

Climate Policy Design: Why Investment Risks Matter

Version August 2026

Angélique Sarre (SMASH-CIRED, EHESS), Yannick Glemarec (CIRED, ENPC), and Louis Daumas (RFF-CMCC European Institute on Economics and the Environment, Politecnico di Milano)

Abstract

Green investment is widely perceived as risky due to innovation uncertainties. This perception raises the cost of capital, which is already high in emerging markets and developing economies. This particularly affects green investment because it tends to have lower operational costs but higher upfront capital expenditure than conventional investment. Using an SFC model, the paper assesses the impact of four climate policies on the economy, the financial system, and the low-carbon transition under two scenarios of green investment risk: (i) a carbon tax; (ii) a green public guarantee; (iii) a mandate, and (iv) green public procurement. Our simulations indicate that high investment risks can undermine the effectiveness of these climate policies while amplifying transition risks. A carbon tax is most effective to incentivize green investment over brown investment when the perception of risks, and therefore, the financing costs associated with green investment, are low. Public guarantees lower financing costs but must be complemented by other de-risking measures when the risk for investors is high. Mandates reduce emissions under both scenarios, but transition risks are more limited when green investment risk is low. Green procurement fosters the transition at a slower pace when risks are high, as firms are less willing to invest in green capital. These findings highlight that no single instrument is universally effective, as each entails trade-offs between environmental effectiveness and macro-financial stability. Nonetheless, the instruments exhibit complementary effects, suggesting that deploying a combination of instruments will prove more cost-effective than relying on one type of instrument.

Keywords: Carbon tax, guarantees, mandate, public procurement, investment risks, financing costs, SFC model.

Contributions: All authors contributed to the concept and design of the study. The modelling work was carried out by Angélique Sarre, with support from Louis Daumas and Quentin Couix. The paper was written by Angélique Sarre.

Key policy insights

- The level of risk on green investment affects the effectiveness of climate policies by influencing firms' investment decisions and banks' financing costs. It also influences the economic and financial consequences of the transition.
- There is no universal environmental public instrument that simultaneously promotes the transition and contains the emergence of transition risks.

- Climate policy instruments are highly synergistic. Combinations of instruments are likely to offer more than the sum of their parts.

1. Introduction

The economic case for a rapid transition to net-zero, climate-resilient, and inclusive societies is robust. Yet, money is not flowing at the scale needed nor in the areas most in need to prevent catastrophic climate change. Investment in climate mitigation must be increased at least sixfold to have an increasingly narrow chance of limiting global heating to 1.5 °C above pre-industrial levels (IPCC, 2022).

This investment gap is particularly acute for green infrastructure in emerging market and developing economies (EMDEs). EMDEs will account for the vast preponderance of new physical capital in the coming three decades. Today, climate finance flows remain heavily concentrated in advanced economies: in 2022, EMDEs (excluding China) accounted for 12% of mitigation financing, while least developed countries received just 1% (CPI, 2024).

Green infrastructure investments combine the risks of conventional infrastructure investment (high capex and long pay-back period) with those of innovation (unproven technical performance and market, policy, and regulatory uncertainty, integration in pre-existing infrastructure and ecosystems) and have heightened exposure to sovereign risks in EMDEs (political and currency risks) (Granoff et al., 2016). These nested risks increase the cost of capital of green infrastructure and reduce their bankability (the likelihood of generating adequate profit to reimburse financiers), making them “hard-to-finance”.

Most green technologies and infrastructure are capital-intensive, making the cost of capital a key barrier to the green transition (IEA, 2024; IRENA, 2023). For instance, financing cost accounts for about a quarter of LCOE for solar plants in advanced economies and for about half of it in developing economies (IEA & IFC, 2023).

A plethora of instruments has been developed to derisk hard-to-finance projects. According to the International Energy Agency’s Policies and Measures Database (IEA, 2014), over 11,000 climate policies and instruments are currently in use to mobilize climate and energy investments globally. There is no consensus on how to best accelerate the green transition. The debate focuses on the respective roles of the public and private sectors in closing the climate financing gap. Some academic researchers and practitioners argue that the state’s burden in financing climate action could be alleviated if information asymmetry between entrepreneurs and financiers were reduced, and climate risks were fully integrated into investment decision-making (Carney, 2015; TCFD, 2023). This would allow private capital to autonomously align with sustainable development, freeing scarce public resources for other critical development priorities. This school of thought recommends the disclosure of climate risks and carbon pricing to internalize the external costs of GHG emissions.

Others emphasize the primary role of private investors while highlighting the state's responsibility in creating an enabling environment and mitigating risks associated with market-creating projects (Waissbein et al., 2013; Polzin et al., 2019). At its most fundamental level, finance is about managing trade-offs between risk and expected return. Investors will expect higher profits if they accept higher risks of losses. To enhance the risk-adjusted return profile of “hard-to-finance” projects and lower financing costs, policymakers need to develop and implement effective derisking strategies. Derisking involves mitigating, transferring, or compensating for risks to make renewable energy technologies more attractive to investors (Glemarec, 2011).

Contrary to this position, some researchers and practitioners advocate for an entrepreneurial state that directly finances or co-finances climate investments with high societal value but low financial returns. Their policy recommendations focus on enhancing integrated planning capacity and restoring fiscal space to empower public institutions in fulfilling their climate mission (Mazzucato & Semieniuk, 2018; Brett, 2024).

Using an SFC model, this paper assesses the impact of four public environmental instruments on the economy, the financial system, and the low-carbon transition in different scenarios of green investment risk: (i) a carbon tax; (ii) a public guarantee on green loans; (iii) a mandate, and (iv) green public expenditure. These instruments reflect two main proposals for closing the green financing gap: (1) aligning finance by integrating climate risks into investment decision-making through a carbon tax, (2) derisking first-mover climate projects via mandates, green public procurement, and guarantees¹. Our focus is therefore on aligning and derisking policies, while the role of direct public investment could be explored in future research.

This analysis aims to provide qualitative insights into how investment risks impact these climate instruments. The central hypothesis of this paper is that the effectiveness of climate policies is constrained by a range of barriers that must first be removed or at least mitigated. In particular, we consider high investment risks and financing costs associated with green investment, as well as path dependency, while acknowledging that additional barriers may also play a significant role (Pahle et al., 2018).

This paper is organized into four parts. Part I makes a review of the literature. Part II describes the methodology. Part III presents the results of the climate policies under two scenarios of risks. Part IV discusses the results and concludes.

2. Literature review

2.1. Carbon tax

¹ A carbon tax might also reduce investment risks if it provides a credible policy signal, but in this paper, we focus only on its cost effects.

A carbon tax is a form of Pigouvian tax aiming at making polluters internalize the climate change externality (Pigou, 1920). Indeed, by pricing CO₂ emissions, a carbon tax pushes emitters to consider the impact of their CO₂ emissions on others. It gives them an economic incentive to change their behavior. Carbon pricing also promotes innovation and incentivizes the generation of new ideas and solutions by creating opportunities to increase profitability or save money through the reduction of GHG emissions. For example, innovation patents tend to respond to carbon pricing (Grubb et al., 2021). Besides, a carbon tax is a source of revenue for the government, which can offset its negative economic impacts through revenue recycling (Stiglitz et al., 2017). This can be challenging, especially for developing countries that rely a lot on energy-intensive activities, fossil fuel exports, or countries with low potential to mitigate impacts due to low wages or existing taxes (IPCC, 2022).

The effectiveness of carbon pricing has been supported by various evidence (IPCC, 2022). For instance, Best & Burke (2018) find that countries with carbon pricing have a higher solar and wind energy adoption. However, current carbon prices are not high enough to meet the decarbonization targets of the Paris Agreement, and only 28% of global emissions were covered in 2024 (Stiglitz et al., 2017; World Bank, 2025a). Besides, Tvinnereim & Mehling (2018) underline in their empirical literature review that even in countries with relatively high carbon taxes, such as Sweden, emissions in covered sectors have only decreased incrementally. Similarly, in their literature review, Lilliestam et al. (2021) conclude that “[...] the empirical evidence for the effectiveness of carbon pricing for triggering technological change is, on the one hand, thin, and on the other hand discouraging.” (page 2).

The presence of other market failures than the GHG externality limits the effectiveness of carbon pricing (Stiglitz et al., 2017; IMF, 2019). For instance, knowledge spillovers incentivize potential adopters to delay adoption to benefit from lower capital costs and improved information (Isoard & Soria, 2001; Lilliestam et al., 2021). Network effects, arising from the interconnections among technological systems and institutions, also favor carbon lock-in (Unruh, 2000). In their empirical study on the automobile industry, Aghion et al. (2016) show the presence of path dependency and local knowledge spillovers favoring ‘dirty’ technologies, and underline that a mild carbon tax will not be enough to trigger the transition. Moreover, carbon prices become ineffective due to path dependency once the productivity gap between the dirty and the green sectors becomes too high (Lamperti et al., 2020).

Incomplete and imperfect financial markets can cause inefficient credit rationing, with large infrastructure projects often struggling to secure necessary funding even when they are economically viable (Stiglitz et al., 2017). This is reinforced for innovative low-carbon projects due to the lack of commercial track records. Moreover, commercial banks may not respond to the carbon price signal under certain economic conditions (Campiglio, 2016). For example, in periods of economic instability, banks might try to equilibrate their balance sheets by constraining credit, instead of looking for the highest rates of return on investment. High capital costs can undermine the effectiveness of carbon pricing as low-carbon technologies are

more capital-intensive than conventional ones. Hirth & Steckel (2016) estimate that with the same carbon price up to USD 50 per ton, emissions are reduced by half with a 3% weighted average cost of capital (WACC), while they do not decrease significantly with a 15% WACC. Moreover, Funke et al. (2024) underline that carbon prices will have a small impact on the buildings and transport sector as green substitutes are associated with high upfront costs. This impedes people without sufficient savings to invest, even if low operating costs could compensate them in the long run. This is even more problematic for emerging economies, where capital costs tend to be higher (IEA & IFC, 2023; Steffen, 2020). Utility-scale solar projects can be two to three times more costly in emerging economies than in advanced economies, due to higher real and perceived risks at the country, sectoral, and project level (IEA & IFC, 2023).

Hence, a combination of policies may be more efficient to reduce GHG emissions than carbon pricing alone, thanks to synergies and complementarities favoring technological diffusion (Stiglitz et al., 2017; Mercure et al., 2014; Campiglio, 2016; Monasterolo et al., 2022; Blanchard et al., 2023). For example, Mercure et al. (2014) show that carbon pricing alone is insufficient to break the current fossil fuel technology lock-in (unless unrealistically high price), but when combined with technology subsidies, feed-in-tariffs, and regulations, emissions are drastically reduced.

2.2. Green mandates

From a theoretical economic perspective, in the absence of perfect information, regulatory instruments are less cost-effective than market-based instruments, because they fail to equate the marginal costs of emissions reductions across heterogeneous firms. Hence, they do not allow for reducing emissions where it is the cheapest. Böhringer et al. (2009) find that the cost of achieving EU mitigation targets increases due to renewable energy standards because it may be more cost-effective to use other mitigation opportunities such as fuel switching, energy efficiency improvements, and energy savings. They estimate that imposing renewable energy standards could raise the mitigation costs by 90 percent, compared to an emissions trading system that has a single carbon price. By prescribing specific technologies, standards could lead to higher mitigation costs as more cost-effective alternatives could have emerged through innovation and market-driven incentives (IPCC, 2022, page 1389).

However, the superiority of one type of instrument over another is difficult to assess according to the literature. For instance, when considering other evaluation criteria such as administrative and fiscal costs, distributional equity, and uncertainty, no instrument is clearly superior (Goulder & Parry, 2008). Rozenberg et al. (2020) show that mandates on new investments are less efficient than optimal carbon pricing because of the use of existing polluting capital until the end of its lifetime. However, this type of mandate does not create stranded assets (premature write-downs, devaluations, or financial liabilities), contrary to a carbon tax. Indeed, mandates affecting new investment decisions do not provide incentives to under-use existing polluting equipment, leading to smoother abatement costs than carbon

pricing. Moreover, Chateau et al. (2024) show that the superiority of one instrument over others is sector-dependent. Using a CGE model, they find that regulating the electricity sector is more effective than implementing a carbon price, as it allows lower energy price increases. However, this is not the case for energy-intensive and trade-exposed sectors, which are characterized by higher and heterogeneous abatement costs. Indeed, the regulation does not allow for allocating emission reductions where abatement is the cheapest, contrary to the carbon tax. Consequently, it will be more costly to use a regulation in these sectors as it will lead to higher abatement costs, which decreases the country's competitiveness. Lastly, Levinson (2019) finds that energy efficiency standards are more regressive than carbon taxes, as poor households tend to own less efficient goods, and as they do not generate revenues that can be redistributed.

One advantage of regulations is that they are effective even in the presence of externalities that undermine the effectiveness of pricing instruments (IPCC, 2022, page 1389). Lamperti et al. (2020) show that even in the presence of path dependence, command-and-control policy interventions remain effective regardless of the timing of their introduction—unlike market-based instruments. Waissbein et al. (2013) underline that policy derisking, such as easier permit processes or fixing long-term renewable energy targets, is essential to develop renewable energy investments in developing countries, as it reduces risks for investors.

Regulation is quite common in environmental policy and is often effective (IPCC, 2014). For example, the Montreal Protocol, which imposed limits on the production of halogen-containing ozone-depleting substances, successfully reduced ozone layer depletion and contributed to mitigating climate warming (Egorova et al., 2023). Besides, Shapiro & Walker (2018) estimate that most of the 60% decrease in air pollutants from US manufacturing between 1990 and 2008 was due to environmental regulation, such as air quality standards. Moreover, nearly half of the CO₂ emission reductions in the sectors covered by the EU ETS between 2005 and 2011 can be attributed to the EU's target of achieving a 20% share of renewable energy in final energy consumption by 2020 (Gloaguen & Alberola, 2013). Additionally, econometric analyses show that regulations stimulate innovation (Grubb et al., 2021).

However, the effectiveness of regulations is limited by various factors. Regulations face monitoring and enforcement challenges, as it may be very costly or infeasible to monitor emissions in some contexts (Goulder & Parry, 2008). Concerning the costs, in their empirical review on climate policy in the EU and the US, Joas & Flachsland (2016) find that transaction costs, including the ex-post costs of administering, monitoring, and enforcing emissions pricing and standards, are low. Moreover, there is a risk of lock-in in sub-optimal technologies (Jaffe et al., 2005; Granoff et al., 2016). Besides, regulations as well as carbon pricing raise the question of political feasibility as they can be unpopular (Douenne & Fabre, 2022; IMF, 2023), subject to business influence (Vesa et al., 2020), and government volatility (Brunner et al., 2012). Lastly, both can lead to carbon leakages, meaning that mitigation measures

implemented in one country or sector can increase emissions in other countries or sectors (IPCC, 2022, page 1318). However, the magnitude and the direction of these effects are uncertain (Bauer et al., 2015).

