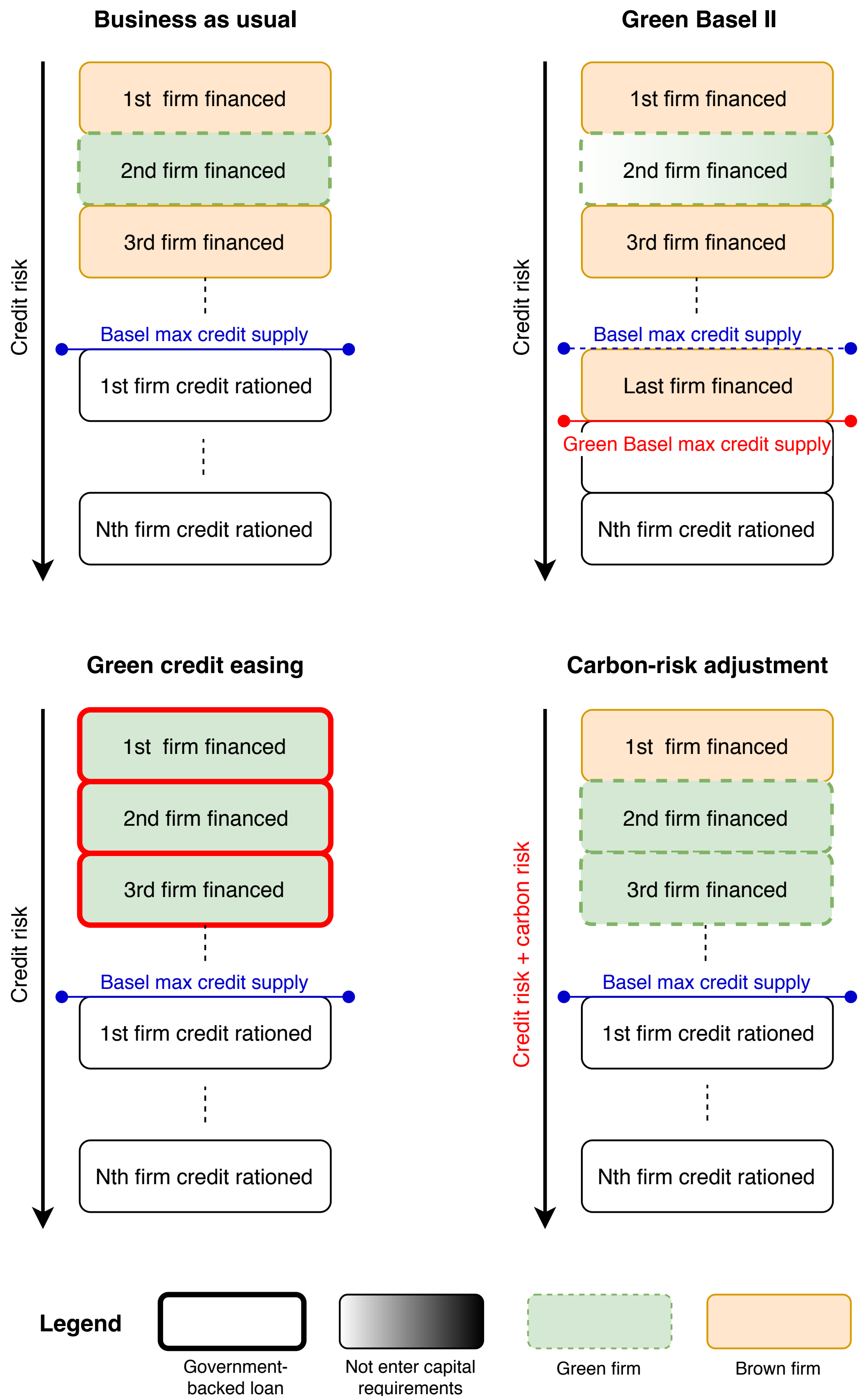


Figure 7: Schematic representation of the financial policy tools examined in this study and their effects on credit provision. Policy interventions are indicated in black color.

5.2 Policy experiments: the micro mechanisms

Each of the three policies that we consider modify green firms' access to credit with respect to the baseline, though in different ways. In turns, altered credit conditions affect the interplay between the productivity- and fragility enhancing effects discussed in the previous section (see Figure 8).

Intuitively, *green credit easing* guarantees that all loans requests filed by green firms are accepted by banks examining them, as the credit risk is completely bore by the government and these assets become - substantially - risk free. *Carbon risk adjustment* produces a prompt increase in the share of green firms receiving credit, which roughly doubles with respect to the baseline. However, the effect is temporary and tends to shrink in the long run, signalling worse credit risk for green businesses. Green firms financed under the *green Basel II* policy scheme rise in the aftermath of policy implementation and stabilize later. How these policies play out depends on the trade-off between the productivity-enhancing and the fragility-enhancing effects of credit provision (see Section 4). To recall, even though access to credit has - on average - a positive effect on firms' performance, when it is provided to firms that are not financially sound it might increase their likelihood of insolvency. Hence, while investments into green firms favour emission reductions and mitigate future physical risks (consistently with Ponta et al., 2018), they can move banks' exposure towards less credit-worth businesses.

Indeed, figure 8 shows that *carbon risk adjustment* and, especially, *green credit easing* entail a short vs. long run trade-off reflecting whether the productivity- or fragility- enhancing effect prevails. While in the short run, penalizing balance-sheet indicators with respect to environmental ones does not affect the relative performance of green (vis-á-vis brown) businesses, over the long run the cumulative effects linked to a progressive deterioration of credit quality substantially reduces productivity, and then competitiveness and market shares.[27] Contrarily, the *green Basel II* policy scheme improves the relative performance of green firms (both in terms of productivity and financial conditions) in the short run, while loosing efficacy over time. Such behaviour is driven by two factors: (i) the policy increases the share of green firms receiving credit yet maintaining the creditworthiness-based ranking in loans' allocation and interest rates setting, and (ii) it expands credit supply, but just until when firms' credit-worth ranking is stabilized.

Tacking stock of such effects over time, it is relevant inspecting how our policies perform with respect to the baseline scenario. Table 4 reports such information, disaggregating between firms receiving credit (binned into quartiles based on their credit risk) and the average firm in the economy. Figures

[27] Productivity affects costs and prices, which in turn determines firms' competitiveness in terms of ability to attract final demand (see Section 6).

in the table are expressed as averages along the simulation normalised by the corresponding value in the baseline: for example, a coefficient of 0.92 indicates that the experiment delivers an average value corresponding to 92% of the baseline counterpart. All three policies reduce the productivity-enhancing effect of credit provision, while exacerbating the fragility-enhancing effect. Such mechanism become increasingly stronger for middle-bottom and bottom quartiles of externally financed firms. This result highlights the strong destabilizing role of credit supplied to fragile businesses, in line with Minskyan-type dynamics. However, the *green Basel II* policy improves both the average productivity of the economy and its credit quality, thanks to the expansionary effect of credit supply, which is also well visible in figures 1 and 2. Indeed, the *green Basel II* scheme is the only intervention altering, everything else being equal, the total supply of credit. In that, firms can enjoy the positive effect of additional loan provision on their investment rate (see the discussion in Section 4). On the contrary, the increased exposure of banks - which is made possible by the presence of green firms in the ranking - is not sufficiently large to show the destabilizing effects of systematically reducing capital requirements (see Figure 4, middle and bottom panels). Our model suggests that credit provision does not harm the economy per-se, but fragility crucially depends on the mechanism of credit allocation. Intuitively, the downside of a *green Basel II* policy consists in a modest efficacy at financing green businesses that, coupled with larger effects on productivity gains that stimulate demand and growth, might fail to cut the total amount of emissions. The analysis of aggregate dynamics follows in section 5.3.1.

By altering banks' exposure towards green vs. brown firms, each policy affects the operative results and balance-sheet conditions in the banking industry with respect to the baseline (see Table 5, where values deserve the same interpretation as in Table 4). The worsening of firms' creditworthiness under *carbon risk adjustment* has the detrimental effect of increasing the instability of banks, which turn out with losses on loans that are about 30% larger than in the baseline and cause a +11% surge in the average periods of negative profits. The immediate consequence of such phenomenon is a reduction of the total supply of credit to the real economy via equity shrinkages (cf. equation 1). In contrast, *green credit easing* moves credit risk away from the banking sector, which is substantially unaffected by the policy: even though the insolvency likelihood of firms increases, the economic consequences of an higher number of bankruptcies are borne by the government and credit provision is thus unaffected by bad debt. *Green Basel II* adversely affects banks' profitability - though to a lesser extent than risk adjustment - but significantly enlarges the supply of credit to the economy (+26% with respect to the baseline).

Overall, two complementary insights emerge from the inspection of the micro-level effects that our policy schemes produce. On one side, when credit allocation decisions start including environmental factors beyond balance-sheet indicators, the fragility-enhancing effect of loan provision risks outweighing the productivity-enhancing effect, with harmful implications to bank stability. On the other, allowing banks exposed to green firms to enlarge credit supply enhances productivity growth and - on average - firms' financial conditions. In the next section, we discuss the macroeconomic implications of such effects both in absence and presence of the climate-related damages caused emissions that are differently mitigated by each policy scheme.

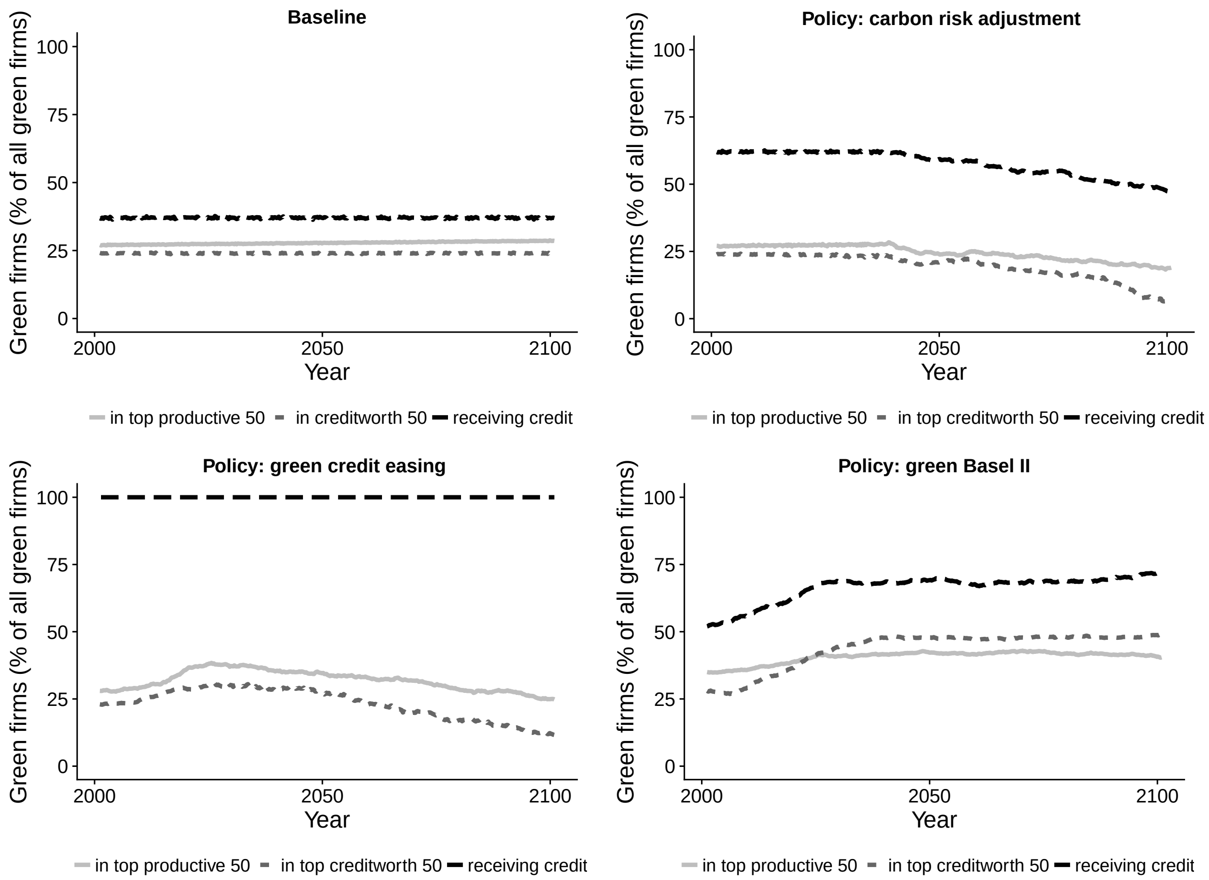


Figure 8: Graphical representation of the effects of green financial policies examined in this study on the relative performance (with respect to the average firm) and access to credit of green firms over the simulation period and in absence of climate change. Lines represent averages across 300 independent runs.

5.3 Policy experiments: aggregate impacts

The aggregate impacts of climate-finance policies depend on the characteristics of the economic system as well as the intensity and nature of climate damages. We compare a scenario with no climate-related impacts with another one characterized by high responsiveness of climate damages to the temperature (in line with Weitzman, 2009; Burke et al., 2015; Hsiang et al., 2017). First, we examine the effects of

Table 4: Effects of the green financial policies on the performance of firms receiving credit in absence of climate change (relative to the baseline: each coefficient reports the average value in the relevant experiment normalised by the corresponding value in the baseline configuration). "Top" means most creditworth. Two-sided t-tests with H_0: "no difference between no policy (baseline) and the policy (the experiment)" in parentheses are performed; (**) the null hypothesis is rejected at 1% level, (*) at 5% significance level. † indicates that the null hypothesis of equal distributions of the variables is rejected according to a Mann-Whitney-Wilcoxon test at 5% significance level.

Policy	**Variable**	**Quartile of firms ranked on creditworthiness**				**Average firm**
		top	**middle-top**	**middle-bottom**	**bottom**	
Baseline (BAU)	productivity 1y ahead	1	1	1	1	1
Risk adjustment		0.92**†	0.88**†	0.84**†	0.8**†	0.89**†
Credit easing		0.75**†	0.77**†	0.81**†	0.85**†	0.85**†
Green Basel II		1.01	0.98	0.97	0.96*	1.26**†
Baseline (BAU)	creditworthiness 1y ahead	1	1	1	1	1
Risk adjustment		0.86**†	0.72**†	0.64**†	0.41**†	0.76**†
Credit easing		0.66**†	0.69**†	0.78**†	0.82**†	0.73**†
Green Basel II		0.96	0.95*†	0.92**†	0.90**†	1.15**†

Table 5: Effects of the green financial policies examined in this study on the performance of banks in absence of climate change (relative to the baseline: each coefficient reports the average value in the relevant experiment normalised by the corresponding value in the baseline configuration). Two-sided t-tests with H_0: "no difference between no policy (baseline) and the policy (the experiment)" in parentheses are performed; (**) the null hypothesis is rejected at 1% level, (*) at 5% significance level. † indicates that the null hypothesis of equal distributions of the variables is rejected according to a Mann-Whitney-Wilcoxon test at 5% significance level.

Policy	**Losses on loans**	**Frequency of periods with negative profits**	**Total credit supply**
Baseline (BAU)	1	1	1
Risk adjustment	1.31**†	1.11**†	0.92*†
Credit easing	0.91**†	0.93*†	1.08*†
Green Basel II	1.10**†	1.05	1.26**†

one policy at the time (cf. section 5.3.1) and, second, the case of a policy mix (cf. section 5.3.2).

5.3.1 Green financial policies: individual effects

Table 6 collects the results of our policy experiments with and without the impact of climate change. The main difference between the two scenarios lies in the ability of the various policies to mitigate emissions growth and the associated damages.

Let us start with our central results about policy effectiveness under climate change. All three mechanisms act as mild mitigation policies, allowing a reduction of emissions growth rates and thus softening climate damages (see also Raberto et al., 2018). The mitigation mechanism behind a *green Basel II* policy goes through an increase in the pace of renovation of the capital stock (which is stimulated by climate damages) with machines that, thanks to technical change, are (on average) more productive and less emission-intense. In general, *carbon risk adjustment* is the least effective intervention, suggesting that information disclosure on emission intensity and the inclusion of carbon risk in credit allocation are not sufficient to redirect technology and production toward sustainable growth and to absorb increased financial fragility.

Thanks to the productivity-enhancing effect green capital requirements significantly improve the growth performance of the economy when climate shocks affect capital, as also emerged in Section 4. However, such effect is not significant when rising temperatures depress the productivity of firms. These results are consistent with the evidence collected in Figure 4 (top right panel). Looser credit conditions - which allow banks to increase credit supply - induce a disproportionately stronger effect on firms' investment rate when climate change impacts the capital stock of firm. Such effect is also preserved - yet lessened - in the scenario where both capital and labour productivity impacts are considered. Credit easing through government-backed loans to green firms significantly enhances banking stability across all impact scenarios (see Table 12 and section 5.1); indeed, it acts as a system-stabilizer thanks to its countercyclical nature. When the economy enters a downturn and the likelihood of firm bankruptcy raises, green credit guarantees alleviate the negative impact of non-performing loans on the balance-sheets of banks, preserving their ability to lean (against the wind, and prioritizing green firms). This mitigates the "automatic destabilizer" effect of procyclical standard Basel II capital requirements (Dosi et al., 2015; Popoyan et al., 2017) and leverage the productivity-enhancing effect of credit provision. The downside of credit easing policies is that they enlarge the burden of public debt and, especially when left alone (i.e. without any other intervention), the average debt to GDP ratio sensibly increases with respect to the baseline.[28]

Both beneficial and adverse effects of *green credit easing* are exacerbated by climate shocks: while public guarantees on loans are obviously more effective when counterparty risk increases, more frequent failures impose a larger burden on public finances. Similarly, the concerns to productivity growth that *carbon risk adjustment* brings about amplify under climate damages, as such policy does not entail any direct mechanism that balances either the decrease in investment propensity or the increased default rates that comes with labour and capital shocks (crf. Figure 4, top right panel). To the opposite, non-performing loans shrink banks' equities and further reduce credit supply. Intuitively, the effectiveness of green financial policies introducing a distortion in the supply of credit depends on the actual coun-

[28]In particular, the debt to GDP ratio augments with respect to the BAU case, and then stabilizes with minor fluctuations around the historical average.

terbalancing of risks that would not be accounted otherwise. This is evident from Panel A in Table 6, where policies are analyzed in absence of climate change and hence, long-run physical risks. *Carbon risk adjustment* and *green credit easing* significantly weakens the performance of the economy (consistently with analysis of section 5.1), though their effects on the banking sector are substantially different. Carbon-risk adjustment tends to hamper GDP growth and, further, it exacerbates financial instability by increasing banks' failure rate. Indeed, when the economy does not suffer from climate damages and emission reductions yields no effects on firms' activities, the credit risk of firms uniquely depends on their financial structure, and any attempt to foster green investments altering credit allocation decisions increases the fragility of the system and the burden of public debt, either via bailout costs or paying back the guarantee on green loans. Such costs, which are due to an increase in the credit risk the economy has to bear, come along with a cut of the growth rate of emissions (by 5% and 7% respectively) that, in contrast, reduces the long run physical risks of climate change. Thanks to mitigation, *green credit easing* proves to be more effective at reducing banking crisis under climate change than without it. Differently, *green Basel II* exploits the prevalence of the productivity-enhancing effect of credit provision and boosts the performance of the economy, but fails to produce any significant mitigation effect.

5.3.2 Green financial policies: policy mix

Table 6 compares the effects of all policies to their joint combination with and without climate impacts. To ease their readability, results obtained testing policy mixes composed of couples of instruments are visible in figure 9; the interested reader finds in Appendix 6 detailed tables summarizing and statistically testing all policy combinations.

The negative effects of green-financial policies are partially washed-out when the interventions are combined. Indeed, a policy mix composed of the three tools allows the economy moving towards (i) higher growth, (ii) enhanced banking stability and thinner public debt and (iii) sensibly lower carbon emissions. This virtuous cycle dynamically reduces the destabilizing effects of climate change, thus spurring output growth (averaging +21% with respect to the baseline) and shrinking bank failures (averaging -21% with respect to the baseline). Our results suggest the non-additivity of macroprudential policy tools (in line with Popoyan et al., 2017). Green financial policies are more powerful when capital stock impacts are considered (see Table 6 and contrast panel A with panel B). As mentioned above, the productivity-enhancing role of credit provision tend to dominate when firms need additional credit to cope with capital losses induced by climate change. Indeed, capital renewal fosters the diffusion of novel and relatively more productive machines, while credit easing absorbs risks stemming from an increased

Table 6: **Normalized values of target macroeconomic variables across policy experiments**. Absolute value of simulation t-statistic of two-sided tests with H_0: "no difference between no policy (baseline) and the policy (the experiment)" in parentheses; (**) the null hypothesis is rejected at 1% level, (*) at 5% significance level. † indicates that the null hypothesis of equal distributions of the variables is rejected according to a Mann-Whitney-Wilcoxon test at 5% significance level. Values and tests are based on 300 independent model runs for each policy experiment. The value corresponding to the business as usual (no policy, i.e. our baseline) is used to normalize and shown between brackets. The scenario "With climate impacts" refers to the case with both labor and capital shocks.

	GDP growth	# Bank bailouts	Debt to GDP	Emissions growth
Panel A: *No climate impacts*				
Baseline (BAU)	1 [0.032]	1 [0.014]	1 [0.82]	1 [0.019]
Risk adjustment	0.92**†	1.14**†	1.39**	0.95*
	(2.35)	(2.98)	(4.71)	(1.92)
Green credit easing	1.11*	0.90*†	1.42**†	0.93**†
	(1.78)	(1.87)	(4.33)	(2.10)
Green Basel II	1.17**†	1.06	0.87**†	0.99
	(2.25)	(1.48)	(8.26)	(0.86)
Policy mix	1.15**†	0.85**†	1.27**†	0.86**†
	(2.49)	(3.52)	(6.39)	(4.57)
Panel B: *With climate impacts (capital and labour).*				
Baseline (BAU)	1 [0.024]	1 [0.035]	1 [2.09]	1 [0.014]
Risk adjustment	0.90**†	1.09*	1.04	0.95*
	(2.53)	(1.82)	(1.49)	(1.88)
Green credit easing	1.15*†	0.85**†	1.11*†	0.92**†
	(2.58)	(2.77)	(1.84)	(2.70)
Green Basel II	1.11*†	0.94	0.95*	0.93*†
	(1.80)	(1.87)	(1.70)	(1.88)
Policy mix	1.24**†	0.71**†	0.97*	0.76**†
	(3.50)	(6.04)	(1.78)	(4.02)

leverage that firms must sustain. Instead, when labour productivity is impacted by the climate, our set of green financial policies are less effective in counterbalancing the long run effects (Figure 9 and Tables 11-14). In those circumstances, policymakers should rely more on adaptation and mitigation policies outside the banking system or affecting different channels with respect to those explored in this paper.

Further, we find either synergetic or conflicting effects when the proposed policy mechanisms are coupled. Indeed, while it is intuitive that they all channel funds towards green firms, the impact of their interactions on the stability of the banking sector and public finances is less obvious. Coupling green capital requirements with government-backed loans raises growth (+13% under labor-productivity damages and +30% under capital damages; see Table 11) and stability (bailouts are reduced by 20% under labor productivty damages and 14% under capital damages; see Table 12), without worsening the debt to GDP ratio (see Table 13). Government-backed loans indeed mitigate the risk associated with banks' credit expansion under the *green Basel II* rule. Such complementary relationship becomes particularly relevant when climate damages affect labour productivity, and the positive effect of credit expansion brought about by *green Basel II* shrinks (see Sections 5.1 and 5.3.1). Intuitively, the productivity-enhancing effect of additional credit provision is out-weighted by the direct effect of the climate, and the instability-enhancing effect tend to prevail. On the contrary, the *green Basel II* policy does not provide significant benefits when coupled with carbon-risk adjustment, which acts a milder surrogate of green credit easing in channelling funds to green businesses but does not insulate the banking system from the ensuing risks. Indeed, we find evidence of negative interactions (indicating substitutability) between green credit guarantees and carbon-risk adjustment: their combination increases debt in all the impact scenarios, with a tiny effect on the dynamics of output and emissions (see Tables 11 and 14), signalling that excessive green financing might be detrimental to financial stability (Matikainen, 2017).