2.3. Guarantees

A credit loan guarantee insulates lenders from the issuer's performance, default, or bankruptcy. In the event of default from the issuer, investors are guaranteed to receive from the guarantor payment of principal and accrued interest on the debt when due. Thus, debt issuances are rated based upon the rating of the guarantor in lieu of the issuer. It enables issuers to access the capital market at a lower cost with a higher credit rating than would be achievable on a standalone basis.

Financial markets are characterized by asymmetric information, where borrowers have more information than lenders on their repayment ability, which leads to inefficient credit rationing (Stiglitz & Weiss, 1981). In this context, guarantees can emerge on financial markets under certain conditions (Honohan, 2010). Firstly, if guarantors have an information advantage compared to lenders. Secondly, if they have a risk-pooling advantage, as their portfolio is more geographically diverse than that of the lender. Thirdly, if they benefit from a regulatory arbitrage, such as a foreign guarantor that is not subject to the same regulatory requirements as a local lender. However, coordination failure and first mover disadvantage prevent private providers from entering the market for credit guarantees, such as public intervention is required (de la Torre et al., 2007). The provision of public guarantees increases market activity, which enables lenders to learn about the creditworthiness of the borrowers (Hansen et al., 2020). Further, public guarantees are more effective and less costly than other directed lending when carefully designed (Arping et al., 2010). They have the advantage from a fiscal viewpoint of only being paid out in case of default, and they present a high leverage effect as they only cover part of the total risks that are shared with private loans and equities (Hourcade et al., 2021).

To evaluate the effectiveness of guarantees, numerous empirical studies have examined whether they mitigate credit rationing, influence banks' risk-taking, and enhance firms' investment. Abraham and Schmukler (2017) provide a comprehensive review of this literature and report mixed evidence. On one hand, they find that guarantees help reduce credit rationing, as the majority of the guaranteed loans have been granted to firms that otherwise would not have obtained finance. On the other hand, these guarantees are sometimes associated with higher default rates, raising concerns about moral hazard. Besides, evidence on firms' investment, productivity, and employment is also mixed. More recently, various studies analyzed the role of public credit guarantee schemes during the Covid-19 (Jimenez et al., 2024; Nicolas et al., 2023; Buchetti et al., 2024). Buchetti *et al.* (2024) underline that public guarantees during the Covid-19 in Europe were used to increase green lending by protecting banks from higher default risks, as lending to green companies is perceived as riskier by European banks.

When the high perception of risk by financiers leads to high capital costs, derisking instruments such as a loan guarantee program can allow the reduction of financing costs and thus favor the low-carbon transition (Steckel & Jakob, 2018). Haas and Kempa (2023) use a principal-agent model to study how credit rationing affects low-carbon investment. They show that combining the Pigouvian tax with public loan guarantees resolves credit rationing and yields a first-best outcome. Loan guarantees address credit rationing at a lower cost than interest rate subsidies. However, the impact of guarantees alone is limited. Credit market interventions alone cannot resemble the first-best outcome, notably because of their negative impact on the public budget. Waidelich et al. (2023) develop a model of banks providing loans to clean energy projects that the banking sector is not (yet) familiar with. They show that guarantees support banks in internalizing learning spillovers.

Despite their potential role in mobilizing private finance, guarantees accounted for 5.5% of mitigation finance by Multilateral Development Banks (MDBs) in 2020 (IMF, 2022). Indeed, their deployment faces a range of demand and supply barriers, such as the complexity of application and reporting processes, the lack of technical assistance to develop viable projects, and high costs and fees (Garbacz et al., 2021; CPI, 2025).

2.4. Green public procurement

According to economic theory, public intervention is justified to stimulate innovation as it tends to be undersupplied due to market failures. Indeed, when a firm invests in R&D, it generates knowledge for others while bearing all the costs. Many OECD countries adopted green public procurement measures to promote environmental innovation (OECD, 2003). These measures prioritize environmental criteria in government purchasing decisions. Green public procurement is not a stand-alone policy but a complement to broader environmental policies, as it targets only the public sector directly (OECD, 2003). However, the stakes are significant: for example, in 2023, public purchases of goods, services, and capital accounted for 12.7% of GDP in OECD countries (OECD, 2025), giving the public sector substantial market-shaping leverage.

Green public procurement has been presented both as an educational tool and as a means to encourage the development and adoption of innovative technologies (Anderson et al., 2001). Indeed, if successful, green public procurement may favor higher demand for new technologies. By building a commercial track record, it reduces uncertainty and provides information to other economic actors about the viability and potential benefits of green products. On the supply side, increased demand encourages firms to scale up production, which may lower unit costs through economies of scale and improve efficiency through learning-by-doing (OECD, 2003).

According to IPCC (2022, p. 1685): "Overall, public procurement has high potential to incentivize innovation in climate technologies, but the evidence is mixed, particularly in developing countries". Reviewing 25 evaluations, Peñasco et al. (2021) relate that green

procurement improves environmental indicators, but only one study examines innovation and reports a positive effect. In their empirical analysis on German firms, Krieger & Zipperer (2022) find that green public procurement favors higher demand for small and medium firms, leading to the introduction of new environmental products. Regarding impacts on competitiveness, such as industry creation, productivity, and economic growth, the evidence remains limited and mixed (IPCC, 2022). For example, Peñasco et al. (2021) review four qualitative studies on European countries: one reports a positive impact on competitiveness, one a negative impact, and two find no impact. They also identify a single evaluation of green public procurement on distributional outcomes (qualitative analysis), which suggests positive effects.

The implementation of green public procurement faces various limitations. A survey of sustainable procurement (SP) practices conducted among more than 280 public procurement practitioners from 20 countries shows that financial concerns remain the most significant barrier to SP, as many public sector procurers remain reluctant to pay higher costs for sustainable purchases (Brammer & Walker, 2011). As emphasized by Baron (2016), there is a need to shift from evaluating only acquisition costs to adopting life-cycle costing, since low-emission equipment often entails higher upfront expenses but can deliver savings and benefits over its lifetime. Another barrier to green public procurement lies in the limited availability of resources and skills within public administrations to effectively design, implement, and monitor such procurement processes (Baron, 2016). Related to this, Blanchard et al. (2023) underline that environmental criteria in public procurement are imperfect substitutes for emission taxation, as they imply an implicit carbon price (in euros per ton of CO₂ avoided). However, public procurement officers do not have the necessary resources to calculate these implicit costs or to verify the environmental claims made by suppliers.

This literature review highlights that each policy faces significant implementation challenges, including limited capacity, political feasibility, and enforcement issues. This paper does not consider these implementation difficulties. Instead, it focuses on the impacts of high investment risks on these policies.

2.5. Similar studies

Ecological stock–flow consistent (SFC) and agent-based approaches have been increasingly used over the last years to evaluate climate policies from a macroeconomic, financial, and ecological perspective (Dafermos and Nikolaidi, 2022; Dunz et al., 2021; Monasterolo et al., 2019; Lamperti et al., 2021).

Dafermos and Nikolaidi (2022) use the SFC model DEFINE to identify policy mixes that allow for fostering the transition without undermining macrofinancial and social stability. To do this, they focus on three types of policy instruments: green fiscal policies (carbon taxes, green subsidies, and green public investment); green monetary policies (dirty penalizing factor, green supporting factor, and green quantitative easing); and sufficiency policies (decline in consumption with less working hours). Thanks to the broad spectrum of elements considered

in DEFINE, they evaluate the impacts of these policy mixes on ecological indicators (temperature, material use, waste), macroeconomic indicators (unemployment and wage share), and financial indicators (firms' defaults, banks' leverage ratio, public debt). Their results underline the need to have a combination of several climate policies. Indeed, some policies, such as the carbon tax and sufficiency policies, when implemented alone, lead to transition risks that disappear when they are combined with other policies. For instance, the carbon tax leads to positive effects on ecological indicators but negative macroeconomic and financial effects as it increases loan defaults and decreases firms' profits. These effects are compensated, if carbon tax revenues are recycled in the form of green subsidies to firms. In the case of higher green public investment, economic activity increases, and emissions are reduced. In the short run, public deficit increases, but thanks to higher economic activity, it decreases in the long run. Interestingly, they underline that higher economic activity increases materials extraction and waste, thus leading to ecological issues.

Dunz et al. (2021) create an SFC model to study two policies aiming at scaling up climate investment, and the impact of the banks' anticipation of these policies on their lending conditions. Firstly, they examine the impact of a global carbon tax and a Green Supporting Factor (GSF)—which lowers capital requirements for green investments—on the development of green investment and financial stability, assuming no anticipatory behavior from banks. The GSF allows for scaling up green investment in a limited way and could affect banks' financial stability. Indeed, to have a strong positive impact on green investment, the decrease in the interest rate for green loans must be large. Hence, the lending channel alone might not be enough to trigger the low-carbon transition. Moreover, the authors underline that a strong decrease in interest rates for green loans could create a "green bubble" in the absence of a standardized green taxonomy. The GSF can harm banks' financial stability as it increases the non-performing brown loans due to lower brown firms' profitability and lower banks' capital adequacy ratio (CAR)² due to lower interest rates for green firms. The carbon tax leads to negative macroeconomic and financial impacts due to lower firms' profitability, but they are compensated when the redistribution of the carbon tax to households is introduced. Secondly, they analyze the impact of the anticipation of the carbon tax on banks. In the model, banks form expectations on the future profitability of brown and green firms and adjust their lending interest rates accordingly before the implementation of the carbon tax. This allows to have a smoother transition rather than a policy shock. Consequently, the introduction of the carbon tax leads to lower GDP losses than without anticipation. These results underline the need to build trust in the banking sector with credible policies to favor policy success.

The Dystopian Schumpeter meeting Keynes (DSK) agent-based model has been used to study a broad range of climate policies (Lamperti & Roventini, 2022). For instance, Wieners et al. (2022) show that a low carbon tax is ineffective at triggering the green transition due to inertia in the process of technological change, while high carbon prices foster economic instability.

² The capital adequacy ratio is an indicator reflecting the risk of insolvency from excessive loans for a bank.

Command-and-control regulations combined with green subsidies allow a strong reduction of emissions while increasing employment and maintaining macro-financial stability, though adversely affecting public deficit. The introduction of a mild carbon tax mitigates such frictions and neutralizes the adverse effects on the public budget, thereby delivering a win-win policy package. Additionally, Lamperti et al. (2021) use the DSK model to analyze green financial policies, including the use of green public credit guarantees. Their results underline that guarantees act as a stabilizer as they decrease the negative impact of defaulted loans for banks in periods of economic downturn. However, they enlarge the burden of public debt and only reduce emissions moderately. The authors stress that green public guarantees can be a good complement to green capital requirements. Indeed, green capital requirements increase the supply of green loans, leading to financial instability, as green loans may be more risky than conventional ones. In this context, a guarantee reduces the risk of losses for banks. Meanwhile, higher growth due to increased credit supply will limit the increase in public debt caused by the guarantee.

Our contribution to the literature lies in the modelling of climate policies under different scenarios of risk associated with green capital investment. Specifically, we incorporate two dimensions of risk. First, we account for the actual financial risk—namely, the risk that green loans issued to finance green capital are not repaid and default³. Banks shape their lending interest rates according to this financial risk. Second, we consider the perceived risk-reward profile of green investment by firms, which influences their willingness to invest in green projects. This scenario-based approach enables us to evaluate how green investment risks influence the effectiveness of the climate policies in driving the low-carbon transition, the resulting economic and financial consequences, and when they must be complemented by additional policy instruments.

3. Methodology

3.1. Model overview

In this paper, we build the SFC model « Climate Investment in a Risk-Economy-Finance framework » (CIREF). SFC models are characterized by their focus on the interactions between economic and financial variables through consistent tracking of financial stocks and flows over time (Nikiforos & Zezza, 2017). Following the stock-flow consistent methodology (Godley & Lavoie, 2012), we represent the structure of the economy with a set of financial accounting matrices (see Appendix 4). As usual in SFC frameworks, output is demand-determined, money is endogenous, and agents operate under fundamental uncertainty—making decisions based on empirical information and heuristics rather than optimization (Souffron & Jacques, 2024).

³ Note that our model does not account for the operational or economic consequences of green investment project failures for firms themselves; rather, it focuses on the financial risk borne by banks in the event of loan defaults.

This type of model allows for considering short-run disequilibrium dynamics such as financial crisis or path dependency (Souffron & Jacques, 2024; Mercure et al., 2016).

CIREF, inspired by Dunz et al. (2021) and Dafermos & Nikolaidi (2021), represents a closed economy with seven type of agents who can be gathered into five categories (Figure 1). First, all firms produce with three inputs: labor, green capital, and brown capital. The brown capital producers produce brown capital, and the green capital producers produce green capital. Firms, households, and the government invest in both types of capital⁴. The consumption goods producers produce consumption goods that are bought by households and the government. Firms finance their investment firstly with retained profits and then with corporate bonds and loans, depending on the financing costs of these two options.

Second, households invest in green and brown capital and consume consumption goods. They receive wages from firms and dividends (distributed profits) from firms and banks, as they own a part of all firms and banks. To finance their investment, households take out loans from banks, and their income finances the rest.

Third, the government invests directly in green and brown capital and buys consumption goods. The government receives revenue from taxation, state-owned enterprises (distributed profits from the firms it owns), and the central bank (all profits). To finance its investment and expenditure, the government uses its revenue, and when it does not cover its costs, it issues government bonds. When the government is in a situation of economic surplus, it redeems the bonds to reduce its debt. When a public guarantee is implemented, the government makes loss reserves and saves them in a reserves account at the central bank.

Fourth, banks provide loans to households and firms and buy government bonds. Households and firms can default on their loans, which negatively affects banks (lower interest payments and repayments). In the case where a public guarantee on firms' green loans is implemented, the banks are partly covered in case of loan default: the government compensates the loss of the banks by repaying them.

Fifth, the central bank fixes the base interest rate, provides liquidity to banks (advances), and buys government bonds (residual purchaser).

The model operates in a fully recursive manner, with agents' decisions determined by information from previous periods.

⁴ Green/brown capital represents capital with low/high carbon intensity during construction or utilization such as machines for firms, housing for households or public infrastructure for the government.

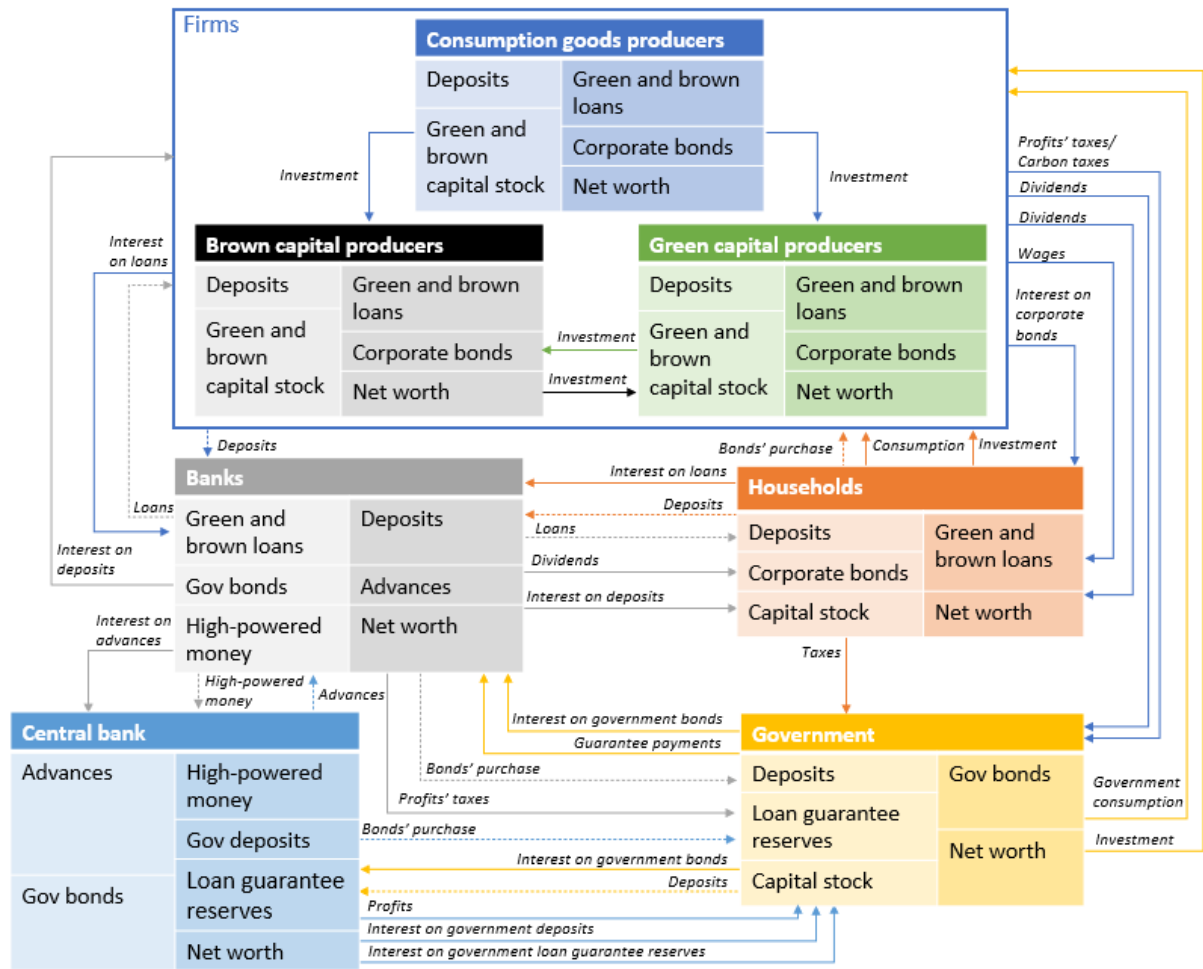


Figure 1: Diagram representation of CIREF. Solid lines represent transaction flows and dashed lines represent financial flows. Each table represents the balance sheet of each economic agent with its assets and liabilities. Representation inspired by Dunz et al. (2021).

3.2. Theory of change

In the absence of policy intervention, green capital maintains a low share compared to brown capital within the model. This is driven by four key factors.

First, agents underestimate climate risk when making their investment decisions⁵. For instance, Campiglio et al. (2023) underline that climate-related risks are inefficiently priced and financial markets underreact to them. Goldstein et al. (2019) find that firms frequently overlook risks beyond their immediate operations and underestimate the potential for non-linear climate impacts and tipping points. While we do not represent the consideration of climate risk by agents in our model, it is a key factor to understand why investment does not go towards green capital.

Second, the risks of green investment are higher for investors. Low-carbon projects typically involve high capital expenditures (CAPEX) and low operating costs (OPEX), resulting in

⁵ Note that physical damages of climate change are not considered in our analysis.

substantial upfront costs and long payback periods (IEA, 2024). These features expose investors to significant risk, especially given uncertainties about future returns. Additionally, many low-carbon technologies remain relatively immature, increasing the likelihood of unexpected construction costs and performance issues (Hourcade et al., 2021). Structural barriers—such as inadequate infrastructure, weak regulatory frameworks, underdeveloped markets, limited technical capacity, and insufficient knowledge networks—further elevate green investment risk (Negro et al., 2012). As a result, default rates on green loans tend to be higher than for brown loans (Buchetti et al., 2024). Climate policy uncertainty further increases the riskiness of green investment. These factors contribute to elevated capital costs for green investment—especially in emerging economies (IEA & IFC, 2023; Steffen, 2020). For instance, renewable energy investments in developing countries are often considered high-risk due to macroeconomic instability, currency volatility, political uncertainty, and weak institutional capacity (World Bank, 2023).

Third, path dependency favors carbon lock-in. Indeed, brown capital tends to be more productive than green capital due to its dominant position in the economy, leading to knowledge accumulation and spillovers (Romer, 1990). Delaying the transition will increase the technological gap between “clean” and “dirty” sectors (Acemoglu et al., 2012). Network effects, arising from the interconnections among technological systems and institutions, also favor carbon lock-in (Unruh, 2000; Negro et al., 2012).

Fourth, green capital may be priced higher than brown capital. However, this is not always the case when considering lifetime costs. According to the IEA (2024), clean and efficient technologies are now often the most cost-effective over time, as they offer lower operating costs. For instance, in 2023, around 95% of new utility-scale solar photovoltaic and onshore wind installations had lower generation costs than new coal and natural gas plants (IEA, 2024). For simplification, the prices of green and brown capital are equal in our modelling exercise, except for the adjustment induced by carbon pricing.

In the following sections, we present the transmission channels of each modeled instrument on the transition, the economy, and the financial system.

3.2.1. *Transmission channels of a carbon tax*

Figure 2 presents the transmission channels of a carbon tax in the model. Firms pay a carbon tax on their production depending on the amount of brown capital in total capital used for production. They finance the carbon tax with their profits and transfer a part of the costs of the carbon tax to consumers via an increase in the markup price. The carbon tax thus increases the price of brown capital and consumption goods, but also the price of green capital, as all firms use green and brown capital to produce. In their investment decision, firms take into account the prices of green and brown capital, but they also consider that if they use more brown capital to produce, they will pay more carbon tax. Hence, as the carbon tax increases the cost of using brown capital, the share of firms’ investment going to brown capital decreases, and the share going to green capital increases (Figure 2).

The level of the carbon tax plays a key role here. Indeed, in their investment decision, firms take into account the risk of investing in green/brown capital. At the beginning of the transition, the risk of investing in green capital is higher than the risk on brown capital. Indeed, green capital is still not developed, so the production ecosystem (infrastructure, regulatory framework, and expertise) is not adequate (Negro et al., 2012). Moreover, firms also consider the financing cost of green/brown capital in their investment decision. As green investment is perceived⁶ as more risky by banks (new technologies, no track records, no financing experience...), they put higher interest rates on their green loans (Buchetti et al., 2024). Consequently, a low carbon tax may not significantly increase the share of firms' investment in green capital, due to the higher risk and financing cost of green capital. If the carbon tax is high enough to compensate higher financing cost and risk on green capital investment, a higher share of firms' investment goes to green capital. This leads to a decrease in the amount of brown capital and an increase in the amount of green capital in the economy. However, if the carbon tax exerts a strong recessionary impact on the economy, it can potentially reduce overall investment and thereby limit the pace of the transition (Magacho et al., 2024).

As the share of green capital in the economy increases, firms develop learning effects. For instance, Way et al. (2022) find that the costs of solar photovoltaics, wind, and batteries have dropped exponentially at a rate near 10% per year for several decades, thanks to economies of scale and learning. Higher learning increases green projects' success and thus decreases the probability of defaults on green loans (Figure 2). Besides, banks develop experience in financing green investment projects and decrease their lending interest rates on firms' green loans even more, favoring higher green investment by firms. Egli, Steffen, and Schmidt (2018) provide empirical data showing that financing experience contributed to the reduction of the capital costs of photovoltaic and onshore wind projects (by 1% and 4%, respectively) in Germany between 2000 and 2017. Besides, the increase in green capital productivity, the decrease in green capital prices (green firms pay less carbon tax as they invest a lot due to high demand), and the greening of the economy⁷ lead households and the government to also invest more in green capital.

The aggregated impact of the carbon tax on the economy is uncertain. Dafermos & Nikolaidi (2022) show that when carbon tax revenues are not recycled, the macroeconomic impact of the carbon tax is negative, as it leads to a reduction of firms' profits, lower investment, higher defaults, and lower government revenues. However, when they are used to provide green subsidies to firms, they tend to have a positive macroeconomic effect (Dafermos & Nikolaidi, 2022). Lamperti & Roventini (2022) show that high carbon prices foster economic instability and that carbon revenue recycling schemes towards firms or households do not completely eliminate these effects. In our modelling, carbon tax revenues go to the public budget and are

⁶ We talk about the perceived risk by banks as we assume that if banks were considering transition and physical risks, the risk of investing in green capital may be actually smaller than the risk of investing in brown capital.

⁷ We assume that all agents follow what is happening in the rest of the economy to reflect that as the production ecosystem adapts to more green capital, they go towards green capital.

fully used to finance public investment and consumption. Hence, the carbon tax can have a positive effect on GDP if the increase in government spending compensates for the adverse effects described above.

Concerning financial stability, banks see an increase in the number of defaulted loans as the profits from the brown capital producers decrease. Moreover, as firms lend more to green investment projects, which have a higher rate of defaults in the short run, banks' financial stability decreases, but in the long run, the probability of default on green loans decreases.

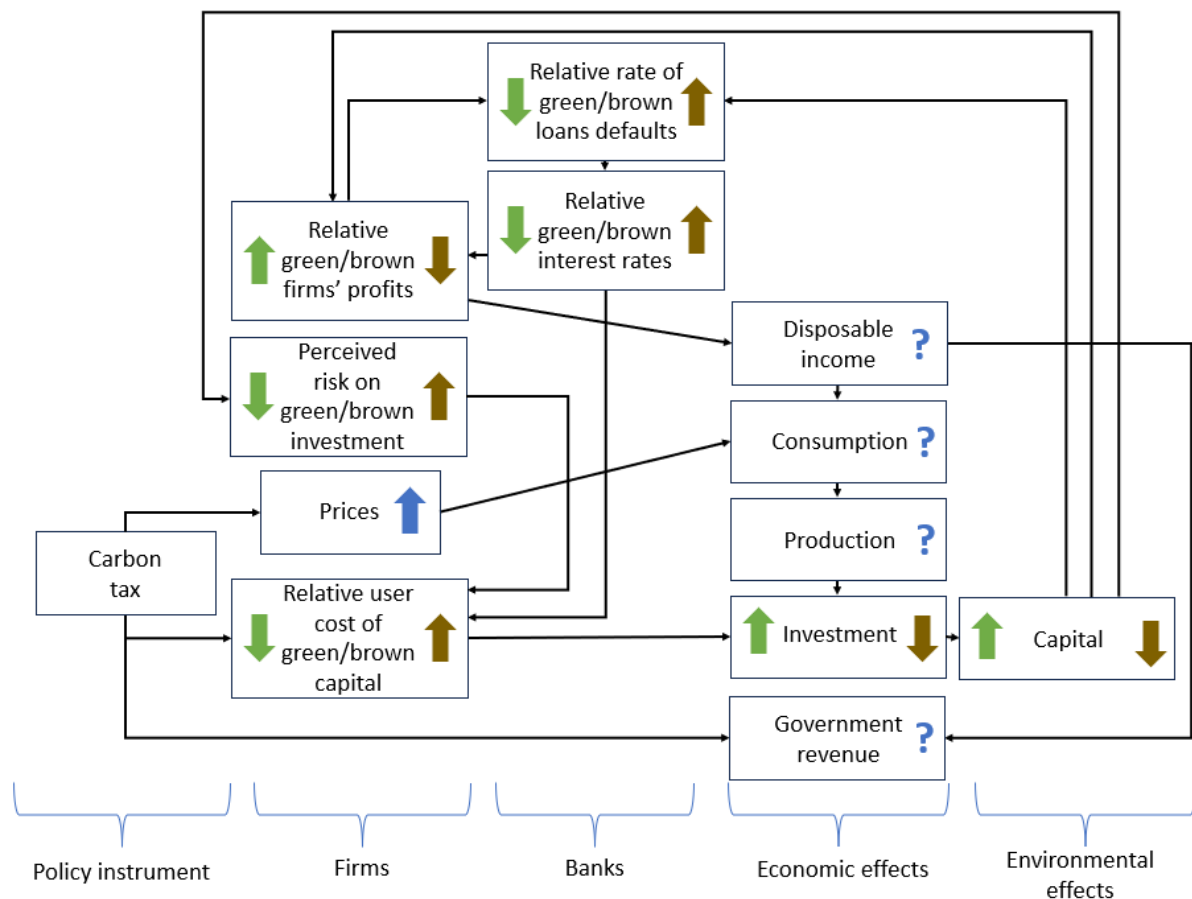


Figure 2: Transmission channels of a carbon tax

3.2.2. Transmission channels of green mandates

A green mandate fixes a target on the share of green capital that firms, households, and government must reach. In reality, it could take the form of standards imposing low-carbon technologies (i.e., electrification standards, energy-efficient buildings standards...). In our model, regulations have a direct impact on green capital as we assume that agents comply with them. To reach this target, their share of green capital investment increases over time. Consequently, the stock of green capital increases in the economy. Over time, this leads to a decrease in the risk for investing in green capital for firms and in banks' green lending interest rates as they develop learning-by-doing effects. This reinforces the increase in the share of green investment for firms, leading to higher green capital in the economy.

The overall macroeconomic impact of green mandates is uncertain. In the short run, they may have negative effects, as agents are required to invest in green capital, which typically entails higher financing costs and lower productivity. In the long run, the impact could be positive as financing costs decrease.

Concerning financial stability, green mandates could increase financial instability in the short run by increasing investment in green capital, which has a higher rate of defaults. This effect should be temporary as the rate of defaults decreases over time.