Overall, results point to dominance of positive interactions, especially in presence of climate impacts. The emission mitigating effect induced by both *carbon risk adjustment* and *green credit easing* is not affected by their coupling with *green Basel II* capital requirements. To the opposite, the downside effects of the former (enhanced financial fragility and/or lower growth) are more than off-set by the policy mix. In particular, the productivity-enhancing effect of the *green Basel II* framework counterbalances the detrimental impact of public guarantees on productivity advances, while the higher risk of financial instability due to *carbon risk adjustment* is absorbed by the *green credit easing* insurance scheme. The first of these two phenomena is reinforced by climate shocks, which increase the willingness of firms to invest in new machines. Hence, coupling the three green financial policies proposed in this paper seems providing sufficient conditions for a win-win-win virtuous cycle that balances the productivity-enhancing effects of credit provision to green firms and the additional risk than credit growth brings about.

Notwithstanding these results, simulation outcomes show that the aggregate macroeconomic costs of climate impacts are still large for any combination of green-financial policies (see Tables 11 and 12), which cannot provide full adaptation and complete resilience of our economic system to the negative effects of strong climate change as in an SSP5-like future like the one we test in this paper. This is in line with the results in Lamperti et al. (2018b), Dafermos et al. (2018) and Hannam et al. (2015) and calls for wider combination of interventions — including fiscal, innovation and industrial policies — jointly acting on different aspects of the economic system to reduce emissions and foster system resilience.

6 Discussion and conclusions

Recent studies showed both that damages of unmitigated climate changes could be substantially increased by banking crises and more generally financial market instability (Battiston et al., 2016; Lamperti et al., 2019; Dafermos et al., 2018; Monasterolo, 2020) and that the banking system is already exposed to climate physical risks (Noth and Schüwer, 2014). At the same time, banks have a pivotal role to foster the transition to sustainable growth by channelling credit towards green firms and exposures away from carbon-intense assets. A smooth transition would require a system that mitigates emissions while keeping the banking system stable in the face of physical and transition risks.

In this paper, we shed light on such issues by extending the *Dystopian Schumpeter meeting Keynes (DSK)* model (Lamperti et al., 2018a,b) to account for decentralized credit interactions between heterogeneous banks and firms. The model is employed to study the coevolution of climate change, financial stability, business cycles and endogenous growth. We then use such framework as a "laboratory" to test the impact of three "green" financial policies, namely green Basel-type capital requirements, green public guarantees to credit, and carbon-risk adjustment in credit ratings. Our attention is on the interplay of physical risks, green investment and credit market regulations, while we do not consider climate-policy risks (e.g. stranded assets).

We find that the DSK model is able to account for coupled climate and economic dynamics and to reproduce a large ensemble of micro and macro regularities concerning credit and real-economy dynamics. Despite the indirect calibration approach we follow is not adequate to deliver quantitative predictions, we obtain a set of robust qualitative insights. We isolate two outcomes of credit provision on firms and banks' performance: a productivity-enhancing effect linked to investment in more productive and greener capital goods and a fragility-enhancing effect due to increased leverage. Banking sector instability magnifies the impact of climate change via firm bankruptcies and endogenously-emerging banking crises. Green-financial policy tools alter the mechanism of credit allocation and, hence, firms' investment into new capital goods. The three policy always mitigate carbon emissions, but their impact on the financial and real sectors, as well as on public finance is not trivial due to the non-linear effects stemming from the interactions of credit supply and heterogeneous climate damages hitting firms. However, the emergent non-additivity of the policies seems beneficial to the system: the combination of the three green financial interventions provides a sufficient condition for a win-win-win virtuous cycle of (i) sustained growth, (i) enhanced banking resiliency and lower public debt, and (i) mitigated emissions. While in-

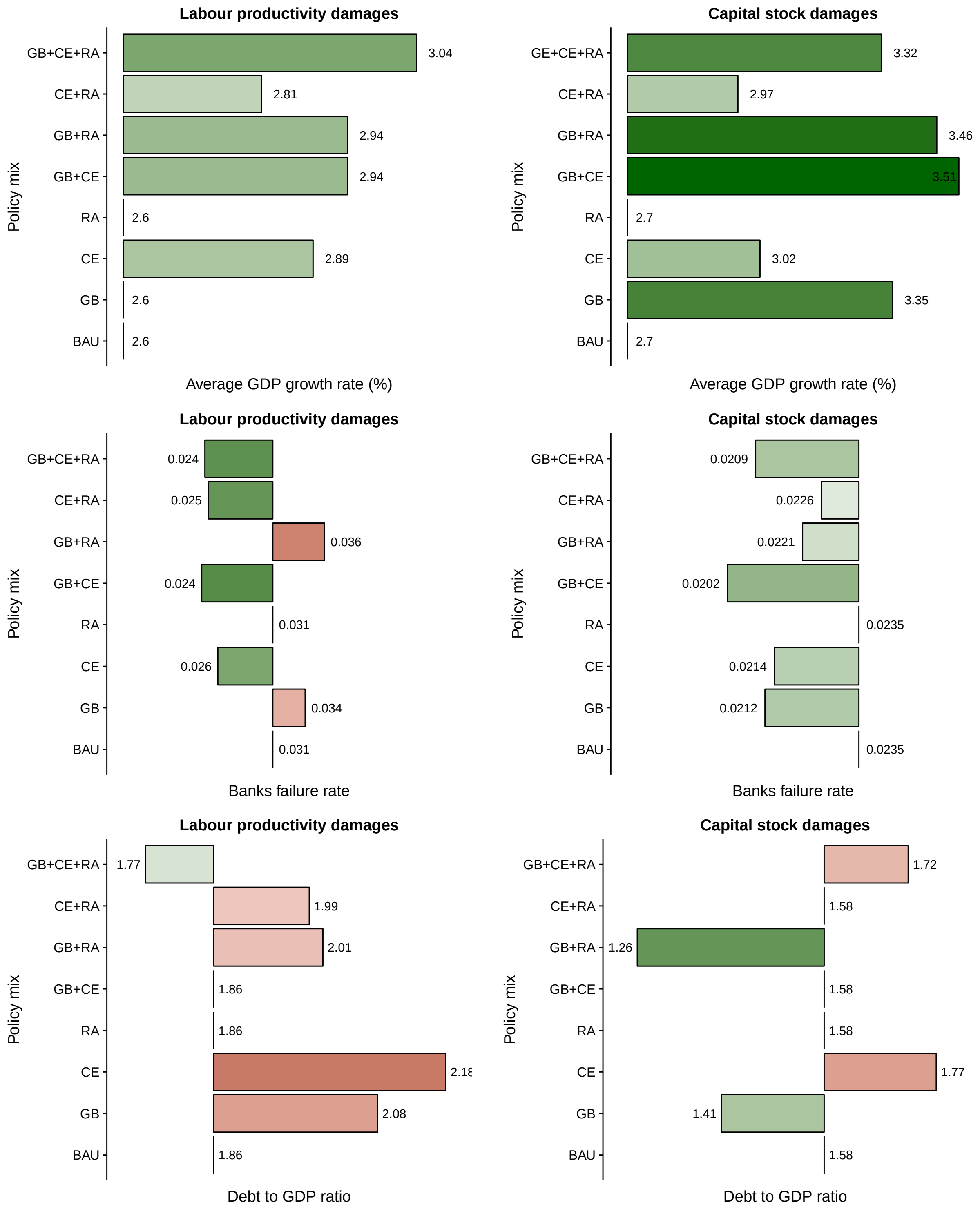


Figure 9: Graphical representation of the effects of different policy combinations on average output growth rate, banks failure rate and debt to GDP ratio. The graph is centered on the business as usual (BAU); colors indicate the strength of variation with respect to the BAU, with green pointing to improvements and black to worsening. Policy schemes that do not produce statistically significant differences with respect to the BAU report values corresponding to the BAU. Tests' p-value and t-statistic are reported in Tables 11, 12 and 13.

triguing, we interpret these sufficient conditions with caution: our results suggest that, at least for the parameter configuration the model is calibrated to and for the implementation we have considered, the three policies allow solving the fragility-productivity-emission trade-offs that emerge when they are disjointed; however, calibration to region- or country- specific data would be needed to guide policy design in practice.

Our findings underline the importance of coupling green Basel requirements (as advocated in Campiglio, 2016) with government's intervention cooling down the risks from green projects (Safarzyńska and van den Bergh, 2017; Monasterolo and Raberto, 2018; Raberto et al., 2018) and backing green loans. Indeed, the instability provided by regulations aimed at increasing the appeal of green assets - which might be of lower credit quality than brown ones (Mazzucato and Semieniuk, 2018)- can be complemented by the expansionary effects of credit supply. However, as climate damages might out-weight these beneficial impacts of credit fuelling and exacerbate its fragility-enhancing mechanism, a public guarantee on green assets is needed to insulate the banking system, which would reduce losses and restore the efficacy of the credit channel. In that, our results are consistent with the discussion in Krogstrup and Oman (2019), where the authors stress that emission-mitigating credit allocation policies implemented by central banks and financial regulators might have real effects comparable to fiscal policies. Despite we acknowledge this could be an issue for central banks' independence, we believe that - if proved successful against the threat of large climate risks - green financial policies can be used to supplement more standard climate policy tools to put the economy on a zero-emission sustainable growth path.

Before discussing possible extensions of our work we acknowledge a limitation. Our results hold for the parameter configuration we retrieve through calibration. Although it results in simulated dynamics that allow extensive stylised facts replication, a global sensitivity analysis could provide additional robustness to our findings. We leave such exercise to future research, perhaps relying upon surrogates to remove constraints on computational time (e.g. Lamperti et al., 2018). Our work can be further expanded in different dimensions. First, we could introduce other climate shocks affecting e.g. energy efficiency or inventories and study their effects of macro-financial dynamics. Relatedly, the same policy and impact assessments performed in this paper can be re-evaluated using alternative formulations of climate damages, for example relying on estimates from the blossoming climate econometrics literature (see Hsiang, 2016, for a survey). Second, we should provide a richer characterization of the financial system in order to study the impact of other green policies such as green quantitative easing and the possible role of a public investment bank supporting investment in sustainable technologies. Finally, we should better analyze the possible interactions between green-financial policies and firms' technological and investment decisions. Indeed, the introduction of an environmental-friendly financial regulation could induce firms to reduce their emissions by "greening" their production, thus boosting the impact of these new policies.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 822781- GROWINPRO. The authors thank Giovanni Dosi, Giorgio Fagiolo, Mauro Napoletano and Alessandro Sapio for having contributed to previous versions of the model used in this paper. The authors also thank Mattia Guerini for having contributed to managing the code the present analysis has built on. The authors are also grateful to all participants to EAEPE 2019 and 2020 annual conferences for useful discussions.

References

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2012). The environment and directed technical change. *American Economic Review 102*(1), 131–66.

Akerlof, G. A. (2002). Behavioral macroeconomics and macroeconomic behavior. *American Economic Review 92*(3), 411–433.

Ascari, G., G. Fagiolo, and A. Roventini (2015). Fat-tails distributions and business-cycle models. *Macroeconomic Dynamics 19*, 465–476.

Assenza, T., D. D. Gatti, and J. Grazzini (2015). Emergent dynamics of a macroeconomic agent based model with capital and credit. *Journal of Economic Dynamics and Control 50*, 5 – 28. Crises and Complexity - Complexity Research Initiative for Systemic InstabilitieS (CRISIS) Workshop 2013.

Attanasio, A., A. Pasini, and U. Triacca (2012). A contribution to attribution of recent global warming by out-of-sample granger causality analysis. *Atmospheric Science Letters 13*(1), 67–72.

Ausloos, M., J. Miśkiewicz, and M. Sanglier (2004). The durations of recession and prosperity: does their distribution follow a power or an exponential law? *Physica A: Statistical Mechanics and its Applications 339*(3–4), 548 – 558.

Balint, T., F. Lamperti, A. Mandel, M. Napoletano, A. Roventini, and A. Sapio (2017). Complexity and the economics of climate change: a survey and a look forward. *Ecological Economics 138*, 252–265.

Bartelsman, E. J. and M. Doms (2000). Understanding productivity: Lessons from longitudinal microdata. *Journal of Economic literature 38*(3), 569–594.

Battiston, S., G. Caldarelli, M. D'Errico, and S. Gurciullo (2016). Leveraging the network: a stress-test framework based on debtrank. *Statistics & Risk Modeling 33*(3-4), 117–138.