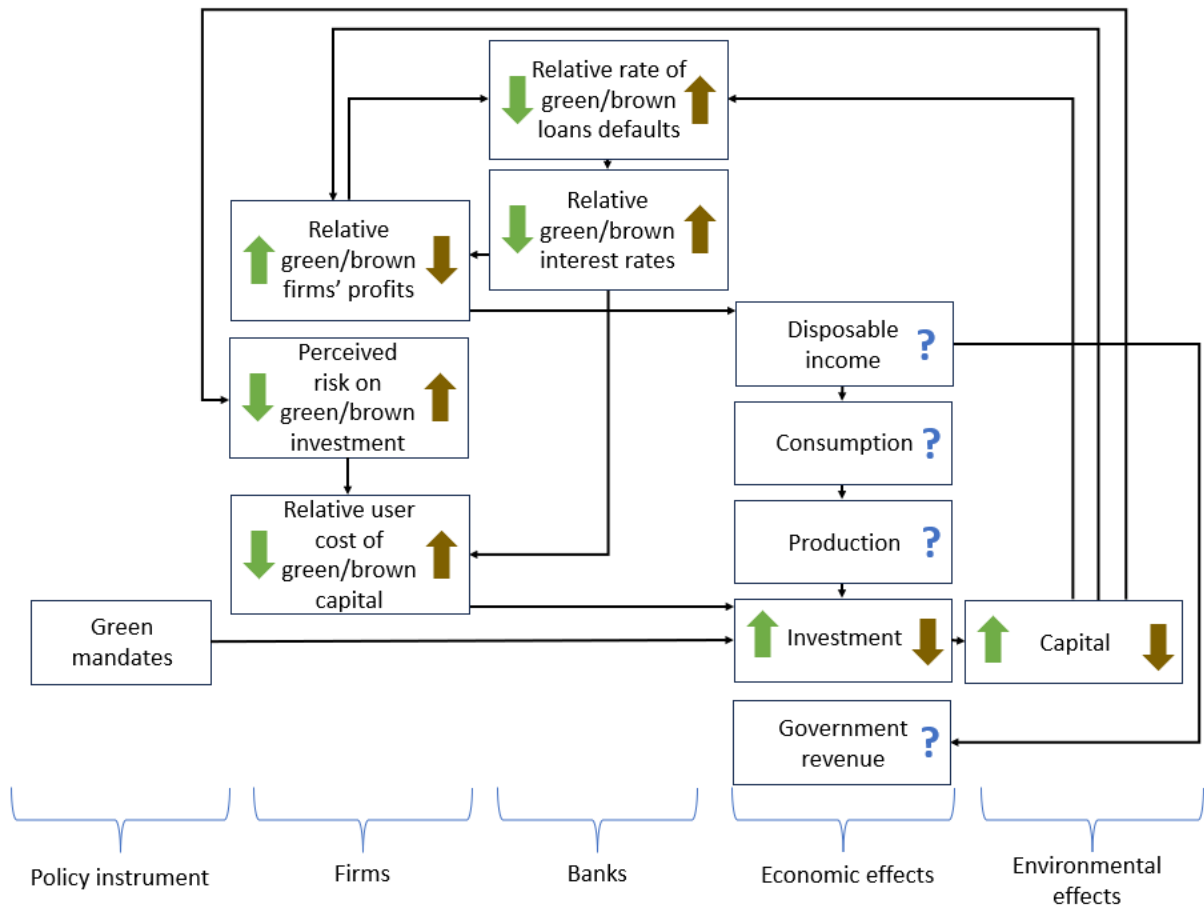


Figure 3: Transmission channels of green mandates

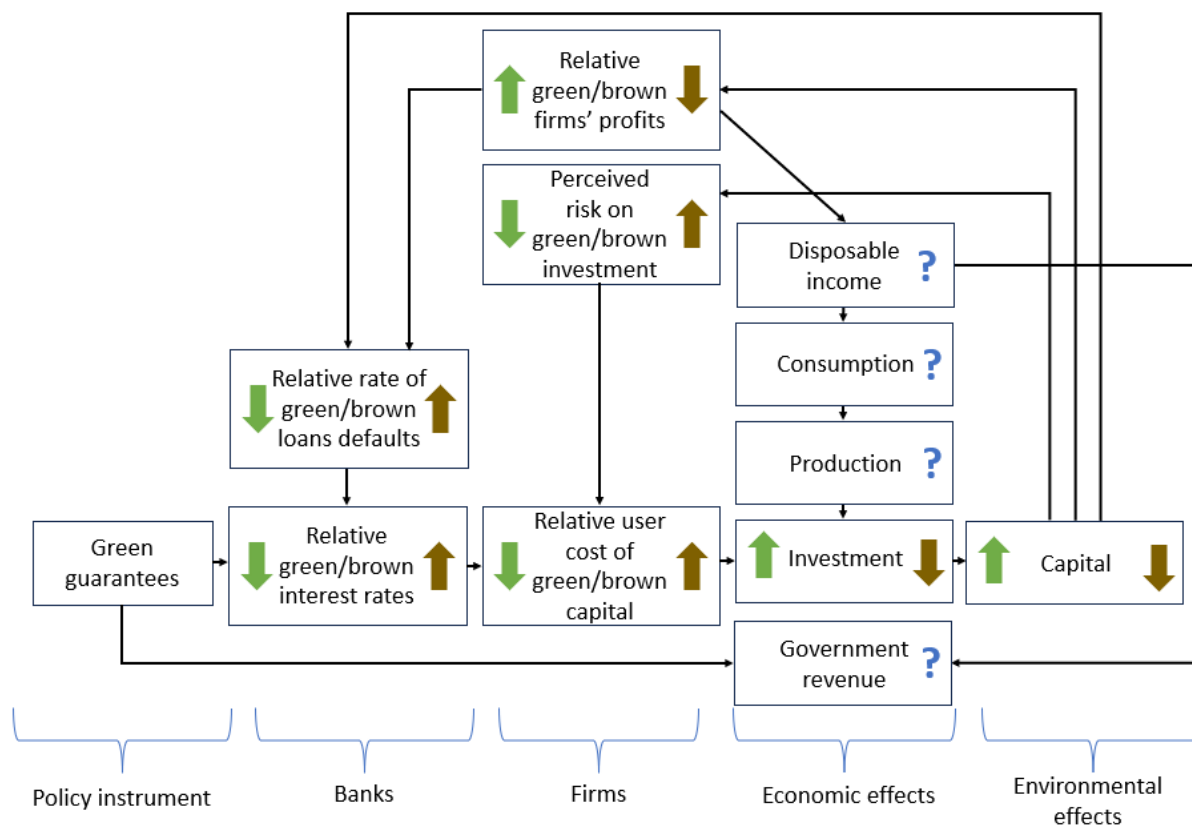
3.2.3. Transmission channels of guarantees

A guarantee on firms' green loans decreases the risk of defaults on green loans for banks, as the government compensates the banks in case of default. Consequently, banks lend at lower interest rates for green capital investment by firms. In their investment decision, firms consider the financing costs and the perception of investment risks on each type of capital. In order to have an impact, the guarantee on green loans has to lead to a strong decrease in the financing cost of green capital to compensate for the risks of green investment for firms, when these risks are perceived as high. If this is the case, thanks to lower financing costs, firms invest more in green capital, and the amount of green capital in the economy increases (Figure 4). Over

time, firms and banks develop learning effects as the production of green capital increases, which decreases interest and default rates.

On the financial side, banks' capital adequacy ratio –reflecting the risk of insolvency from excessive loans– improves thanks to higher retained profits due to the compensation from the government in case of green loans' defaults. Consequently, banks decrease their base lending interest rate, which applies to all loans. The interest rates on green loans decrease more than the interest rates on brown loans, thanks to the guarantee. Note that the interest rates on brown capital producers' loans could increase due to lower profits.

The aggregated impact of the guarantee on the economy depends on different factors. First, it depends on the impact on firms' profits: the decrease in green capital costs tends to increase firms' profits, but the demand for brown capital decreases, pushing downward the profits of the brown capital producers. Second, it varies with the cost of the guarantee for the government. In the short run, it is likely that the government sees an increase in its deficit as green projects are riskier. In the long run, the probability of defaults on green loans decreases thanks to learning-by-doing effects, so the cost of the guarantee scheme for the government decreases. However, if the amount of green loans increases massively to finance the transition, government debt could still increase in the long run. To limit this effect, the guarantee scheme should be temporary: it is applied in the short term to finance pilot projects to reduce the risks for investors and banks, but once the risks have been reduced, the guarantee is not needed anymore. The increase in public debt is even higher in countries that need to make large amounts of loss reserves to reassure banks of their repayment ability. In our modelling, the government does not adjust its spending when public debt increases.



3.2.4. *Transmission channels of green public expenditure*

The amount of green capital in the economy increases as the government directly increases its demand for green capital (Figure 5). This leads to a decrease in the risk for investing in green capital for banks and firms. Indeed, government investment in green capital allows banks and firms to see which green projects are working, and thus to target bankable green projects. Thanks to this learning effect, the default rate on green loans decreases, and banks decrease their lending interest rates on green loans relatively to brown loans. Consequently, firms have an incentive to invest more in green capital than in brown capital because the financing cost of green capital has decreased, and the perceived risk relative to green capital investment has decreased too. Moreover, the increase in the production of green capital enhances its productivity. Besides, firms and households tend to adjust their behavior in line with broader economic trends: as the economy becomes greener, their investments gradually shift toward

greener assets as well. The increase in green investment by firms and households leads to higher demand for loans, which deteriorates the financial stability of banks.

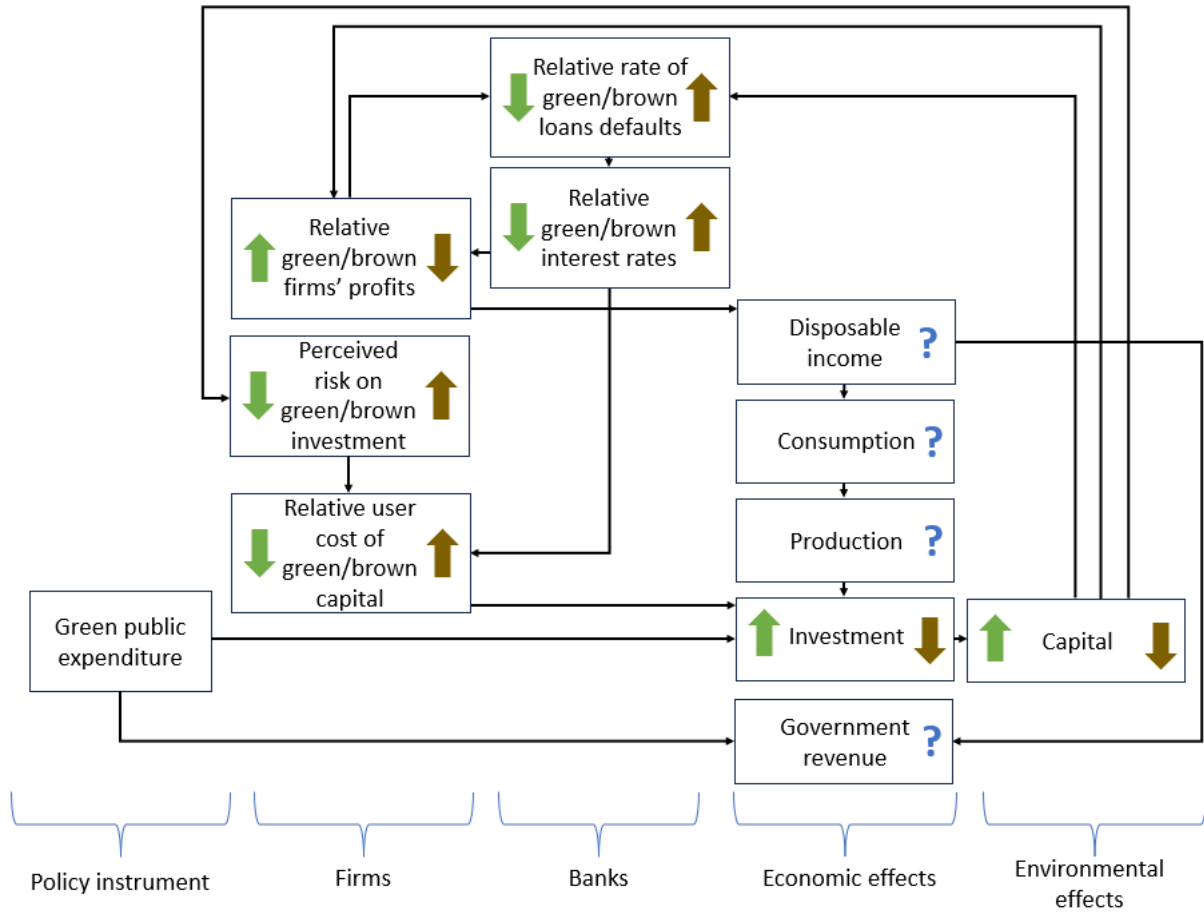


Figure 5: Transmission channels of green public expenditure

3.3. Key equations

In this section, we present the main equations allowing understand our modelling of each policy in CIREF. In the following equations, subscripts F , B , G , H , Bk , CB and Gov are used to denote consumption goods firms, brown capital firms, green capital firms, households, banks, the central bank, and the government, respectively.

3.3.1. Agents' capital investment decision

First, we present how firms, households, and the government make their choice between investing in green or brown capital. The shares of brown and green capital investment are determined through a portfolio allocation choice model⁸ for each firm (1). In their investment decisions, firms consider the user cost of capital, the perceived risks associated with each type of investment (ω^B and ω_t^G), and the productivity of each type of capital (ϵ_t^B and ϵ_t^G). The user

⁸ Tobin's asset-allocation model (Tobin, 1969) has become a standard component in SFC models (Kemp-Benedict & Godin, 2017). It relates financial asset returns to wealth allocation: if an asset offers a higher return compared to other assets, more wealth is allocated to it. Here, we follow Dunz et al. (2021) and apply it to firms' investment allocation.

cost of capital is the cost borne by the firm for the utilization of capital assets. It is equal to the sum of the unit cost of buying capital (prices: p_t^B and p_t^G); the financing cost of capital, approximated here with the interest rates on loans (r_t^{nB} and r_t^{nG}) and bonds ($r_{b,t}^{nB}$ and $r_{b,t}^{nG}$) multiplied by their shares in external financial needs ($\sigma_{L,t}^{nB}$ and $\sigma_{L,t}^{nG}$, the shares of external financial needs covered by brown and green loans respectively); and the unit cost of capital depreciation (depreciation rates: δ^B and δ^G). In this modelling exercise, depreciation rates are assumed to be identical across capital types, so they do not affect firms' investment decisions. Likewise, initial prices are also set equal for simplification. Moreover, in the case where a carbon tax policy is implemented, the carbon tax will increase the cost of using brown capital to produce, so firms take this into account by considering the ratio between the cost of producing with brown capital and the cost of producing with green capital. The estimated cost of producing with brown capital is equal to the sum of the unit cost of labor (UC_{t-1}^n) and the unit cost of carbon taxation, whereas, the cost of producing with green capital is simply the unit cost of labor (UC_{t-1}^n). Note that the unit cost of carbon taxation consider the amount of carbon tax paid by the firm on its brown capital that the firm does not translate in higher consumer prices ($CT_{t-1}^n - \kappa_{CT}CT_{t-1}^n$). In the case where a green mandate is implemented, the share of brown capital is equal to the minimum between the one computed with the portfolio allocation model and the one allowing to comply with the regulation ($1 - \overline{\phi_t^{LG}}$).