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

Battiston, S. and I. Monasterolo (2020a). Assessing forward-looking climate risks in financial portfolios: A science-based approach for investors and supervisors. In M. Jun, B. Caldecott, and U. Volz (Eds.), *Case Studies of Environmental Risk Analysis Methodologies*, pp. 52–72.

Battiston, S. and I. Monasterolo (2020b). The climate spread of sovereign and corporate bonds. Available at SSRN (abstract id=3376218).

Bikker, J. A. and P. A. Metzemakers (2005). Bank provisioning behaviour and procyclicality. *Journal of international financial markets, institutions and money 15*(2), 141–157.

Blanchard, O., E. Cerutti, and L. Summers (2015). Inflation and Activity – Two Explorations and their Monetary Policy Implications. NBER Working Papers 21726, National Bureau of Economic Research, Inc.

Bottazzi, G. and A. Secchi (2003). Common properties and sectoral specificities in the dynamics of us manufacturing companies. *Review of Industrial Organization 23*(3-4), 217–232.

Bottazzi, G. and A. Secchi (2006). Explaining the distribution of firm growth rates. *The RAND Journal of Economics 37*(2), 235–256.

Burke, M., S. M. Hsiang, and E. Miguel (2015). Global non-linear effect of temperature on economic production. *Nature 527*(7577), 235.

Burns, A. F. and W. C. Mitchell (1946). *Measuring Business Cycles*. National Bureau of Economic Research.

Caiani, A., A. Godin, E. Caverzasi, M. Gallegati, S. Kinsella, and J. E. Stiglitz (2016). Agent based-stock flow consistent macroeconomics: Towards a benchmark model. *Journal of Economic Dynamics and Control 69*, 375 – 408.

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

Carleton, T. A. and S. M. Hsiang (2016). Social and economic impacts of climate. *Science 353*(6304), aad9837.

Carnevali, E., M. Deleidi, R. Pariboni, and M. V. Passarella (2020). Cross-border financial flows and global warming in a two-area ecological sfc model. *Socio-Economic Planning Sciences*, 100819.

Castaldi, C. and G. Dosi (2009). The patterns of output growth of firms and countries: Scale invariances and scale specificities. *Empirical Economics 37*(3), 475–495.

Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni (2009). International climate policy architectures: Overview of the EMF 22 international scenarios. *Energy Economics suppl. 2*(31), S64–S81.

Clò, S., A. Cataldi, and P. Zoppoli (2015). The merit-order effect in the italian power market: The impact of solar and wind generation on national wholesale electricity prices. *Energy Policy 77*, 79–88.

CTI (2018). Mind the gap: The 1.6 trillion energy transition risk. Technical report, Carbon Tracker Initiative.

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

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

Dawid, H. and D. Delli Gatti (2018). Agent-based macroeconomics. In C. Hommes and B. LeBaron (Eds.), *Handbook of Computational Economics, Volume IV*. Elsevier.

DeCanio, S. J. and W. E. Watkins (1998). Investment in energy efficiency: do the characteristics of firms matter? *Review of Economics and Statistics 80*(1), 95–107.

Dell, M., B. F. Jones, and B. A. Olken (2009). Temperature and income: Reconciling new cross-sectional and panel estimates. *American Economic Review 99*(2), 198–204.

Dell, M., B. F. Jones, and B. A. Olken (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics 4*(3), 66–95.

Dell, M., B. F. Jones, and B. A. Olken (2014). What do we learn from the weather? the new climate–economy literature. *Journal of Economic Literature 52*(3), 740–798.

Di Guilmi, C., M. Gallegati, and P. Ormerod (2004). Scaling invariant distributions of firms' exit in oecd countries. *Physica A: Statistical Mechanics and its Applications 334*(1-2), 267–273.

Diaz, D. and F. Moore (2017). Quantifying the economic risks of climate change. *Nature Climate Change 7*(11), 774–782.

Diaz-Rainey, I., B. Robertson, and C. Wilson (2017). Stranded research? leading finance journals are silent on climate change. *Climatic Change 143*(1-2), 243–260.

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

Dietz, S., E. French, C. Garcia-Manas, W. Irwin, P. Jackson, B. Rauis, R. Sullivan, and J. Sung (2017). Management quality and carbon performance of cement producers. Technical report, Transition Pathway Initiative.

Dikau, S. and J. Ryan-Collins (2017). Green central banking in emerging market an developing country economies. Technical report, New Economics Foundation.

Doda, B. (2014). Evidence on business cycles and emissions. *Journal of Macroeconomics 40*, 214 – 227.

Doms, M. and T. Dunne (1998). Capital adjustment patterns in manufacturing plants. *Review of Economic Dynamics 1*(2), 409–429.

Dosi, G. (2007). Statistical regularities in the evolution of industries. a guide through some evidence and challenges for the theory. In F. Malerba and S. Brusoni (Eds.), *Perspectives on innovation*, pp. 1110–1121. Cambridge University Press.

Dosi, G., G. Fagiolo, M. Napoletano, and A. Roventini (2013). Income distribution, credit and fiscal policies in an agent-based Keynesian model. *Journal of Economic Dynamics and Control 37*(8), 1598 – 1625. Rethinking Economic Policies in a Landscape of Heterogeneous Agents.

Dosi, G., G. Fagiolo, M. Napoletano, A. Roventini, and T. Treibich (2015). Fiscal and monetary policies in complex evolving economies. *Journal of Economic Dynamics and Control 52*, 166 – 189.

Dosi, G., G. Fagiolo, and A. Roventini (2010). Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles. *Journal of Economic Dynamics and Control 34*(9), 1748–1767.

Dosi, G., M. Napoletano, A. Roventini, and T. Treibich (2017). Micro and macro policies in the keynes+ schumpeter evolutionary models. *Journal of Evolutionary Economics 27*(1), 63–90.

Dosi, G., M. Pereira, A. Roventini, and M. E. Virgillito (2017). When more flexibility yields more fragility: the microfoundations of keynesian aggregate unemployment. *Journal of Economic Dynamics & Control 81*, 162–186.

Dosi, G., M. C. Pereira, A. Roventini, and M. E. Virgillito (2018). Causes and consequences of hysteresis: Aggregate demand, productivity and employment. *Industrial and Corporate Change 27*, 1015–1044.

Dosi, G. and A. Roventini (2019). More is different ... and complex! the case for agent-based macroeconomics. *Journal of Evolutionary Economics forthcoming*.

Dunz, N., A. Naqvi, and I. Monasterolo (2020). Climate transition risk, climate sentiments, and financial stability in a stock-flow consistent approach. *Journal of Financial Stability* (forthcoming). available at SSRN (abstract id= 3520764).

D'Orazio, P. and L. Popoyan (2019). Fostering green investments and tackling climate-related financial risks: which role for macroprudential policies? *Ecological Economics 160*, 25–37.

EBP (2018). Towards a green finance framework.

Fagiolo, G., C. Birchenhall, and P. Windrum (2007). Empirical validation in agent-based models: Introduction to the special issue. *Computational Economics 30*(3), 189–194.

Fagiolo, G., M. Guerini, F. Lamperti, A. Moneta, and A. Roventini (2019). Validation of agent-based models in economics and finance. In C. Beisbart and N. J. Saam (Eds.), *Computer Simulation Validation. Fundamental Concepts, Methodological Frameworks, Philosophical Perspectives.* Springer International Publishing; also available as Scuola Superiore Sant'Anna LEM Working Papers Series 2017/23.

Fagiolo, G., M. Napoletano, and A. Roventini (2008). Are output growth-rate distributions fat-tailed? some evidence from OECD countries. *Journal of Applied Econometrics 23*(5), 639–669.

Fagiolo, G. and A. Roventini (2012). Macroeconomic policy in DSGE and agent-based models. *Revue de l'OFCE 5*(124), 67–116.

Fagiolo, G. and A. Roventini (2017a). Macroeconomic policy in DSGE and Agent-Based Models redux: New developments and challenges ahead. *Journal of Artificial Societies and Social Simulation 20*(1), 1.

Fagiolo, G. and A. Roventini (2017b). Macroeconomic policy in DSGE and agent-based models redux: New developments and challenges ahead. *Journal of Artificial Societies and Social Simulation 20*(1).

Foos, D., L. Norden, and M. Weber (2010). Loan growth and riskiness of banks. *Journal of Banking & Finance 34*(12), 2929–2940.

Geels, F. W. (2013). The impact of the financial–economic crisis on sustainability transitions: Financial investment, governance and public discourse. *Environmental Innovation and Societal Transitions 6*, 67–95.

Gerst, M., P. Wang, A. Roventini, G. Fagiolo, G. Dosi, R. Howarth, and M. Borsuk (2013). Agent-based modeling of climate policy: An introduction to the ENGAGE multi-level model framework. *Environmental Modelling & Software 44*, 62 – 75. Thematic Issue on Innovative Approaches to Global Change Modelling.

Goldstein, A., W. R. Turner, J. Gladstone, and D. G. Hole (2018). The private sector's climate change risk and adaptation blind spots. *Nature Climate Change*, 1.

Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica 82*(1), 41–88.

Greenwald, B. C. and J. E. Stiglitz (1993). Financial market imperfections and business cycles. *The Quarterly Journal of Economics 108*(1), 77–114.

Guerini, M. and A. Moneta (2017). A method for agent-based models validation. *Journal of Economic Dynamics and Control 82*, 125–141.

Gurley, J. G. and E. S. Shaw (1955). Financial aspects of economic development. *The American Economic Review 45*(4), 515–538.

Haldane, A. G. and A. E. Turrell (2018). An interdisciplinary model for macroeconomics. *Oxford Review of Economic Policy 34*(1-2), 219–251.

Hannam, P. M., Z. Liao, S. J. Davis, and M. Oppenheimer (2015). Developing country finance in a post-2020 global climate agreement. *Nature Climate Change 5*(11), 983.

Hasselmann, K. and D. V. Kovalevsky (2013). Simulating animal spirits in actor-based environmental models. *Environmental Modelling & Software 44*, 10 – 24. Thematic Issue on Innovative Approaches to Global Change Modelling.

Hassler, J. and P. Krusell (2018). Chapter 8 - environmental macroeconomics: The case of climate change. In P. Dasgupta, S. K. Pattanayak, and V. K. Smith (Eds.), *Handbook of Environmental Economics*, Volume 4 of *Handbook of Environmental Economics*, pp. 333 – 394. Elsevier.

HLEG (2017). Financing a sustainable european economy. Technical report, European Commission. High Level Expert Group on Sustainable Finance - interim report.

HLEG (2018). Final report 2018 by the high-level expert group on sustainable finance.

Howitt, P. (1992). Interest rate control and nonconvergence to rational expectations. *Journal of Political Economy 100*(4), 776–800.

Hsiang, S. (2016). Climate econometrics. *Annual Review of Resource Economics 8*, 43–75.

Hsiang, S., R. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D. J. Rasmussen, R. Muir-Wood, P. Wilson, M. Oppenheimer, K. Larsen, and T. Houser (2017). Estimating economic damage from climate change in the united states. *Science 356*(6345), 1362–1369.

Jaimovich, N. and M. Floetotto (2008). Firm dynamics, markup variations, and the business cycle. *Journal of Monetary Economics 55*(7), 1238–1252.

Janicki, H. P. and E. S. Prescott (2006). Changes in the size distribution of us banks: 1960-2005. *Economic Quarterly 92*(4), 291–317.

Kindleberger, C. P. (1978). *Manias, panics, and crashes*. Basic Books.

Kolk, A., D. Levy, and J. Pinkse (2008). Corporate responses in an emerging climate regime: The institutionalization and commensuration of carbon disclosure. *European Accounting Review 17*(4), 719–745.

Krogstrup, S. and W. Oman (2019). Macroeconomic and financial policies for climate change mitigation: A review of the literature. Technical report, International Monetary Fund.

Kuznets, S. S. and J. T. Murphy (1966). *Modern economic growth: Rate, structure, and spread*, Volume 2. Yale University Press New Haven.

Laeven, L. and F. Valencia (2012). Systemic banking crises database: An update. IMF Working Papers 12/163, International Monetary Fund.

Laeven, L. and F. Valencia (2018). Systemic banking crises revisited. IMF Working Papers 18/206, International Monetary Fund.

Lamperti, F. (2018a). Empirical validation of simulated models through the gsl-div: an illustrative application. *Journal of Economic Interaction and Coordination 13*(1), 143–171.

Lamperti, F. (2018b). An information theoretic criterion for empirical validation of simulation models. *Econometrics and Statistics 5*, 83–106.

Lamperti, F., V. Bosetti, A. Roventini, and M. Tavoni (2019). The public costs of climate-induced financial instability.

Lamperti, F., G. Dosi, M. Napoletano, A. Roventini, and A. Sapio (2018a). And then he wasn't a she: Climate change and green transitions in an agent-based integrated assessment model. LEM working paper series, Scuola Superiore Sant'Anna, Institute of Economics.

Lamperti, F., G. Dosi, M. Napoletano, A. Roventini, and A. Sapio (2018b). Faraway, so close: Coupled climate and economic dynamics in an agent-based integrated assessment model. *Ecological Economics 150*, 315 – 339.

Lamperti, F., A. Mandel, M. Napoletano, A. Sapio, A. Roventini, T. Balint, and I. Khorenzhenko (2018). Towards agent-based integrated assessment models: examples, challenges, and future developments. *Regional Environmental Change*, 1–16.

Lamperti, F. and C. E. Mattei (2018). Going up and down: Rethinking the empirics of growth in the developing and newly industrialized world. *Journal of Evolutionary Economics 28*(4), 749–784.

Lamperti, F., M. Mazzucato, A. Roventini, and G. Semieniuk (2019). The green transition: Public policy, finance, and the role of the state. *Vierteljahrshefte zur Wirtschaftsforschung/Quarterly Journal of Economic Research 88*(2), 73–88.

Lamperti, F., I. Monasterolo, and A. Roventini (2019). Climate risks, economics and finance: Insights from complex systems. In *The Systemic Turn in Human and Natural Sciences*, pp. 97–119. Springer.

Lamperti, F., A. Roventini, and A. Sani (2018). Agent-based model calibration using machine learning surrogates. *Journal of Economic Dynamics and Control 90*, 366–389.

Leary, M. T. (2009). Bank loan supply, lender choice, and corporate capital structure. *The Journal of Finance 64*(3), 1143–1185.

Leaton, J. (2012). Unburnable carbon—are the world's financial markets carrying a carbon bubble. Technical report, Carbon Tracker Initiative.

Lown, C. and D. P. Morgan (2006). The credit cycle and the business cycle: new findings using the loan officer opinion survey. *Journal of Money, Credit and Banking*, 1575–1597.

Matikainen, S. (2017). Green doesn't mean risk-free: why we should be cautious about a green supporting factor in the eu. Technical report.

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

Matthews, H. D., S. Solomon, and R. Pierrehumbert (2012). Cumulative carbon as a policy framework for achieving climate stabilization. *Phil. Trans. R. Soc. A 370*(1974), 4365–4379.

Mazzucato, M. and G. Semieniuk (2018). Financing renewable energy: Who is financing what and why it matters. *Technological Forecasting and Social Change 127*, 8–22.

McFarland, J. M. (2008). Warming up to climate change risk disclosure. *Fordham J. Corp. & Fin. L. 14*, 281.

McGlade, C. and P. Ekins (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2 c. *Nature 517*(7533), 187.

Mendoza, E. G. and M. E. Terrones (2012). An anatomy of credit booms and their demise. Technical report, National Bureau of Economic Research.

Mercure, J.-F., H. Pollitt, A. M. Bassi, J. E. Viñuales, and N. R. Edwards (2016). Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. *Global Environmental Change 37*, 102 – 115.

Mercure, J. F., H. Pollitt, J. E. Viñuales, N. R. Edwards, P. B. Holden, U. Chewpreecha, P. Salas, I. Sognnaes, A. Lam, and F. Knobloch (2018). Macroeconomic impact of stranded fossil fuel assets. *Nature Climate Change 8*(7), 588–593.

Minsky, H. P. (1977). The financial instability hypothesis: An interpretation of keynes and an alternative to "standard" theory. *Challenge 20*(1), 20–27.

Minsky, H. P. (1986). *Stabilizing an Unstable Economy: The Lessons for Industry, Finance and Government*. Yale University Press.

Monasterolo, I. (2020). Climate change and the financial system. *Annual Review of Resource Economics 12*, 299–320.

Monasterolo, I., S. Battiston, A. C. Janetos, and Z. Zheng (2017). Vulnerable yet relevant: the two dimensions of climate-related financial disclosure. *Climatic Change 145*(3), 495–507.

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

Monasterolo, I., A. Roventini, and T. J. Foxon (2019). Uncertainty of climate policies and implications for economics and finance: An evolutionary economics approach. *Ecological Economics 163*, 177–182.

Montesquieu, d. (1748). *The Spirit of Laws*.

Moosa, I. A. (2000). Cyclical asymmetry in energy consumption and intensity: the japanese experience. *OPEC Review 24*(1), 53–59.

Napoletano, M., A. Roventini, and S. Sapio (2006). Are business cycles all alike? a bandpass filter analysis of Italian and US cycles. *Rivista Italiana degli Economisti 1*, 87–118.

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

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 201609244.

Noth, F. and U. Schüwer (2014). The effect of natural disasters on bank failures. *Available at SSRN 2506710*.

O'Neill, B. C., E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, and D. P. van Vuuren (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change 122*(3), 387–400.

Ozturk, I. (2010). A literature survey on energy–growth nexus. *Energy Policy 38*, 340–349.

Peters, G. P., G. Marland, C. Le Quere, T. Boden, J. G. Canadell, and M. R. Raupach (2012). Rapid growth in CO2 emissions after the 2008-2009 global financial crisis. *Nature Climate Change 2*(1), 2–4.

Petrick, S. et al. (2013). Carbon efficiency, technology, and the role of innovation patterns: evidence from german plant-level microdata. Technical report, Institute for the World Economy.

Pfeiffer, A., C. Hepburn, A. Vogt-Schilb, and B. Caldecott (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the paris agreement. *Environmental Research Letters 13*(5), 054019.

Ponta, L., M. Raberto, A. Teglio, and S. Cincotti (2018). An agent-based stock-flow consistent model of the sustainable transition in the energy sector. *Ecological Economics 145*, 274–300.

Popoyan, L., M. Napoletano, and A. Roventini (2017). Taming macroeconomic instability: Monetary and macroprudential policy interactions in an agent-based model. *Journal of Economic Behavior & Organization 134*, 117–140.

Punzi, M. T. (2019). Role of bank lending in financing green projects: A dynamic stochastic general equilibrium approach. *Handbook of Green Finance: Energy Security and Sustainable Development*, 1–23.

Raberto, M., B. Ozel, L. Ponta, A. Teglio, and S. Cincotti (2018). From financial instability to green finance: the role of banking and credit market regulation in the eurace model. *Journal of Evolutionary Economics*, 1–37.

Raberto, M., A. Teglio, and S. Cincotti (2012). Debt, deleveraging and business cycles: An agent-based perspective. *Economics: The Open-Access, Open-Assessment E-Journal 6*.

Reinhart, C. M. and K. S. Rogoff (2009). *This time is different: Eight centuries of financial folly*. princeton university press.

Rezai, A. and S. Stagl (2016). Ecological macroeconomics: Introduction and review. *Ecological Economics 121*, 181–185.

Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and P. Rafaj (2011). Rcp 8.5—a scenario of comparatively high greenhouse gas emissions. *Climatic Change 109*(1-2), 33.

Riahi, K., D. P. van Vuuren, E. Kriegler, J. Edmonds, B. C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J. C. Cuaresma, S. KC, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L. A. D. Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J. C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, and M. Tavoni (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change 42*, 153 – 168.

Rogoff, K. (2016). Extreme weather and global growth. Project Syndicate - Sustainability and Environment + Economics.

Rozenberg, J., A. Vogt-Schilb, and S. Hallegatte (2014). Transition to clean capital, irreversible investment and stranded assets. Policy Research Working Paper Series 6859, The World Bank.

Safarzyńska, K. and J. C. van den Bergh (2016). Integrated crisis-energy policy: Macro-evolutionary modelling of technology, finance and energy interactions. *Technological Forecasting and Social Change*.

Safarzyńska, K. and J. C. van den Bergh (2017). Financial stability at risk due to investing rapidly in renewable energy. *Energy Policy 108*, 12–20.

Sensfuß, F., M. Ragwitz, and M. Genoese (2008). The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in germany. *Energy policy 36*(8), 3086–3094.

Solow, R. M. (2005). Reflections on growth theory. In P. Aghion and S. N. Durlauf (Eds.), *Handbook of Economic Growth*, Volume 1, Part A, pp. 3 – 10. Elsevier.

Spencer, T. and J. Stevenson (2013). Eu low-carbon investment and new financial sector regulation: What impacts and what policy response. Technical report, IDDRI Sciences Po, Paris.

Sterman, J. D., T. Fiddaman, T. Franck, A. Jones, S. McCauley, P. Rice, E. Sawin, and L. Siegel (2013). Management flight simulators to support climate negotiations. *Environmental Modelling & Software 44*, 122–135.

Stiglitz, J. (2015). Towards a general theory of deep downturns. Working Paper 21444, NBER.

Stiglitz, J. E. and A. Weiss (1981). Credit rationing in markets with imperfect information. *The American Economic Review 71*(3), 393–410.

Stock, J. H. and M. W. Watson (1999). Business cycle fluctuations in us macroeconomic time series. In *Handbook of Macroeconomics*, Volume 1, Part A, pp. 3 – 64. Elsevier.

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

Taylor, J. B. (1993). Discretion versus policy rules in practice. In *Carnegie-Rochester conference series on public policy*, Volume 39, pp. 195–214. Elsevier.

Triacca, U. (2001). On the use of granger causality to investigate the human influence on climate. *Theoretical and Applied Climatology 69*(3-4), 137–138.

van der Hoog, S. and H. Dawid (2017). Bubbles, crashes, and the financial cycle: The impact of banking regulation on deep recessions. *Macroeconomic Dynamics*, 1–42.

Van Lerven, F. and J. Ryan-Collins (2018). Adjusting banks' capital requirements in line with sustainable finance objectives. *New Economics Foundation, Briefing note*.

van Vuuren, D. P., E. Kriegler, B. C. O'Neill, K. L. Ebi, K. Riahi, T. R. Carter, J. Edmonds, S. Hallegatte, T. Kram, R. Mathur, and H. Winkler (2014). A new scenario framework for climate change research: scenario matrix architecture. *Climatic Change 122*(3), 373–386.

Wälde, K. and U. Woitek (2004). R&D expenditure in G7 countries and the implications for endogenous fluctuations and growth. *Economics Letters 82*(1), 91–97.

Weitzman, M. L. (2009). On modeling and interpreting the economics of catastrophic climate change. *The Review of Economics and Statistics 91*(1), 1–19.

Weyant, J. (2017). Some contributions of integrated assessment models of global climate change. *Review of Environmental Economics and Policy 11*(1), 115–137.

Windrum, P., G. Fagiolo, and A. Moneta (2007). Empirical validation of agent-based models: Alternatives and prospects. *Journal of Artificial Societies and Social Simulation 10*(2), 8.

Wolf, S., S. Fürst, A. Mandel, W. Lass, D. Lincke, F. Pablo-Martí, and C. Jaeger (2013). A multi-agent model of several economic regions. *Environmental Modelling & Software 44*, 25–43.

Wright, I. (2005). The duration of recessions follows an exponential not a power law. *Physica A: Statistical Mechanics and its Applications 345*(3), 608–610.

Zarnowitz, V. (1985). Recent work on business cycles in historical perspective: A review of theories and evidence. *Journal of Economic Literature 23*(2), 523–580.

Appendix A - parameters

Table 7: Model parameters and initial conditions.