For a given type of capital, the coefficients λ associated with its own user cost and perceived risk are negative, and the one associated with its own productivity is positive. Instead, the coefficients associated with the user cost and perceived risk of the other type of capital are positive, and the coefficients associated with the productivity of the other type of capital are negative. For example, the coefficient λ_3^B is negative to reflect that an increase in the financing costs of brown capital leads to a decrease of the share of brown capital investment, whereas the coefficient λ_4^B is positive to reflect that an increase in the financing costs of green capital leads to an increase of the share of brown capital investment.

The share of brown capital investment in total investment of firms $n = F, G, B$ is given by:

$$\begin{aligned} \phi_t^{nB} = \min \Bigg(& \lambda_{0,t}^B + \lambda_1^B p_{t-1}^B + \lambda_2^B p_{t-1}^G + \lambda_3^B (\sigma_{L,t-1}^{nB} r_{t-1}^{nB} + (1 - \sigma_{L,t-1}^{nB}) r_{b,t-1}^{nB}) \\ & + \lambda_4^B (\sigma_{L,t-1}^{nG} r_{t-1}^{nG} + (1 - \sigma_{L,t-1}^{nG}) r_{b,t-1}^{nG}) + \lambda_5^B \delta^B + \lambda_6^B \delta^G + \lambda_7^B \omega^B + \lambda_8^B \omega_t^G \\ & + \lambda_9^B \epsilon_{t-1}^B + \lambda_{10}^B \epsilon_{t-1}^G + \lambda_{11}^B \left(UC_{t-1}^n + \frac{CT_{t-1}^n - \kappa_{CT}CT_{t-1}^n}{Y_{t-1}^n} \right) \\ & + \lambda_{12}^B UC_{t-1}^n; (1 - \overline{\phi_t^{LG}}) \Bigg) \end{aligned} \quad (1)$$

The share of green investment in total investment of firms is the opposite of the share of brown investment:

$$\phi_t^{nG} = 1 - \phi_t^{nB} \quad (2)$$

The autonomous brown capital demand, $\lambda_{0,t}^B$, depends on the evolution of brown capital in total capital in the economy. It adjusts gradually to reflect path dependency. Indeed, firms' investment decisions are path dependent due to technological, institutional, and behavioral lock-in effects (Kotilainen et al., 2019).

$$\lambda_{0,t}^B = \lambda_{0,t-1}^B + \kappa_I (sh_{t-1}^{k_B} - sh_{t-2}^{k_B}) \quad (3)$$

with $sh_{t-1}^{k_B}$ the share of brown capital in the economy and κ_I the sensitivity of the autonomous brown capital demand to changes in $sh_t^{k_B}$.

The perception of risks on green capital by firms, ω_t^G , is a logistic function of the share of green capital in the economy (Figure 6)⁹. The assumption is that as the share of green capital in the economy grows, the socio-technical system (regulatory frameworks, infrastructures, workforce skills, etc.) evolves, becoming increasingly aligned with green capital production (Negro et al., 2012; Söderholm, 2020). Moreover, firms develop experience to produce green capital, so the risk decreases as the transition occurs¹⁰. Pan & Köhler (2007) argue that learning curves follow an S-shape due to the lifecycle of technologies, which go through various phases from laboratory-invention, to explosive take-off, continued high growth, slowdown, and maturity. Similarly, according to Rogers (2010), the adoption of a technology follows an S-shape as the diffusion of the technology increases information and reduces uncertainty.

$$\omega_t^G = \begin{cases} \omega_0^G, & \text{if } sh_{t-1}^{k_G} \leq sh_{MIN}^{k_G} \\ \omega_B + \frac{\omega_0^G - \omega_B}{1 + \exp(par_f(sh_{t-1}^{k_G} - par_g))}, & \text{if } sh_{MIN}^{k_G} < sh_{t-1}^{k_G} < sh_{MID}^{k_G} \\ \omega_B, & \text{if } sh_{t-1}^{k_G} \geq sh_{MID}^{k_G} \end{cases} \quad (4)$$

with ω_0^G the initial level of risk of investing in green capital; ω_B the risk of investing in brown capital; $sh_{MIN}^{k_G}$ the threshold of the share of green capital in the economy above which the risk on green capital starts to decrease; $sh_{MID}^{k_G}$ the threshold of the share of green capital in the economy above which the risk on green capital becomes equal to the risk on brown capital; par_f controls the speed of the decrease; par_g is the midpoint (value of the share of green capital for which the decrease of the risk is the most significant). We adopt the conservative assumption that the risk associated with brown investment remains constant and does not increase during the transition.

⁹ Firms do not consider the probability of defaults in their perception of risk, as they do not observe these probabilities of defaults compared to banks.

¹⁰ Note that we do not consider the impact of unsuccessful commercial precedents in our modelling exercise. However, unsuccessful commercial precedents might have a negative impact on firms' green investment decisions in the short run.

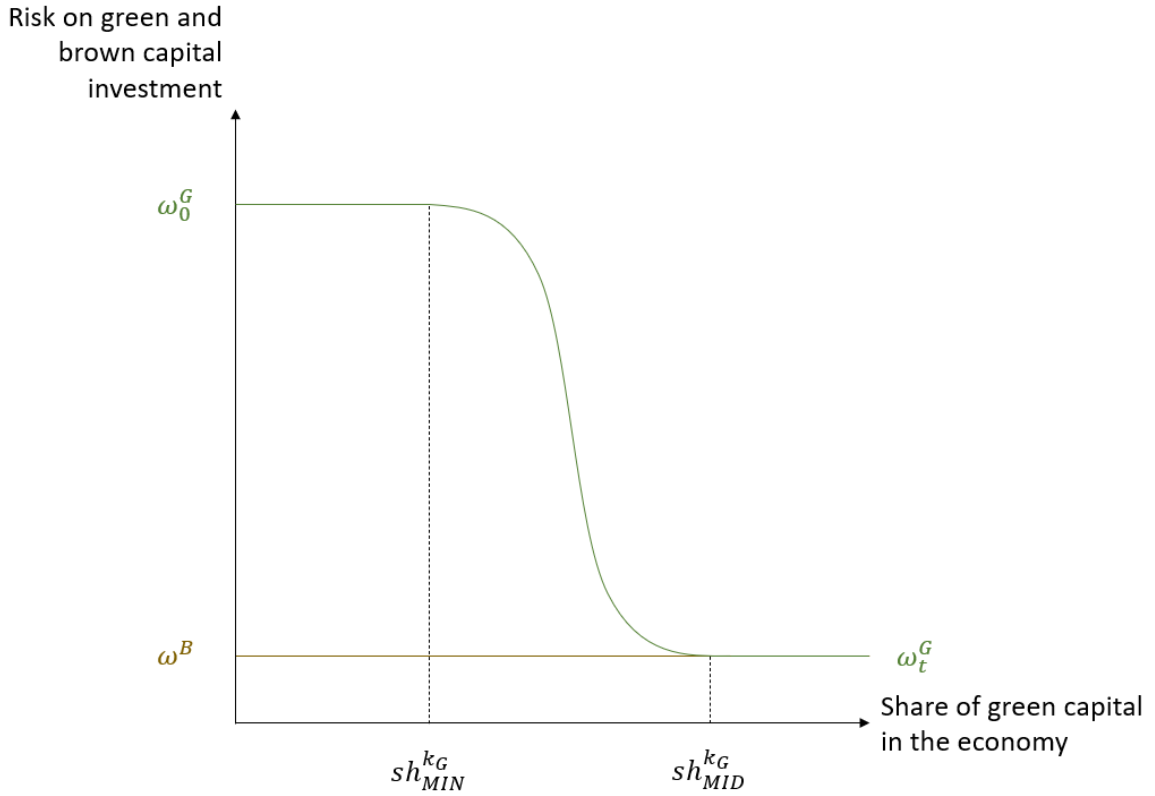


Figure 6: Evolution of perceived risks on green and brown capital investment for firms

The productivity of green capital is a logistic function of the share of green capital in the economy (Figure 7). The higher the share, the more it tends towards its maximal productivity (equals to the initial value of brown capital productivity).

$$\epsilon_t^G = \begin{cases} \epsilon_0^G, & \text{if } sh_{t-1}^{k_G} \leq sh_{MIN}^{k_G} \\ \epsilon_0^B + \frac{\epsilon_0^B - \epsilon_0^G}{1 + \exp(par_a(sh_{t-1}^{k_G} - par_b))}, & \text{if } sh_{MIN}^{k_G} < sh_{t-1}^{k_G} < sh_{MAX}^{k_G} \\ \epsilon_0^B, & \text{if } sh_{t-1}^{k_G} \geq sh_{MAX}^{k_G} \end{cases} \quad (5)$$

with ϵ_0^B , the initial level of brown capital productivity, ϵ_0^G , the initial level of green capital productivity, and $sh_{MAX}^{k_G}$, the maximum value of the share of green capital in the economy at which green capital productivity becomes equal to its maximum value.

The productivity of brown capital varies in the opposite direction from green capital productivity. The assumption is that as the share of green capital in the economy grows, the socio-technical system (regulatory frameworks, infrastructures, workforce skills, etc.) evolves, becoming increasingly aligned with green capital production (Negro et al., 2012; Söderholm, 2020).

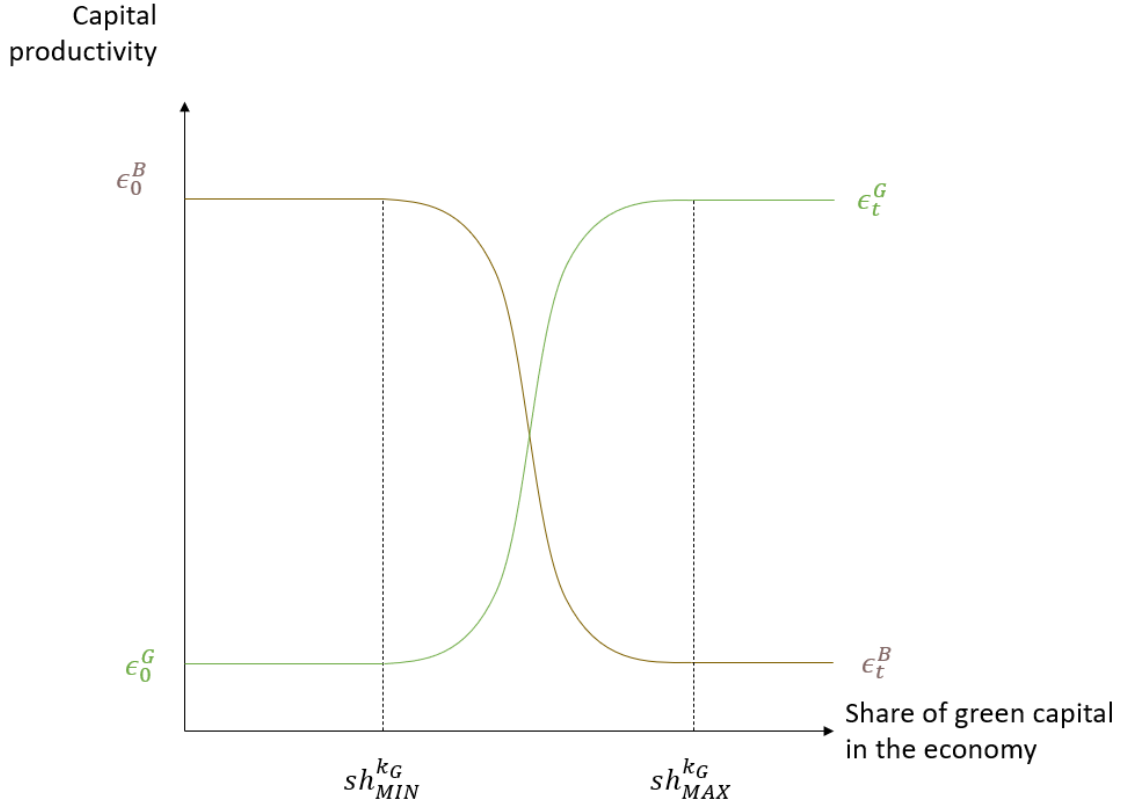


Figure 7: Evolution of green and brown capital productivities depending on the share of green capital in the economy.

The share of brown investment in total investment of households is done with a Tobin portfolio allocation model similar to firms. The decision of households depends on the price and the productivity of each type of capital (following Dunz et al., 2021). In the case where a green mandate is implemented, the share of households' brown investment is equal to the minimum between the share computed with the Tobin model and the share allowing to follow the regulation $(1 - \overline{\phi}_t^{LG})$.

$$\phi_t^{HB} = \min \left((\lambda_{0,t}^{HB} + \lambda_1^{HB} p_{t-1}^B + \lambda_2^{HB} p_{t-1}^G + \lambda_3^{HB} \epsilon_{t-1}^B + \lambda_4^{HB} \epsilon_{t-1}^G); (1 - \overline{\phi}_t^{LG}) \right) \quad (6)$$

The government has the same portfolio allocation model as households.

3.3.2. Banks' lending interest rates

The financing cost plays a key role in the firms' investment decision, especially banks' lending interest rates. Banks determine their base interest rate, which applies to all loans, depending on their capital adequacy ratio (CAR)¹¹, the interest rate of the central bank ($\bar{r}$), and a minimum profit markup on top of the risk-free interest rate (spr^L) (Dafermos & Nikolaidi, 2022):

¹¹ The capital adequacy ratio (CAR) is an indicator used to assess whether banks hold sufficient capital to absorb a reasonable level of losses and avoid insolvency.

$$r_t^L = (\bar{r} + spr^L) \left(1 - \kappa_0 \frac{CAR_t - CAR^T}{CAR^T} \right) \quad (7)$$

where κ_0 is the CAR adjustment rate reflecting that when the CAR decreases compared to its target CAR^T , banks increase their interest rates to increase their profits and to decrease loans' demand to maintain their CAR at the target level.

The interest rate on brown loans for firms n depends on banks' base interest rate and on the perception of risk by banks, which is reflected in the average rate of defaults on brown loans (following Dunz et al., 2021) and firms' debt-service ratio (following Dafermos & Nikolaidi, 2022). The inclusion of the debt-service ratio reflects that banks impose a higher interest rate when firms become more financially fragile (Juselius & Drehmann, 2020).

$$r_t^{n_B} = r_t^L + \kappa_1 \frac{DL_t^{n_B}}{L_{t-1}^{n_B}} + \kappa_2 dsr_t^n \quad (8)$$

with $DL_t^{n_B}$ the defaults of firms n on their brown loans happening in period t on their brown loan stock of the previous period $L_{t-1}^{n_B}$; κ_1 the sectoral interest rate adjustment rate related to brown firms' defaults; and κ_2 the sectoral interest rate adjustment rate related to firms' debt-service ratio dsr_t^n .

The total amount of defaulted loan m is the sum of the defaults on all loans vintages¹² ($m = B_G, B_B, G_G, G_B, F_G, F_B$, where the subscript B represents the brown loans and G the green loans):

$$DL_t^m = \sum_{v=0}^{t-1} \varphi_{v,t}^m L_{v,t-1}^m \quad (9)$$

with $\varphi_{v,t}^m$ the probability of default at period t on the loans contracted at period v .

The probability of defaults on brown loans only depends on the illiquidity ratio of the firms, as the brown technology is mature (logistic function, following Dafermos & Nikolaidi, 2022). Firms' illiquidity ratio is an indicator of the ability of firms to repay their debt (Dafermos & Nikolaidi, 2022). It is the ratio of firms' cash outflows to cash inflows. The main difference between the debt-service ratio and the illiquidity ratio is that the latter considers the new flow of credit in cash inflows.

$$illiq_t^n = \frac{KB_t^n + REP_t^n + WB_t^n + T_t^n + CT_t^n}{Y_t^n + L_{t,t}^{n_B} + L_{t,t}^{n_G} + \overline{p_b^{n_B}} \Delta b_t^{n_B} + \overline{p_b^{n_G}} \Delta b_t^{n_G} + r_t^D \Delta D_t^n} \quad (10)$$

The illiquidity ratio reflects that when cash outflows increase compared to cash inflows, the probability of defaults increases. This allows us to represent that as the transition occurs, brown firms see a decrease in their profits, leading to a lower illiquidity ratio and thus a higher

¹² We introduce loan vintages as green loans belonging to separate generations have different probabilities of defaults and as it allows a better representation of the dynamics of principal repayments and interest changes.

rate of defaults. Hence, the probability of defaults on the brown loan vintage v of firms n in period t is given by:

$$\phi_{v,t}^{n_B} = \phi_t^{illiq_n} \quad (11)$$

where:

$$\phi_t^{illiq_n} = \frac{1}{1 + def_0 e^{(def_1 - def_2 illiq_{t-1}^n)}} \quad (12)$$

with def_0 , def_1 and def_2 parameters of the default rate function.

Firms' debt-service ratio is the ratio between debt payment commitments, which is the sum of capital bill (KB_t^n , interest payments on loans and corporate bonds) and loan repayments (REP_t^n), and gross profits before interests (Y_t^n output and WB_t^n the wage bill).

$$dsr_t^n = \frac{KB_t^n + REP_t^n}{Y_t^n - WB_t^n} \quad (13)$$

The interest rate on green loans for firms n is expanded compared to the interest rate on brown loans to include the rate of guarantees ρ_G . When a guarantee is implemented, banks consider the risk of default of the guarantor when determining their interest rates. In our modelling, when a 100% guarantee is implemented $r_t^{nG} = r_t^L$, meaning that banks do not charge a higher interest rate than their base interest rate, as we assume that the guarantor has a low risk of default.

$$r_t^{nG} = r_t^L + (1 - \rho_G) \left(\kappa_1 \frac{DL_t^{nG}}{L_{t-1}^{nG}} + \kappa_2 dsr_t^n \right) \quad (14)$$

The probability of default on firms' green loans depends on firms' illiquidity ratio (12), but it also depends on two additional factors compared to brown loans. First, it depends on the share of green capital in the economy in the period when the loan started (v). This reflects the presence of learning-by-doing effects from firms as the technology becomes mature (Way et al., 2022), and from the financial sector as banks become more familiar with green projects (Egli et al., 2018). We use a discrete approximation of a logistic function as it takes time to develop learning effects (Pan & Köhler, 2007):

$$\phi_v^\epsilon = \begin{cases} \phi_0^\epsilon, & \text{if } sh_v^{kG} \leq sh_{MIN}^{kG} \\ \frac{\phi_0^\epsilon}{1 + \exp(par_e(sh_v^{kG} - par_d))}, & \text{if } sh_{MIN}^{kG} < sh_v^{kG} < sh_{MID}^{kG} \\ 0, & \text{if } sh_v^{kG} \geq sh_{MID}^{kG} \end{cases} \quad (15)$$

with sh_v^{kG} the share of green capital in the economy in the period when the loan vintage started v ; sh_{MIN}^{kG} the threshold of the share of green capital in the economy above which the probability of defaults on green loans starts to decrease; sh_{MID}^{kG} the threshold of the share of

green capital in the economy above which φ_v^ε is equal to zero; par_e the steepness of the approximated logistic function; par_d represents the midpoint of the approximated logistic function. We assume that φ_v^ε remains constant over the lifetime of loans contracted in period v . In other words, the default probability of green loan vintages from previous periods does not change as the share of green capital in the economy evolves. This reflects that a loan issued in period v was associated with a green investment project based on the conditions and technologies available at that time. Even if the share of green capital increases in subsequent periods—implying a general decline in the riskiness of green investments—this does not necessarily reduce the risk associated with earlier investments, which may rely on outdated technologies or less favorable conditions.

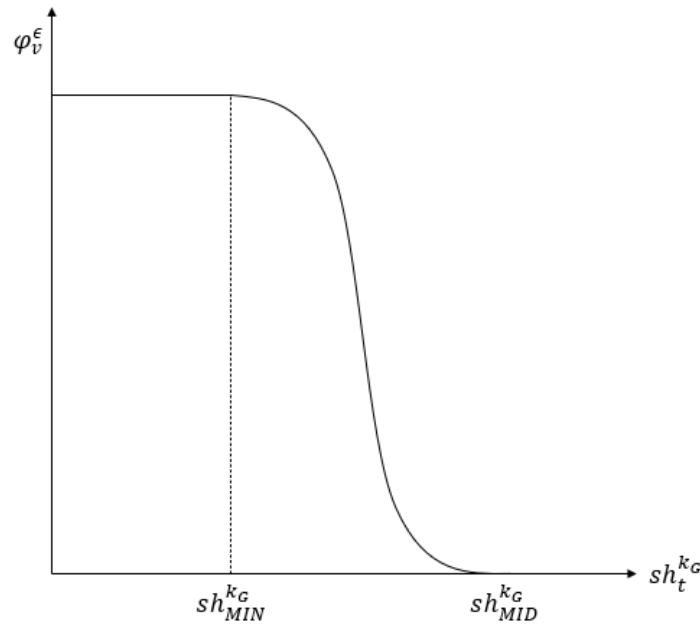


Figure 8: Probability of default on green loans related to the share of green capital in the economy

Second, it is a function of the age of the vintage of loans to reflect that the risk of default on green loans is higher in the first years of green investment projects and that it tends to decrease once projects start to operate (Hourcade et al., 2021; IEA, 2024).

$$\varphi_{v,t}^V = \frac{\varphi_v^\varepsilon}{1 + \exp\left(par_s((t - v) - par_m)\right)} \quad (16)$$

where $t - v$ is equal to the age of the loan at period t where v is the period when the vintage of loans was contracted, φ_v^ε is the probability of defaults related to the share of green capital in the economy on the loan vintage contracted at the period v ¹³; par_s is the steepness of the approximated logistic function; and par_m is the midpoint of the approximated logistic function.

¹³ We assume that as the economy becomes greener, the upfront risks of green projects decrease.

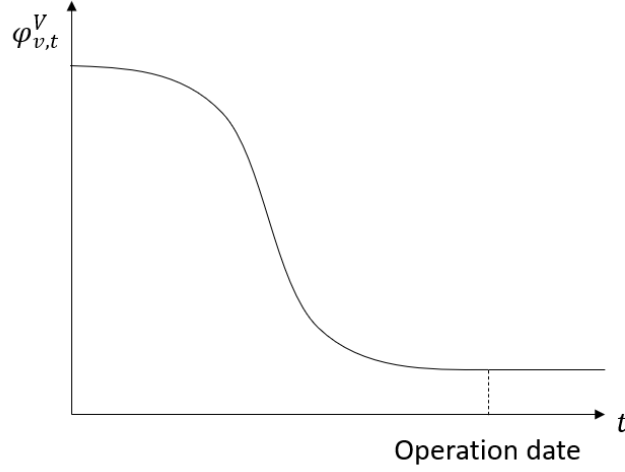


Figure 9: Probability of default related to the age of a vintage of loans

Hence, the probability of defaults on green loans is given by:

$$\varphi_{v,t}^{n_G} = \varphi_t^{illiqn} (1 + \varphi_{v,t}^V) (1 + \varphi_v^\varepsilon) \quad (17)$$

3.3.3. Modeling of policies

3.3.3.1. Carbon tax

We present how the carbon tax on firms' brown capital is implemented in the model. Firms pay a carbon tax on their production depending on their share of brown capital in total capital used for their production (K_t^n). The carbon tax is paid with firms' profits (20).

$$CT_t^n = \tau_t^{CT} Y_t^n \frac{K_t^{n_B}}{K_t^n} \quad (18)$$

with Y_t^n the production of firms n and $K_t^{n_B}$ the stock of brown capital of firms n .

The carbon tax rate τ_t^{CT} increases over time, depending on a constant growth rate¹⁴, g_τ^{CT} , and the difference between the targeted share of green capital and the actual share of green capital in the economy:

$$\tau_t^{CT} = \tau_{t-1}^{CT} \left(1 + g_\tau^{CT} (\overline{sh}^{k_G} - sh_t^{k_G}) \right) \quad (19)$$

The carbon tax reduces firms' profits:

$$\Pi_t^n = Y_t^n - WB_t^n - KB_t^n + r_{t-1}^D D_{t-1}^n - T_t^n - CT_t^n \quad (20)$$

with WB_t^n the wage bill, KB_t^n the capital bill, $r_{t-1}^D D_{t-1}^n$ the interest payments on firms' deposits, and T_t^n the profits taxes.

¹⁴ Calibrated such that the share of green capital in the economy reaches its target when this policy is implemented in scenario 1, see Section 3.4.

Firms translate a part of the increase in production costs due to the carbon tax to consumers by increasing their markup:

$$\theta_t^n = \theta_0 + \kappa_{CT} \frac{CT_{t-1}^n}{Y_{t-1}^n} \quad (21)$$

with κ_{CT} the sensitivity of the markup to carbon tax costs and θ_0 a constant markup reflecting that firms translate a part of the financing cost of capital and the profits' tax on consumer prices.

Consumer prices depend on the unit production cost and the markup θ_t^n :

$$p_t^n = UC_t^n (1 + \theta_t^n) \quad (22)$$

where UC_t^n is the unit production cost, which only depends on the cost of labor, as the cost of capital is financed with the firms' profits. This means that firms translate the increase in labor costs fully to consumers.

As shown in Eqs. (1) and (6), the carbon tax plays a role in agents' investment decisions directly through the change in prices. In this analysis, we assume that the carbon tax is not redistributed and is used by the government to increase its consumption and its investment due to higher carbon tax fiscal revenues (Appendix 4.1.3). Government revenue comes from income and carbon taxes, redistributed profits from state-owned enterprises (DP_t^{Gov}), central bank profits (Π_t^{CB}), interests on its deposits in the central bank ($\bar{r}D_{t-1}^{Gov}$), and interests on its loan guarantee reserves in the central bank in case of the implementation of a guarantee scheme ($\bar{r}RES_{t-1}^{Gov}$):

$$R_t^{Gov} = T_t^H + T_t^{Bk} + \sum_n T_t^n + \sum_n CT_t^n + DP_t^{Gov} + \Pi_t^{CB} + \bar{r}D_{t-1}^{Gov} + \bar{r}RES_{t-1}^{Gov} \quad (23)$$

3.3.3.2. Green mandates

In case of the modelling of a green mandate, the allocation of firms', households' and government' investment depends on the share of green capital allowing to follow the regulation (Eq.(1) and (6)). If the allocation of investment towards green investment from the Tobin allocation model is smaller than the regulation, the share of green capital investment will be equal to $\overline{\phi_t^{LG}}$. Similarly, as long as the allocation of brown capital is higher than the regulation, the share of brown capital is equal to $(1 - \overline{\phi_t^{LG}})$. The share of green capital allowing to follow the regulation evolves through time at a constant growth rate¹⁵, $g_{\overline{\phi}}$. Indeed, for simplicity, we assume that the regulation will directly impact the investment linearly without time effect.

¹⁵ Calibrated such that the share of green capital in the economy reaches its target when this policy is implemented in scenario 1, see Section 3.4.

$$\overline{\phi}_t^G = \begin{cases} \overline{\phi}_t^G = \overline{\phi}_{t-1}^G + g_{\overline{\phi}^G}, & \text{if } \phi_{t-1}^{n_G} < \phi_{MAX}^{n_G} \\ \overline{\phi}_t^G = \overline{\phi}_{t-1}^G, & \text{if } \phi_{t-1}^{n_G} \geq \phi_{MAX}^{n_G} \end{cases} \quad (24)$$

with ϕ_{MAX}^G the maximum share of green capital investment¹⁶.

We then apply a logistic function to the share of green capital to limit the shocks when the share of green capital investment approaches its maximum value ϕ_{MAX}^G . It is this share of green capital which is used in the Tobin allocation model.

$$\overline{\phi}_t^{LG} = \phi_{MIN}^G + \frac{\phi_{MAX}^G - \phi_{MIN}^G}{1 + \exp\left(-\text{par}_j(\overline{\phi}_t^G - \text{par}_k)\right)} \quad (25)$$

with ϕ_{MAX}^G the maximum share of green capital investment; ϕ_{MIN}^G the minimum share of green investment; par_j the steepness of the approximated logistic function ; par_k the midpoint of the approximated logistic function.

3.3.3.3. Green loans guarantees

In case of loan defaults, the government pays back the bank a part of the amount of the green loan that the firm is not able to repay¹⁷. Hence, banks adjust their green lending interest rates (Eq.(14)).

The rate of guarantee starts at 90% and then decreases at a constant rate¹⁸, g_{ρ_G} , when the share of green capital in the economy approaches its target. Indeed, the rate of guarantee can decrease as the rate of green loan defaults decreases when the share of green capital in the economy increases. This decreases green loan interest rates such as the guarantee is less needed.

$$\rho_{G_t} = \rho_{G_{t-1}} \left(1 - g_{\rho_G}(\overline{sh}^{k_G} - sh_t^{k_G})\right) \quad (26)$$

On the side of the cost, the guarantee increases government spending whenever a guaranteed loan defaults, such as total government spending is the sum of government consumption, interest payments on government bonds, and guarantee payments¹⁹:

$$G_t^{Gov} = C_t^{Gov} + r^{Gov}GB_{t-1} + \rho_G \sum_n DL_{t-1}^{n_G} \quad (27)$$

¹⁶ We assume that the economy still needs a minimum amount of brown capital after the transition such that the share of green/brown investment is bounded between ϕ_{MIN}^Z and ϕ_{MAX}^Z .