Description	Symbol	Value
parameters not involved in calibration		
Monte Carlo replications	MC	300
Time steps in economic system	T	400
Number of firms in capital-good industry	F_1	50
Number of firms in consumption-good industry	F_2	200
Number of bank's clients	α_b	20
parameters involved in calibration		
Capital-good firms' mark-up	μ_1	0.04
Consumption-good firm initial mark-up	$\bar{\mu}_0$	0.28
Energy monopolist' mark-up	μ_e	0.01
Uniform distribution supports	$[\varphi_1, \varphi_2]$	$[0.10, 0.90]$
Wage setting $\Delta \bar{AB}$ weight	ψ_1	1
Wage setting Δcpi weight	ψ_2	0
Wage setting ΔU weight	ψ_3	0
R&D investment propensity (industrial)	ν	0.02
R&D allocation to innovative search	ξ	0.5
Firm search capabilities parameters	$\zeta_{1,2}$	0.3
R&D investment propensity (energy)	ξ_e	0.01
Share of energy sales spent in R&D	v_e	0.01
Initial share of green energy		0.2
Beta distribution parameters (innovation)	(α_1, β_1)	$(3, 3)$
Beta distribution support (innovation)	$[\chi_1, \bar{\chi}_1]$	$[-0.075, 0.075]$
New customer sample parameter	$\bar{\omega}$	0.5
Desired inventories	l	0.1
Physical scrapping age (industrial)	η	19
Physical scrapping age (energy)	η_e	80
Payback period (industrial)	b	3
Payback period (energy)	b_e	10
Mark-up on base loan interest rate	μ_b	0.30
Scaling parameter for interest rate cost	k_{scale}	0.10
Extremes of support for bailout policy	$[\phi_1, \phi_2]$	$[0.10, 0.90]$
Inflation adjustment parameter	γ_π	1.10
Unemployment adjustment parameter	γ_U	1.10
Income tax rate	tax_i	0.15
Profit tax rate	tax_p	0.15
Unemployment subsidy rate	w^U	0.35
Carbon-climate sensitivity	λ_{CCR}	1.8
First order damage response to temperature	c_1	0
Second order damage response to temperature	c_2	0.0022

Appendix B - DSK model complements

In this appendix we present the full formal structure of the model discussed in section 3, as also described in detail in Lamperti et al. (2018b) and Dosi et al. (2015).

Modeling details - capital-good and consumption-good sectors

Firms' production

The unit cost of production of both capital- and consumption-good firms depends on labor productivity (indicated by apex LP), workers' wage (w)[29], energy efficiency (indicated by apex EE), as well as energy price (p^e):

$$c_i^{cap}(t) = \frac{w(t)}{B_{i,\tau}^{LP}} + \frac{p^e(t)}{B_{i,\tau}^{EE}}, \tag{13}$$

$$c_j^{con}(t) = \frac{w(t)}{A_{i,\tau}^{LP}} + \frac{p^e(t)}{A_{i,\tau}^{EE}}, \tag{14}$$

where B indicates the productivity of capital good firms' machines and A the productivity of consumption good firms' technology, as embedded in their machines, and obtained from their capital-good supplier. τ refers to the vintage of these technologies.

Consumer-good firms produce a homogenous good using their stock of machines, energy and labor under constant returns to scale. Firms plan their production according to adaptive demand expectations. Specifically, the desired level of production Q_j^d of consumption-good firms depends upon adaptive expectations $D_j^e = f[D_j(t-1), D_j(t-2), ..., D_j(t-h)]$, desired inventories ($N_j^d$), and the actual stock of inventories (N_j):

$$Q_j(t)^d = D_j^e(t) + N_j^d(t) - N_j(t), \tag{15}$$

where $N_j(t) = \iota D_j^e(t),\ \iota \in [0, 1]$.

If the current capital, $K_j(t)$, is not sufficient to satisfy the desired level of production, they can invest and buy new machines. As machines embed state-of-the-art technologies, innovations diffuse from the capital- to the consumption good sector. Technical change can also induce firms to replace their current stock of machines with more productive (and environmental-friendly) ones.

Technical change

When investing in R&D, capital-good firms perform both process-innovation/imitation (to reduce their own costs) and product innovation/imitation (to make their machines more attractive to consumption-good firms). R&D expenditures are split between both activities according to the parameter $\xi \in [0, 1]$.

In particular, they want to improve their machines along three dimensions: their embedded labor productivity (LP), their energy-efficiency (EE) and their emission intensity (EI). The first step of the process of technical change defines stochastically whether they will innovate (formally, it is a random draw from a Bernoulli distribution with parameter $\vartheta_i^{in}(t) = 1 - \exp^{-\varsigma_1 INNOV_i(t)}$, with $0 \leq \varsigma_1 \leq 1$), and the second step defines the characteristics of the machines which result from this process. The same mechanism is at place in the case of imitation. The new vintage (i.e. vintage $\tau + 1$) is described as:

[29] In this version of the model, workers are homogeneous and they all earn the same wage, which value evolves over time (see eq. 35 in the Appendix). Instead Dosi et al. (2017) present a full microfoundation of the labor supply as well as the matching process between firms and heterogeneous workers.

$$
\begin{aligned}
A^k_{i,\tau+1} &= A^k_{i,\tau}(1+\chi^k_{A,i}) \quad \text{for } k = LP, EI & (16)\\
B^k_{i,\tau+1} &= B^k_{i,\tau}(1+\chi^k_{B,i}) \quad \text{for } k = LP, EI, & (17)
\end{aligned}
$$

$$
\begin{aligned}
A^{EF}_{i,\tau+1} &= A^{EF}_{i,\tau}(1-\chi^{EF}_{A,i}) & (18)\\
B^{EF}_{i,\tau+1} &= B^{EF}_{i,\tau}(1-\chi^{EF}_{B,i}), & (19)
\end{aligned}
$$

where $\chi^k_{A,i}$ and $\chi^k_{B,i}$ are independent draws from $Beta(\alpha^k, \beta^k)$ distributions over the supports $[\underline{x}^k, \overline{x}^k]$, respectively for $k \in \{LP, EE, EF\}$. The higher the support of each distribution, the higher the technological opportunities. The firm then decides to adopt the new vintage if both price and efficiency are better than their current one:

$$
\frac{p^{new}}{c^{con}_j(t) - c^{new}} = \frac{p^{new}}{\left[\frac{w(t)}{A^{LP}_{i,\tau}} + \frac{c^{en}(t)}{A^{EE}_{i,\tau}}\right] - c^{new}_j} \leq b \tag{20}
$$

where p^{new} is the price and c^{new} is the unitary cost of production associated to the new machine. b is a pay-back (or patience) parameter.

Markups and market share dynamics

Capital-good firms' price is set with a fixed mark-up ($\mu_1 > 0$) on their unit cost of production. Their market shares evolve endogenously from their clients' decisions to invest (and how much), but also from the changes in their client portfolio: in every period, capital-good firm communicate the characteristics of their machines in a "brochure" to their set of customers as well as a subset of potential ones. This subset is a random sample which size is half the size of the existing customer base of that supplier.

Consumption-good firms' price is set with a variable mark-up (μ_j) on their unit cost of production:

$$
p^{con}_j(t) = c^{con}_j(t)[1 + \mu_j(t)]. \tag{21}
$$

The mark-up evolves depending on market share dynamics, f_j:

$$
\mu_j(t) = \mu_j(t-1)\left[1 + \upsilon \frac{f_j(t-1) - f_j(t-2)}{f_j(t-2)}\right] \tag{22}
$$

with $0 \leq \upsilon \leq 1$.

In turn, market shares in the downstream sector evolve according to a quasi-replicator dynamic linking past market shares to firm competitiveness E_j:

$$
f_{j,t} = f_{j,t-1}\left(1 + \chi \frac{E_{j,t} - \overline{E}_t}{\overline{E}_t}\right), \tag{23}
$$

with $\chi > 0$ and $E_{j,t} = -\omega_1 p_{j,t} - \omega_2 l_{j,t}$ (considering the firm's price and the amount of unfilled demand). where $\omega_{1,2} > 0$.

Profits and taxes

Firm profits are set as the difference between firm revenues and expenses. In particular, in the consumption-good sector, debt costs are included:

$$
\Pi_{j,t} = S_{j,t} + r^D NW_{j,t-1} - c_{j,t}Q_{j,t} - r^{deb}_{j,t} Deb_{j,t}, \tag{24}
$$

with total sales $S_{j,t} = p_{j,t}D_{j,t}$, production costs $c_{j,t}Q_{j,t}$, and debt costs $r^{deb}_{j,t}Deb_{j,t}$, where Deb denotes the stock of debt. Firms pay taxes on their profits at the tax rate tax_p. In particular in the consumption-good sector, the stock of liquid assets ($NW_{j,t}$) evolves as:

$$NW_{j,t} = NW_{j,t-1} + (1 - tr)\Pi_{j,t} - CI_{j,t},$$

with CI_j internal funds used by firm j to finance investment. Firms with negative net wealth ($NW_j < 0$) or excessively low market share ($f_j < 10^{-5}$) go bankrupt and exit the market. When a consumption good firm exits the market, a random copy of an incumbent firm enters it.

Modeling details - energy sector

Energy plants

In what follows we identify variables of green plants with ge ("green energy") and those of brown plants with de ("dirty energy"). The energy industry produces and sells electricity to firms in the capital-good and consumption-good industries on demand. Demand for electricity, D_e, is then matched to the aggregate energy production, Q_e, obtained from the portfolio of plants. We assume that energy cannot be stored.

"Brown" plants burn fossil fuels (e.g. coal, oil) with heterogeneous, vintage-specific thermal efficiencies A^{τ}_{de}, which expresses the amount of energy produced for each unit of employed non-renewable resource (fossil fuel) and emission intensities em^{τ}_{de}, which indicates the amount of emissions per unit of energy produced.[30] For simplicity, we assume that power plants have a unitary capacity and, in the case of brown energy, they consume one unit of fuel. Hence, the average production cost for a brown plant of vintage τ is:

$$c_{de}(\tau, t) = \frac{p_f(t)}{A^{\tau}_{de}(t)}, \tag{25}$$

where p_f is the price of fossil fuels, exogenously determined on an international market.[31] "Green" plants produce (such as wind and sunlight) energy at a null production cost, i.e. $c_{ge}(t) = 0$.

We assume that plants with the lowest unitary generation costs are the first to be activated, in line with the actual functioning of the electricity industry (Sensfuß et al., 2008; Clò et al., 2015). The total (potential) production of green plants is K_{ge}, and IM is the set of plants which should be activated to fulfill the energy demand. Then if total demand is lower than total green capacity ($D_e(t) \leq K_{ge}(t)$), the set of infra-marginal power plants IM includes only green plants and the total production cost is zero. Instead if $D_e(t) > K_{ge}(t)$, some dirty plants need to be activated too. The total production cost then corresponds to the sum of the production costs of the various types of brown plants activated at energy demand level $D_e(t)$. Assuming that the absolute frequency of vintage τ plants is $g_{de}(\tau, t)$, if dirty plants are operative the total production cost is:

$$PC_e(t) = \sum_{\tau \in IM} g_{de}(\tau, t) c_{de}(\tau, t) A^{\tau}_{de}(t) \tag{26}$$

The energy price is computed by adding a fixed markup $\mu_e \geq 0$ to the average cost of the most expensive infra-marginal plant:

$$p_e(t) = \mu_e, \tag{27}$$

if $D_e(t) \leq K_{ge}(t)$, and

$$p_e(t) = \bar{c}_{de}(\tau, t) + \mu_e \tag{28}$$

if $D_e(t) > K_{ge}(t)$, where $\bar{c}_{de}(\tau, t) = \max_{\tau \in IM} c_{de}(\tau, t)$. By setting a markup on this unit cost level, there is a positive net revenue on all infra-marginal plants.

[30] τ denotes the technology vintage.

[31] Notice that electricity production is a highly capital-intensive process, which mainly requires power generation assets and resources (either fossil fuels or renewable sources), while the labor input is minimal. We thus assume away labor from electricity production.