¹⁷ For simplification the government does not compensate the loss of interest payments in the model. Besides, we consider that loss given defaults are equal to defaults. In reality, a firm that defaults on a loan in period t due to a temporary cash constraint, might still be able to repay the loan later. If the guarantor believes this is the case, it might provide the borrower with a loan to enable repayment to the bank and thus avoid default. This can allow the guarantor to limit actual losses.

¹⁸ Calibrated such that the share of green capital in the economy reaches its target when this policy is implemented in scenario 1, see Section 3.4.

¹⁹ Note that we do not consider the origination and management costs of the guarantee for simplification.

The government has to make reserves to reassure banks that it has enough money to compensate them. We assume that we are in the case of an investment-grade country with high credit ratings, such as the amount of reserves that the government has to make is low. The reserves are equal to a percentage ρ_{RES} of the amount of green loans covered by the guarantee system:

$$RES_t^{Gov} = \rho_{RES} \rho_G \sum_n L_t^{nG} \quad (28)$$

with L_t^{nG} the stock of green loans of firms n at period t . The loan guarantee reserves go to a 'reserves account' of the government in the central bank, which remunerates the government at the same interest rate as government deposits (Eq.(23)).

3.3.3.4. Green public expenditure

The green public expenditure policy redirects public investment towards green capital, such as the share of green investment by the government increases following a logistic function to reach 80%, 20 years after the start of the implementation of the policy. Hence, the share of brown capital investment is given by:

$$\phi_t^{GovB} = \phi_0^{GovB} + \frac{(1 - \overline{sh^{kG}}) - \phi_0^{GovB}}{1 + \exp(-par_l(t - par_n))} \quad (29)$$

with ϕ_0^{GovB} , the initial share of brown capital investment of the government, par_l and par_n parameters of the logistic function.

Moreover, the government increases its green capital expenditure. This supplementary amount of green investment is a share of output:

$$\overline{I_t^{Gov}} = s_{I_{G,t}} Y_{t-1} \quad (30)$$

This share is determined by a logistic function, such that it decreases when the share of green capital in the economy approaches its target:

$$s_{I_{G,t}} = s_{I_{G,t-1}} \left(1 + g_{s_{I_G}} (\overline{sh^{kG}} - sh_t^{kG}) \right) \quad (31)$$

with $g_{s_{I_G}}$ a constant parameter²⁰.

This plays on government deficit, as when the revenue of the government is not enough to finance its spending, its investment, and its deposits, the public deficit increases. The government finances its deficit by issuing bonds that are bought by the banks and the central bank:

$$\Delta GB_t = G_t^{Gov} + I_t^{Gov} - R_t^{Gov} + \Delta D_t^{Gov} + \Delta RES_t^{Gov} \quad (32)$$

²⁰ Calibrated such that the share of green capital in the economy reaches its target when this policy is implemented in scenario 1, see Section 3.4.

3.4. Scenarios

We analyze the impact of the four climate policies separately into two scenarios of risk. In scenario 1, the actual risk of investing in green capital is low, meaning that the probability of defaults on green loans is low (Figure 10). In scenario 2, the probability of defaults on green loans is high, reflecting high actual risks. In the two scenarios, the perception of risk by firms and banks is aligned with actual risk. Hence, banks put low (high) interest rates in scenario 1 (scenario 2) and firms perceived low (high) investment risks in scenario 1 (scenario 2). Note that even if risks on green capital are low in scenario 1, they are still higher than those on brown capital.

Scenario 1	Low	High	Scenario 2	Low	High
Interest rates on green loans = perception of risks by banks	X		Interest rates on green loans = perception of risks by banks		X
Perceived risk-reward profile on green capital by firms	X		Perceived risk-reward profile on green capital by firms		X
Probability of defaults on green loans = actual risks	X		Probability of defaults on green loans = actual risks		X

Figure 10: Scenarios of risk

Table 1 summarizes the changes to the initial variable values used to construct each scenario. We perform a sensitivity analysis on the values of these variables (Appendix 3.2). The difference in these values leads to two baselines (Appendix 2). Indeed, the modification of the financing costs due to a change in the probability of defaults on green loans has macroeconomic and financial consequences.

Table 1: Variables that are modified to build each scenario

Scenarios	Initial probability of defaults on green loans $\varphi_{0,0}^{n_G}$	Perceived risk-reward by firms ω_0^G
1	Low, $\varphi_{0,0}^{n_G} = 3.4\%$	Low, $\omega_0^G = 0.501$
2	High, $\varphi_{0,0}^{n_G} = 8\%$	High, $\omega_0^G = 1$

With $\varphi_{0,0}^{n_G}$, the initial probability of defaults on green loans calculated from Eq.(17) with the initial values of φ_0^{illiqn} , φ_{t-v}^V and φ_v^ϵ ; and ω_0^G , the initial risk on green investment for firms.

We assume that, except for the financing costs and the perception of risks by agents, there are no barriers to the implementation of the different policies (green substitutes are available, the government has the capacity to implement the policies, agents have the financial capacity to buy more expensive green capital, etc.). The model is run for 80 years, and each policy is

implemented in the period $t=10$. The level of each policy is calibrated to reach the same share of green capital in the economy (80% in $t=80$) in scenario 1. This level is then applied to scenario 2. Note that in the baseline, no policy is implemented.

3.5. Calibration

The model relies on a set of parameters detailed in the Appendix 4. These parameters are derived from empirical estimates, similar modeling exercises, or set instrumentally to achieve convergence. They are subject to a global sensitivity analysis (Appendix 3.1). The model is first solved at an artificial 'year zero' from which it is brought to a stable, non-oscillatory steady state. This ensures the convergence of key variables and provides consistent starting values for core indicators (Appendix 4.6). The steady state is reached after approximately 100 iterations.

Macroeconomic variables—such as nominal GDP, inflation, capital stock value, wage share, and government deficit—are calibrated to match world data for the year 2019, drawing from Timmer et al. (2015), (World Bank, 2025b), IMF (2020a), and IMF (2020b). Data on default probabilities and bank capital adequacy ratios are based on figures from the European Union (ECB, 2020; European Banking Authority, 2019). The initial values of the perception of risk by firms ω_0^G and the probability of default related to the share of green capital φ_0^ϵ are scenario-specific and subject to a sensitivity analysis (Appendix 3.2).

4. Results

In this section, we present the impacts of each policy using a systems-based analysis following Dafermos & Nikolaidi (2022). This approach relies on the use of various indicators to assess the impacts of climate policies on several dimensions. It does so by analyzing the 'risks' (potential negative outcomes) and the 'opportunities' (potential positive outcomes) of each policy (Mercure et al., 2021), to identify policies—or policy mixes—that maximize opportunities while minimizing risks. It hence differs from cost-benefit analysis, which monetizes all costs and benefits to identify optimal policies. Moreover, this approach distinguishes between short-run and long-run dynamic effects, allowing us to consider that some policies might lead to positive effects in the short run but to instability in the long run.

We focus on three dimensions to assess the impact of the climate policies studied:

- Ecological indicators: the share of green capital and the amount of brown capital in the economy.
- Macroeconomic indicators: real GDP growth and public debt to GDP²¹.
- Financial indicators: the rate of default of firms and the capital adequacy ratio of banks.

²¹ As underlined by Dafermos & Nikolaidi (2022), higher public debt to GDP ratios do not have the same consequences in high-income and low-income countries. Hence, this indicator should be treated with caution.

While it is clear that other dimensions and indicators should be considered, such as inequalities or unemployment, this analysis already yields some insights about the policies studied.

4.1. Transition to a low-carbon economy

First, we study the impact of the policies on the transition to a low-carbon economy. Figure 11 shows that in scenario 1, all policies are calibrated to achieve the transition target of 80% green capital by the end of the simulation. This allows for the comparison of the policies. However, the realism of these policies is questionable. For instance, the literature has shown that the interest rate channel might not be enough to trigger the transition (Dunz et al., 2021), such that guarantees might not work alone (especially in scenario 1, where the difference between the lending interest rates is low).

In scenario 2, the shares of green capital in the economy do not reach the target, except when green mandates are implemented (Figure 11). In the case of the carbon tax, the transition starts to happen at the end of the period. Indeed, in this scenario, investment risk and financing costs are initially too high, so even though the carbon tax increases the cost of investing in brown capital, firms continue to invest in brown capital. However, as the cost of the carbon tax increases over time, firms start switching towards green capital at the end of the simulation. Concerning green mandates, they offer the same effectiveness as in scenario 1. However, this highly depends on our assumption that agents always follow the regulation. In a context of high defaults and high financing costs on green capital investment, agents might not be financially able to switch to green capital. On the side of guarantees, they do not have any impact on the transition in scenario 2. Indeed, even if the financing cost of green capital decreases, the green investment risk in this scenario remains too high, so firms are unwilling to invest in green capital. Lastly, the green public expenditure policy performs slightly less in scenario 2 than in scenario 1 because firms invest less in green capital due to high investment risks and financing costs. In the next subsections, we detail these results.

Green Capital Share in the Economy

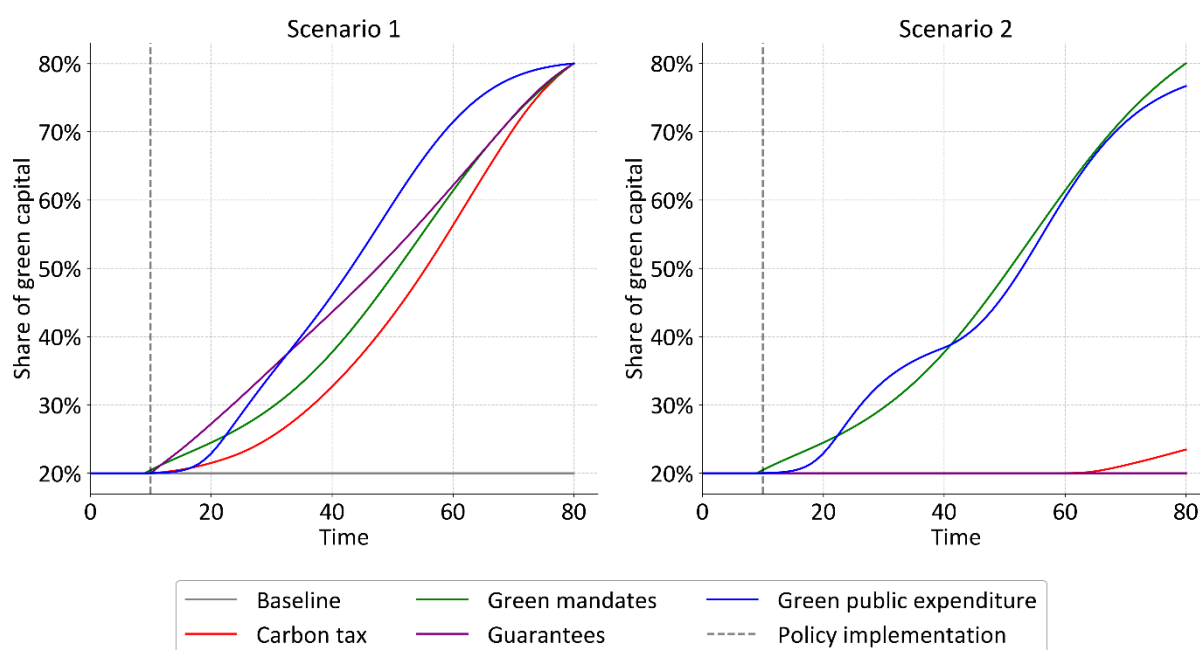


Figure 11: Impact of the policies on the share of green capital in the economy across scenarios

4.1.1. Carbon tax

The carbon tax leads to a strong decrease in the share of firms' investment going to brown capital in scenario 1 (Figure 12)²². Figure 13 analyzes which factors affect firms' investment decisions (see Eq. (1) in Section 3.3.1). We can see that the decrease in their brown investment is mainly due to the increase in the cost of the carbon tax applied to firms' brown capital in the short run. In the long run, this cost decreases as firms switch to green capital to produce.

The relative price of green versus brown capital does not change in the short run, as both types of capital producers are affected by the carbon tax²³ (Figure 13). Consequently, they both increase their prices. Over time, green capital firms can switch faster to green capital as they face higher demand than brown firms, leading to higher investment. Their brown capital stock reduces faster than that of brown firms. Consequently, green firms pay less carbon tax in relative terms than brown firms and are thus able to decrease their prices. The price of green capital decreases relatively to the price of brown capital, making firms more willing to invest in green capital.

Another factor playing in firms' investment decisions is the financing cost (Figure 13). It decreases for green capital investment, as we will explain below. Moreover, as green capital expands in the economy, the perceived risk of investing in green capital from firms decreases, and its productivity increases. Lastly, the autonomous demand of brown capital decreases as green capital becomes more common. Indeed, firms adapt their investment decision to the

²² Note that the share of brown capital investment does not go below 10%. This is an exogenous constraint reflecting that firms always invest in a minimum amount of brown capital that is considered as not substitutable.

²³ In the baseline, both types of capital producers use a majority of brown capital to produce.

socio-technical system (regulatory frameworks, infrastructures, workforce skills, etc.), becoming increasingly aligned with green capital production.

In scenario 2, the carbon tax is ineffective in the short run (Figure 12). Indeed, even if the cost of paying the carbon tax harms firms, they still prefer to invest in brown capital due to high financing costs and high investment risks (Figure 13). In the long run, as the cost of the carbon tax rises (Appendix 1.1, Figure 28), firms begin to increase their investment in green capital.

The carbon tax influences the investment decisions of households and the government by modifying relative prices and productivities of green and brown capital, while these agents also adjust their behavior in response to capital trends in the rest of the economy (Appendix 1.1 Figure 29).