Investments

Investment in the energy sector can be associated to i) the replacement of old and obsolete plants or ii) capacity expansion. Replacement is due to the fact that all (brown and green) plants have a constant life-time corresponding to η_e periods. In turn, in order to fulfill energy demand, new power plants might be necessary, thus requiring capacity investment in the energy sector. An expansion investment is undertaken whenever the maximum electricity production level $\overline{Q}_e(t)$ is lower than electricity demand $D_e(t)$. The amount of new expansion investments EI_e thus equals:

$$EI_e(t) = K_e^d(t) - K_e(t), \tag{29}$$

if $\overline{Q}_e(t) < D_e(t)$, whereas $EI_e(t) = 0$ if $\overline{Q}_e(t) \geq D_e(t)$. Then the question is whether capacity expansion will be done with green or brown new plants. All new plants are built in-house (i.e. within the energy sector), but their production cost is technology-specific. Specifically, the construction costs for new dirty plants are normalized to zero, whereas in order to install a new green plant of vintage τ, a fixed cost IC_{ge}^{τ} needs to be sustained. We assume that new green capacity is constructed if green plants are cheaper than brown counterparts in terms of accounting lifetime costs. This means that green energy technologies are chosen whenever the fixed cost of building the cheapest green vintage is below the discounted (variable) production cost of the most efficient dirty plant. Hence, the following payback rule should be satisfied:

$$\underline{IC}_{ge} \leq b \cdot \underline{c}_{de}, \tag{30}$$

where b is a payback period parameter (as in Dosi et al., 2010, 2013), $\underline{IC}_{ge} = \min_{\tau} IC_{ge}^{\tau}$, and $\underline{c}_{de} = \min_{\tau} c_{de}^{\tau}$.[32] Accordingly, in case of new green capacity, the expansion investment cost amounts to

$$EC_e(t) = \underline{IC}_{ge} EI_e(t); \tag{31}$$

whereas it is zero if the payback rule is not met and the firm builds new dirty plants.

Plants' costs and characteristics evolve over time due to technical change. Mirroring the process in the capital-good industry, the energy plants invest a fraction $v_e \in (0, 1)$ of total past sales in R&D and stochastically improve their cost structure and emission intensity through a two-step procedure. At the end of the period, the central authority computes profits in the energy sector (see eq. 34 below) and levies taxes at the rate tax_p.

Technical change

R&D expenses in the energy sector aim at improving the technology of green and dirty plants. For green plants, this means reducing the fixed cost, while for dirty plants, this means an increase in energy efficiency (A) and a reduction in carbon emissions (em). Part of the budget is allocated to green innovations ($IN_{ge}(t) = \xi_e RD_e(t)$), and the rest to dirty ones. Such expenses in turn increase the probability to pass the first step of the innovation step successfully, for instance in the case of green innovations:

$$\theta_{ge}(t) = 1 - e^{-\eta_{ge} IN_{ge}(t)} \tag{32}$$

with $\eta_{ge} \in (0, 1)$. A similar process is at stake for dirty innovations.

In the second step, energy firms draw a random value from a Beta distribution, $x_{ge} \in (0, 1)$, which lowers the fixed cost of setting up a new green plant, with respect to the previous vintage. For dirty plants, two independent random draws x_{de}^{A} and x_{de}^{em} (again, from a Beta distribution) modify the existing characteristics of dirty plants as follows:

$$A_{de}^{\tau} = A_{de}^{\tau-1}(1 + x_{de}^{A}) \qquad em_{de}^{\tau} = em_{de}^{\tau-1}(1 - x_{de}^{em}) \tag{33}$$

[32] Under the assumption that plants are utilized for energy production the same number of periods, equation 30 boils down to a comparison of levelized costs of energy.

Profits and taxes

The energy monopolist's revenues depend on the energy price $p_e(t)$ and quantity produced $D_e(t)$. Its expenses include both production (total costs $PC_e(t)$) and costs of investing $IC_e(t)$ and innovating $RD_e(t)$.

$$\Pi_e(t) = p_e(t)D_e(t) - PC_e(t) - IC_e(t) - RD_e(t), \tag{34}$$

The energy firm then pays taxes on positive profits at the rate tax_p.

Modeling details - the macroeconomic framework

The wage equation

The market wage rate (w_t) evolves due to institutional and market factors, and is partly indexed to changes in prices (cpi), average productivity ($\bar{AB}$), and the unemployment rate (U):

$$w(t) = w(t-1)\left[1 + \psi_1 \frac{\Delta \bar{AB}(t)}{\bar{AB}(t-1)} + \psi_2 \frac{\Delta cpi(t)}{cpi(t-1)} + \psi_3 \frac{\Delta U(t)}{U(t-1)}\right], \tag{35}$$

with $\psi_{1,2,3} > 0$.

Modeling details - the climate module

From CO_2 emissions to climate damages

In previous studies using this model (Lamperti et al., 2018a,b), the focus was on the detailed non-linear mechanisms linking the economy to climate change. For this purpose, the so-called "climate module" included a representation of the carbon cycle, global warming and damages to the economy. Here we are interested in the overall interrelation between financial and economic activity and climate change, which requires to move the locus of detail to the banking sector. We therefore choose to reduce the complexity of the climate model, while maintaining a reasonable degree of realism. To do so, we employ a one-equation carbon climate model linking cumulative emissions (CE) (the sum of emissions in the three sectors described above) to the evolution of global surface temperature anomaly (TA), as inspired by Matthews et al. (2009) and Matthews et al. (2012).[33] The rate of global temperature change can therefore be related to first order to the rate of increase of cumulative carbon emissions. Hence, we model the rate of global temperature change as a linear function of the growth rate of cumulative carbon emissions. Given initial cumulative emissions and temperature levels, it is possible to project temperature increases over time relying on:

$$\frac{\Delta TA}{\Delta CE} = \lambda_{CCR}, \tag{36}$$

where Δ indicates yearly variations and λ_{CCR} the carbon-climate response.[34]

The distribution of climate damage shocks depends on the temperature level. Indeed, following Nordhaus (2017), the damages function $\Omega(t)$ is a quadratic function of temperature levels,

$$\Omega(t) = \frac{1}{1 + c_1 TA(t) + c_2 TA(t)^2}, \tag{37}$$

[33] Following Matthews et al. (2012), "recent research has shown that global temperature change can be well described by a given cumulative carbon emissions budget. [...] cumulative carbon emissions represent an alternative framework that is applicable both as a tool for climate mitigation as well as for the assessment of potential climate impacts. [...].

[34] In particular, we rely on the central estimate provided in Matthews et al. (2012): $\lambda_{CCR} = 1.8$.

with $c_1, c_2 \in [0; 1]$ first and second-order response parameters, respectively. At the end of each period, all firms (in the capital-, consumption and energy sectors) are hit by the following micro shocks to their labor productivity (A^{LP}) and capital stock (K):

$$D_i(t) = \Omega(t) + \epsilon_i, \qquad \epsilon_i \approx \text{i.i.d. N}(0, 0.01) \tag{38}$$
$$X_i(t) = X_i'(t)[1 - D_i(t)],$$

where i indexes firms in the economy, D represents the micro-level climate shock, $X(t)$ captures the target impact variable one wants to study. Here, we have $X(t) = [A^{LP}; K]$. Finally, X' indicates the level of the variable in absence of the climate shock. While the term D guarantees a simple representation of heterogeneity, we acknowledge that an additive Gaussian shock insufficient to satisfactorily account for the diversity of impacts (e.g. it does not account for spatial and serial correlation).

Additional stylised facts replicated by the DSK model

As it is common in the macro agent-based literature, the model is validated upon its ability to replicate empirical stylized facts (i.e. robust empirical regularities; see Windrum et al., 2007).[35] If the model successfully matches such regularities, this ought to be taken as a robust empirical validation (Fagiolo and Roventini, 2012, 2017b), offering plausibility to its use as a computational laboratory to test impacts and - possibly - policy experiments. Table 8 collects all the stylized facts that the model is able to replicate. As they have been also replicated in other versions of the model, we suggest the interested reader to look at Dosi et al. (2017) and Lamperti et al. (2018b) for a discussion of each of these stylized facts.

In general, the DSK model jointly accounts for a large ensemble of macro and micro empirical regularities characterizing short- and long-run behaviour of modern economies, in the real, credit and energy sectors of the economy. At the macroeconomic level, growth rates and duration of recessions display fat-tailed distributions (Fagiolo et al., 2008; Ascari et al., 2015), business cycles are punctuated by deep crises (Stiglitz, 2015). As a consequence, macroeconomic volatilities are relevant and should also be taken into account in climate change economic analysis as advocated by, e.g., Rogoff (2016). From a short-run perspective, we find that the model exhibits business cycles properties akin to those observed in developed economies, e.g. relative volatility between GDP, consumption and investment and co-movements between output and other macroeconomic variables. R&D expenditures are pro-cyclical and tend to anticipate the economy's fundamentals. This supports the idea that technical change can direct the pattern of growth, but, at the same time, recessions can affect the long-run performance of the economy via hysteresis effects (Blanchard et al., 2015; Dosi et al., 2017) Second, the model matches co-integration relationships between output, energy demand and emissions. Moreover, energy demand, emissions and GDP are strongly synchronized. Third, credit-related variables also display the expected business-cycle properties (cf. Bikker and Metzemakers, 2005; Lown and Morgan, 2006): procyclical firm debt and bank profits, counter-cyclical loan losses. Relatedly, characteristics of banking crises mimic empirical findings about their distribution over time and about their fiscal costs (as reported in the database by Laeven and Valencia, 2012, 2018).

At the microeconomic level, in line with the empirical literature, firms are heterogeneous in terms of productivity, size, growth rates, and energy and carbon efficiency (DeCanio and Watkins, 1998; Bartelsman and Doms, 2000; Dosi, 2007; Petrick et al., 2013). Moreover, they display lumpy investment patterns (Doms and Dunne, 1998).

[35] The interested reader might want to look also at the discussions in Lamperti (2018b,a); Lamperti et al. (2018) and Guerini and Moneta (2017) for novel approaches to the validation of agent-based models.

Table 8: Main empirical stylized facts replicated by the DSK model.

Stylized facts	Empirical studies (among others)
Macroeconomic stylized facts	
SF1 Endogenous self-sustained growth with persistent fluctuations	Burns and Mitchell (1946); Kuznets and Murphy (1966) Zarnowitz (1985); Stock and Watson (1999)
SF2 Fat-tailed GDP growth-rate distribution	Fagiolo et al. (2008); Castaldi and Dosi (2009) Lamperti and Mattei (2018)
SF3 Recession duration exponentially distributed	Ausloos et al. (2004); Wright (2005)
SF4 Relative volatility of GDP, consumption, investments and debt	Stock and Watson (1999); Napoletano et al. (2006)
SF5 Cross-correlations of macro variables	Stock and Watson (1999); Napoletano et al. (2006)
SF6 Pro-cyclical aggregate R&D investment	Wälde and Woitek (2004)
SF7 Cross-correlations of credit-related variables	Lown and Morgan (2006); Leary (2009)
SF8 Cross-correlation between firm debt and loan losses	Foos et al. (2010); Mendoza and Terrones (2012)
SF9 Pro-cyclical energy demand	Moosa (2000)
SF10 Syncronization of emissions dynamics and business cycles	Peters et al. (2012); Doda (2014)
SF11 Co-integration of output, energy demand and emissions	Triacca (2001); Ozturk (2010); Attanasio et al. (2012)
SF12 Banking crises duration is right skewed	Reinhart and Rogoff (2009)
SF13 Fiscal costs from recessions is fat tailed	Laeven and Valencia (2012)
Microeconomic stylized facts	
SF14 Firm (log) size distribution is right-skewed	Dosi (2007)
SF15 Fat-tailed firm growth-rate distribution	Bottazzi and Secchi (2003, 2006)
SF16 Productivity heterogeneity across firms	Bartelsman and Doms (2000); Dosi (2007)
SF17 Persistent productivity differential across firms	Bartelsman and Doms (2000); Dosi (2007)
SF18 Lumpy investment rates at firm-level	Doms and Dunne (1998)
SF19 Persistent energy and carbon efficiency heterogeneity across firms	DeCanio and Watkins (1998); Petrick et al. (2013)
SF20 Firm bankruptcies are counter-cyclical	Jaimovich and Floetotto (2008)
SF21 Firm bad-debt distribution fits a power-law	Di Guilmi et al. (2004)

Appendix C - Balance sheet and transaction flow matrices

Table 9: Balance sheet matrix

	Workers	Sector 1 firms	Sector 2 firms	Energy sector	Banks	Government	Central Bank	$\sum$
Govt. bonds					$+B_b$	$-B$	$+B_{cb}$	0
Govt. deposits						$+GDepo$	$-GDepo$	0
Bank cash					$+BankCash$		$-BankCash$	0
Deposits		$+Depo_{f1}$	$+Depo_{f2}$	$+Depo_e$	$-Depo$			0
Loans			$-NetLoans$		$+NetLoans$			0
Stock of liquid assets		$-NW_{f1}$	$-NW_{f2}$	$-NW_e$	$-NW_b$	$-NW_g$	$-NW_{cb}$	0
$\sum$	0	0	0	0	0	0	0	0

Table 10: Transaction flow matrix.

	Workers	Sector 1 firms		Sector 2 firms		Energy sector	
		current	capital	current	capital	current	capital
Consumption	$-C$	$+C$					
Investment		$+I$		$-I$			
Energy expenditures		$-E_{f1}$		$-E_{f2}$		$+E$	
Govt. expenditures	$+G$						
Wages	$+W$	$-W_{f1}$		$-W_{f1}$		$-W_e$	
Profits, firms		$-\Pi_{f1}$	$+\Pi_{f1}$	$-\Pi_{f2}$	$+\Pi_{f2}$	$-\Pi_e$	$+\Pi_e$
Profits, banks							
Profits, central bank							
Loan interests				$-r^d_{-1}L_{-1}$			
Deposits interests		$+r^D_{-1}Depo_{f1,-1}$		$+r^D_{-1}Depo_{f2,-1}$		$+r^D_{-1}Depo_{e,-1}$	
Bill interests							
Bank cash interests							
Govt. deposits interests							
Taxes		$-Tax_{f1}$		$-Tax_{f2}$		$-Tax_e$	
Change in loans					$+dL$		
Change in deposits			$-dDepo_{f1}$		$-dDepo_{f2}$		$-dDepo_e$
Change in bank cash							
Change in Govt. bonds							
Change in Govt. deposits							
$\sum$	0	0	0	0	0	0	0

		Banks		Government	Central bank		$\sum$
		current	capital		current	capital	
Consumption							0
Investment							0
Energy expenditures							0
Govt. expenditures		$+Gbailout$		$-G - Gbailout$			0
Wages							0
Profits, firms							0
Profits, banks		$-\Pi_b$	$+\Pi_b$				0
Profits, central bank					$-\Pi_{cb}$	$+\Pi_{cb}$	0
Loan interests		$+r^d_{-1}L_{-1}$					0
Deposits interests		$-r^D_{-1}Depo_{-1}$					0
Bill interests		$+r^b_{-1}B_{b,-1}$		$-r^b_{-1}B_{-1}$	$+r^b_{-1}B_{cb,-1}$		0
Bank cash interests		$+r^r_{-1}BC_{-1}$			$-r^r_{-1}BC_{-1}$		0
Govt. deposits interests				$+r^r_{-1}GDepo_{-1}$	$-r^r_{-1}GDepo_{-1}$		0
Taxes		$-Tax_b$		$+Tax$			0
Change in loans			$-dL$				0
Change in deposits			$+dDepo$				0
Change in bank cash			$-dBC$			$+dBC$	0
Change in Govt. bonds			$-dB_b$	$+dB$		$-dB_{cb}$	0
Change in Govt. deposits				$-dGDepo$		$+dGDepo$	0
$\sum$		0	0	0	0	0	0

Appendix D - Policy results, detailed tables

Table 11: Normalized values of average GDP growth rates across experiments. Absolute value of simulation t-statistic of two-sided tests with H_0: "no difference between no policy (baseline) and the policy (the experiment)" in parentheses; (**) the null hypothesis is rejected at 1% level, (*) at 5% level. Values and tests are based on 300 independent model runs for each policy experiment. The value corresponding to the business as usual (no policy) is used to normalize.

Average GDP growth		
	No climate impacts	
	No green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.032]	1.11*
		(1.78)
Standard Basel II, carbon risk adjustment	0.92**	0.89**
	(2.35)	(3.79)
green Basel II, no carbon risk adjustment	1.17**	1.25**
	(2.25)	(3.01)
green Basel II, carbon risk adjustment	1.09**	1.15**
	(2.23)	(2.49)
	labor productivity shocks	
	No green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.026]	1.11**
		(2.06)
Standard Basel II, carbon risk adjustment	0.94	1.08**
	(1.28)	(2.09)
green Basel II, no carbon risk adjustment	0.91	1.13**
	(1.40)	(2.35)
green Basel II, carbon risk adjustment	1.13**	1.17**
	(2.45)	(3.04)
	Capital stock shocks	
	No Green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.027]	1.12*
		(1.89)
Standard Basel II, carbon risk adjustment	0.98	1.10*
	(1.46)	(1.75)
green Basel II, no carbon risk adjustment	1.24**	1.30**
	(3.38)	(4.27)
green Basel II, carbon risk adjustment	1.28**	1.23**
	(4.07)	(4.02)
	labor and capital shocks	
	No Green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.024]	1.15**
		(2.58)
Standard Basel II, carbon risk adjustment	0.90**	1.13**
	(2.53)	(2.38)
green Basel II, no carbon risk adjustment	1.11*	1.22**
	(1.80)	(3.46)
green Basel II, carbon risk adjustment	1.14**	1.24**
	(2.51)	(3.50)

Table 12: Normalized values of the banks' failure rate across experiments. Absolute value of simulation t-statistic of two-sided tests with H_0: "no difference between no policy (baseline) and the policy (the experiment)" in parentheses; (**) the null hypothesis is rejected at 1% level, (*) at 5% level. Values and tests are based on 300 independent model runs for each policy experiment. The value corresponding to the business as usual (no policy) is used to normalize.

Number of banks bailouts		
	No climate impacts	
	No green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.014]	0.90*
		(1.87)
Standard Basel II, carbon risk adjustment	1.14**	0.88**
	(2.98)	(3.45)
green Basel II, no carbon risk adjustment	1.06	0.87**
	(1.48)	(3.70)
green Basel II, carbon risk adjustment	1.45**	0.85**
	(4.25)	(3.52)
	labor productivity shocks	
	No green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.031]	0.83**
		(3.10)
Standard Basel II, carbon risk adjustment	1.08	0.80**
	(1.24)	(3.92)
green Basel II, no carbon risk adjustment	1.10*	0.78**
	(1.93)	(4.14)
green Basel II, carbon risk adjustment	1.16**	0.79**
	(2.08)	(4.59)
	Capital stock shocks	
	No Green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.024]	0.91*
		(1.94)
Standard Basel II, carbon risk adjustment	0.99	0.96*
	(1.15)	(1.90)
green Basel II, no carbon risk adjustment	0.90**	0.86**
	(2.23)	(3.02)
green Basel II, carbon risk adjustment	0.94*	0.89**
	(1.73)	(3.11)
	labor and capital shocks	
	No Green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.035]	0.85**
		(2.77)
Standard Basel II, carbon risk adjustment	1.09*	0.88**
	(1.82)	(2.91)
green Basel II, no carbon risk adjustment	0.94	0.74**
	(1.87)	(4.29)
green Basel II, carbon risk adjustment	0.96*	0.71**
	(1.84)	(6.04)

Table 13: Normalized values of the average (public) debt to GDP ratio across experiments. Absolute value of simulation t-statistic of two-sided tests with H_0: "no difference between no policy (baseline) and the policy (the experiment)" in parentheses; (**) the null hypothesis is rejected at 1% level, (*) at 5% level. Values and tests are based on 300 independent model runs for each policy experiment.

Debt over GDP		
	No climate impacts	
	No green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.82]	1.42**
		(4.33)
Standard Basel II, carbon risk adjustment	1.39**	1.46**
	(4.71)	(4.91)
green Basel II, no carbon risk adjustment	0.87**	1.28**
	(8.26)	(7.11)
green Basel II, carbon risk adjustment	1.23**	1.27**
	(3.47)	(6.39)
	labor productivity shocks	
	No green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [1.86]	1.17*
		(1.70)
Standard Basel II, carbon risk adjustment	1.04	1.07**
	(1.03)	(4.80)
green Basel II, no carbon risk adjustment	1.12**	1.05
	(2.22)	(1.55)
green Basel II, carbon risk adjustment	1.08*	0.95*
	(1.96)	(1.74)
	Capital stock shocks	
	No Green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [1.58]	1.09*
		(1.76)
Standard Basel II, carbon risk adjustment	1.03	1.03
	(1.24)	(1.48)
green Basel II, no carbon risk adjustment	0.89**	1.05
	(2.95)	(1.46)
green Basel II, carbon risk adjustment	0.80**	1.12*
	(3.60)	(1.91)
	labor and capital shocks	
	No Green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [2.09]	1.11*
		(1.84)
Standard Basel II, carbon risk adjustment	1.04	0.97
	(1.49)	(1.78)
green Basel II, no carbon risk adjustment	0.95*	1.01
	(1.70)	(1.23)
green Basel II, carbon risk adjustment	1.02	0.97*
	(1.12)	(1.78)

Table 14: Normalized values of the average growth rate of industrial emissions across experiments. Absolute value of simulation t-statistic of two-sided tests with H_0: "no difference between no policy (baseline) and the policy (the experiment)" in parentheses; (**) the null hypothesis is rejected at 1% level, (*) at 5% level. Values and tests are based on 300 independent model runs for each policy experiment.

Average Industrial Emission Growth		
	No climate impacts	
	No green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.019]	0.93**
		(2.10)
Standard Basel II, carbon risk adjustment	0.95*	0.90**
	(1.92)	(4.31)
green Basel II, no carbon risk adjustment	0.99	0.89**
	(0.86)	(4.92)
green Basel II, carbon risk adjustment	0.90**	0.86**
	(4.83)	(4.57)
	labor productivity shocks	
	No green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.013]	0.82**
		(3.16)
Standard Basel II, carbon risk adjustment	0.96*	0.80**
	(1.75)	(3.01)
green Basel II, no carbon risk adjustment	0.97	0.76**
	(1.63)	(3.96)
green Basel II, carbon risk adjustment	0.87**	0.72**
	(4.42)	(5.07)
	Capital stock shocks	
	No Green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.016]	0.96*
		(1.69)
Standard Basel II, carbon risk adjustment	0.98	0.92**
	(1.47)	(2.12)
green Basel II, no carbon risk adjustment	0.95*	0.90**
	(1.77)	(2.65)
green Basel II, carbon risk adjustment	0.89*	0.86**
	(2.54)	(3.51)
	labor and capital shocks	
	No Green Credit Easing	Green Credit Easing
Standard Basel II, no carbon risk adjustment	1 [0.014]	0.92**
		(2.70)
Standard Basel II, carbon risk adjustment	0.95*	0.90**
	(1.88)	(2.84)
green Basel II, no carbon risk adjustment	0.93*	0.85**
	(1.88)	(3.04)
green Basel II, carbon risk adjustment	0.87**	0.76**
	(3.17)	(4.02)

Appendix E - Robustness

Table 15: Robustness exercises with respect to the identification of green firms. All firms having a level of emission intensity lower than the threshold are eligible for credit conditions reserved to green firm. $\bar{A}^{EI}$ indicates the across-firms average emission intensity.

		variable threshold			**fixed threshold (fixed at t_0)**		
		10% greenest	30% greenest	0.5*$\bar{A}^{EI}_t$	10% greenest at t_0	30% greenest at t_0	0.5*$\bar{A}^{EI}_{t_0}$
GDP growth	baseline	1 [3.2%]	1 [3.2%]	1 [3.2%]	1 [3.2%]	1 [3.2%]	1 [3.2%]
	risk adjustment	0.92**	0.92**	0.92**	0.92**	0.92**	0.92**
	credit easing	1.06	1.17**	1.22**	0.82**	0.77**	0.65**
	green Basel II	1.05*	1.28**	1.30**	0.78**	0.67**	0.52**
# Bailouts	baseline	1 [1.4%]	1 [1.4%]	1 [1.4%]	1 [1.4%]	1 [1.4%]	1 [1.4%]
	risk adjustment	1.14**	1.14**	1.14**	1.14**	1.14**	1.14**
	credit easing	0.98	0.89**	0.88**	0.33**	0.21**	0.17**
	green Basel II	0.99	0.92**	0.90**	1.59**	1.85**	2.41**
Debt to GDP	baseline	1 [0.82]	1 [0.82]	1 [0.82]	1 [0.82]	1 [0.82]	1 [0.82]
	risk adjustment	1.39**	1.39**	1.39**	1.39**	1.39**	1.39**
	credit easing	1.07	1.27**	1.41**	2.44**	2.80**	3.23**
	green Basel II	0.96	0.82**	0.80*	1.74**	2.05**	1.93**