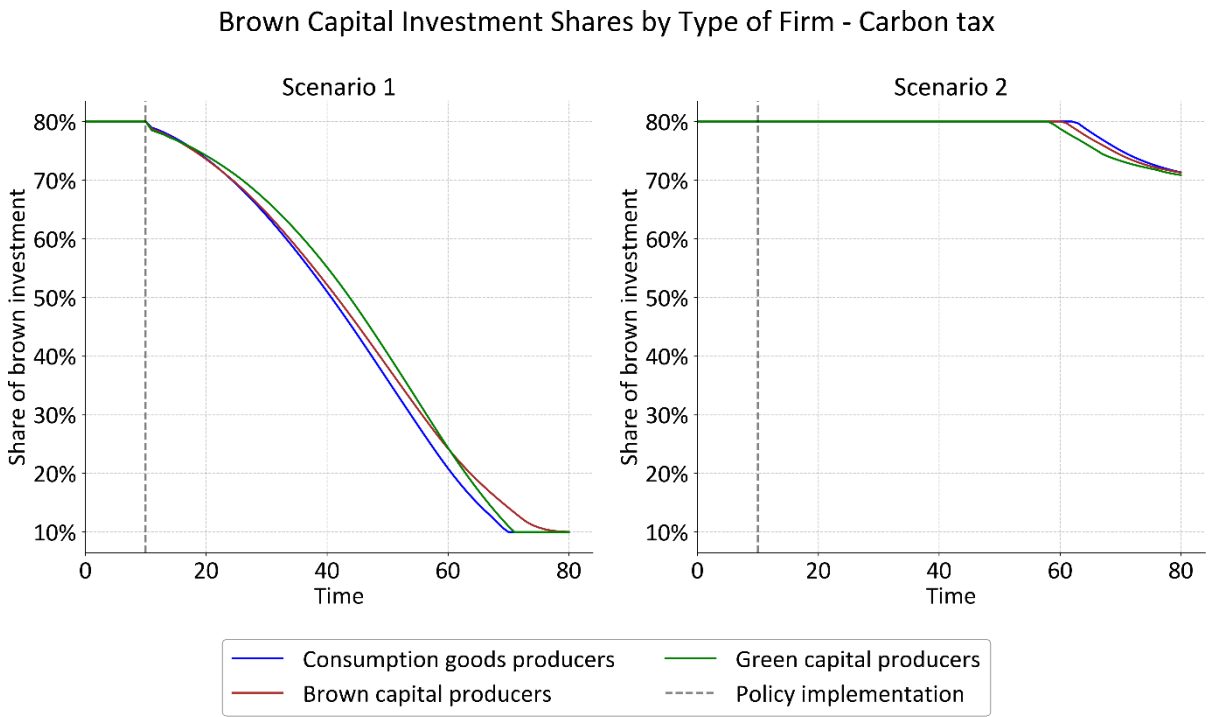


Figure 12: Share of investment going to brown capital by type of firm with a carbon tax across scenarios

Decomposition of the Share of Brown Investment by Consumption Goods Firms - Carbon tax

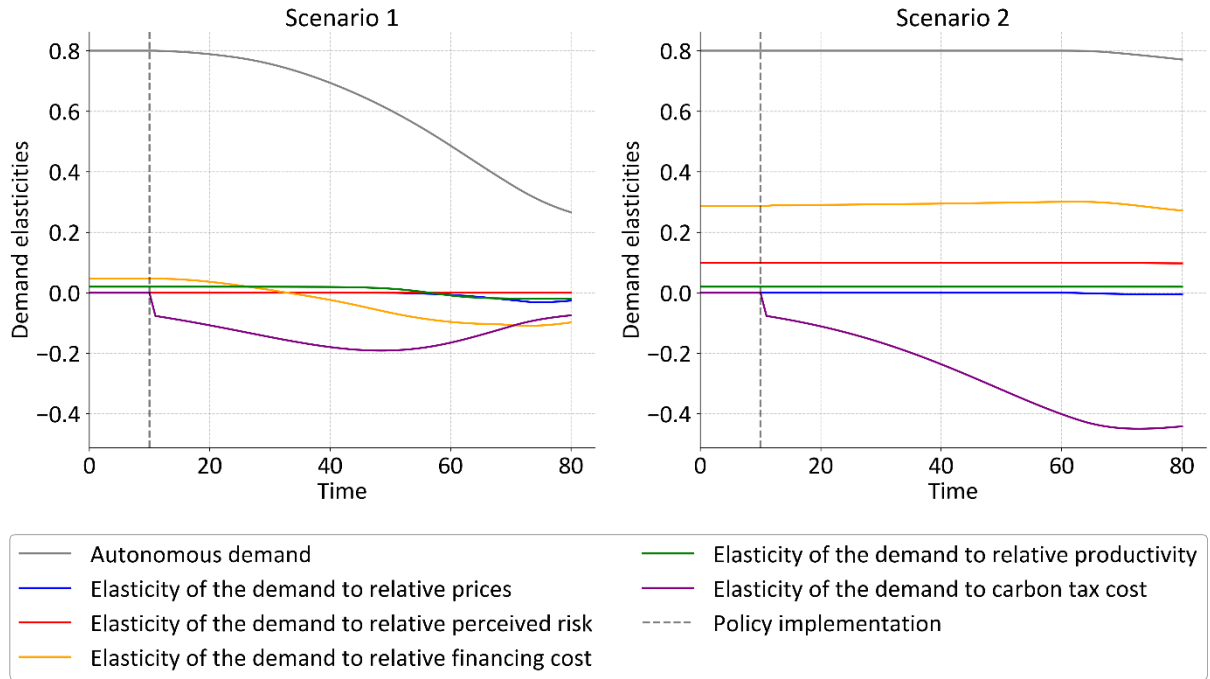


Figure 13: Decomposition of consumption goods firms' investment decision in brown capital relative to green capital with a carbon tax. Positive values indicate positive demand for brown capital, leading to a higher share of brown capital; negative values reflect a negative demand for brown capital, leading to a lower share of brown capital. For example, the elasticity of the demand to relative financing cost is positive in the short run in scenario 1 (orange curve), meaning that the financing cost of brown investment is lower than the financing cost of green investment, thus increasing the share of brown investment. In the long run, this elasticity becomes negative, reflecting that the financing cost on brown investment is higher than the financing cost on green investment, leading to a decrease in the demand for brown investment. This elasticity is computed as $\lambda_3^B(\sigma_{L,t-1}^{n_B}r_{t-1}^{n_B} + (1 - \sigma_{L,t-1}^{n_B})r_{b,t-1}^{n_B}) + \lambda_4^B(\sigma_{L,t-1}^{n_G}r_{t-1}^{n_G} + (1 - \sigma_{L,t-1}^{n_G})r_{b,t-1}^{n_G})$ from Eq.(1).

If we look more precisely at the evolution of financing costs, the cost of financing green capital decreases relatively to that of brown capital in scenario 1 (Figure 14). As the share of green capital in the economy rises, learning effects occur, leading to a reduction in the probability of defaults on green loans. Hence, banks can reduce their lending interest rates on green loans. The probability of defaults on brown firms' loans rises due to reduced demand for brown capital, which in turn leads to higher interest rates on their loans²⁴.

Similarly, green bond interest rates decrease relatively to the ones on brown bonds in scenario 1. Producers of brown capital face a significant increase in interest rates on their brown bonds, as households progressively shift their preferences toward green bonds during the transition. In contrast, green firms initially experience a decrease in interest rates on both their green and brown bonds, as households increase their demand for bonds issued by these firms. Over time, as green firms gain market share, the demand for bonds issued by brown firms declines. This

²⁴ Note that the decrease of brown capital producers' interest rates in the last simulation periods is due to the stabilization of the demand of brown capital.

results in rising interest rates, even on the green bonds of brown firms, tightening their financing conditions. This constrains brown firms' ability to invest in green capital. Meanwhile, green firms continue to attract growing demand for their green bonds, leading to lower interest rates and enabling greater investment in green capital.

In scenario 2, financing costs only start to evolve at the end of the simulation period as the transition is delayed.

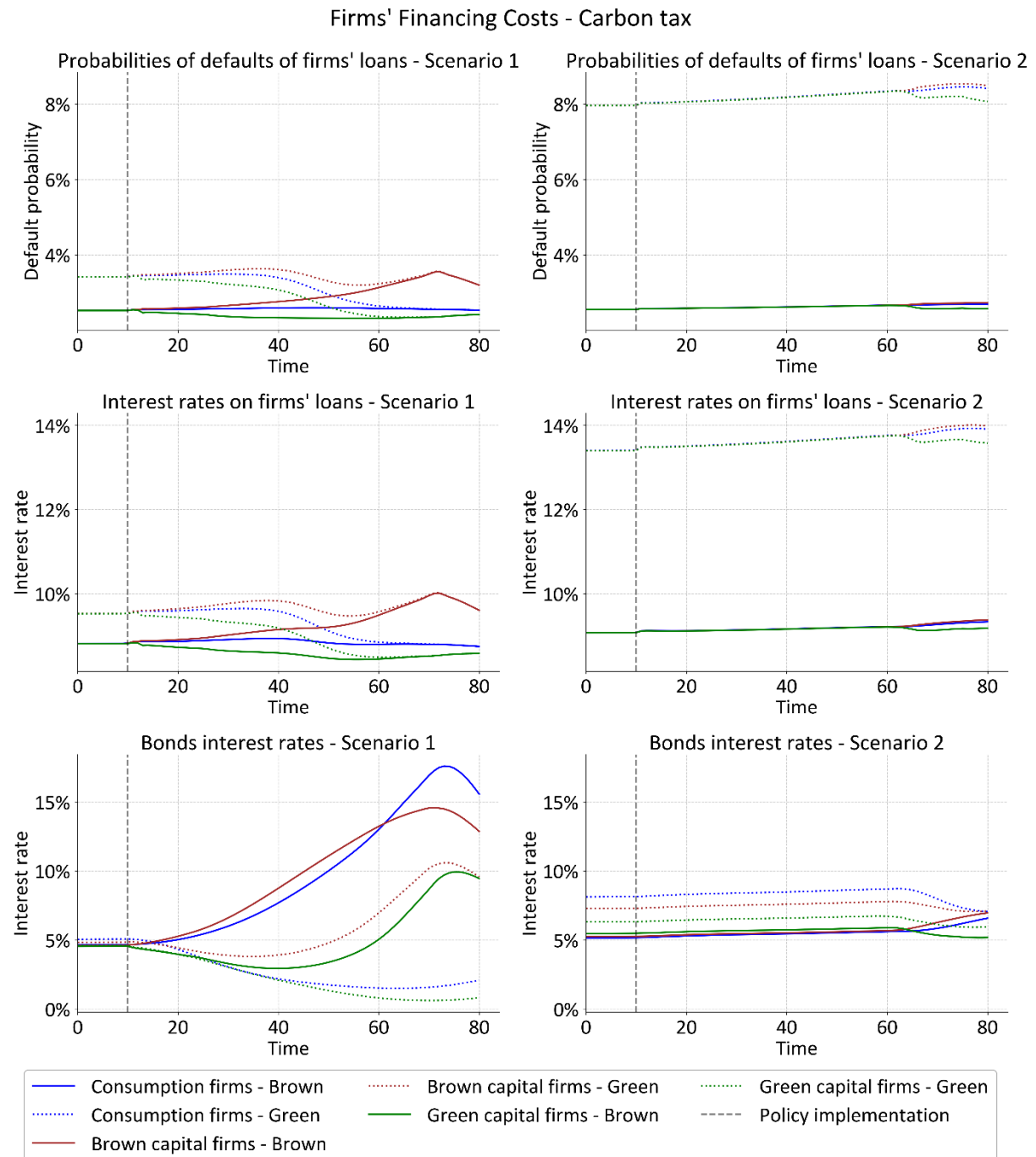


Figure 14: Evolution of firms' probabilities of loan default and financing costs with a carbon tax across scenarios. Solid lines represent firms' probabilities of brown loan default/brown interest rates, and

dotted lines represent firms' probabilities of green loan default/green interest rates. Note that the baseline of scenario 1 and the baseline of scenario 2 are not the same (see Appendix 2).

4.1.2. Green mandates

In the case where green mandates are implemented, the share of investment going to brown capital decreases for all agents as they follow the regulation in both scenarios (Figure 15).

Brown Capital Investment Shares of Firms, Households and the Government - Green mandates

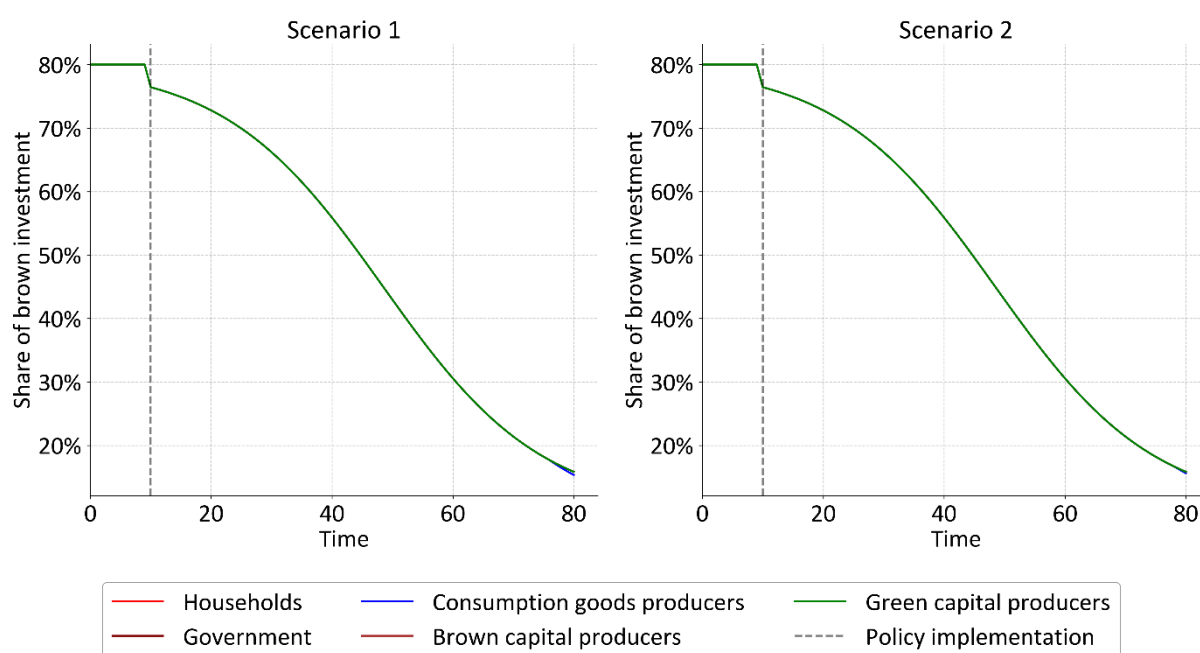


Figure 15: Share of investment going to brown capital by agents with green mandates across scenarios

4.1.3. Guarantees

By partially shielding banks from defaults, the guarantee on firms' green loans reduces their interest rates (Figure 16). This lower exposure to risk also enables banks to decrease interest rates on brown loans²⁵.

²⁵ The brown loan interest rates for brown capital producers in scenario 1 increase because they are subject to lower demand due to the transition towards green capital.

Firms' Loan Interest Rates - Guarantees

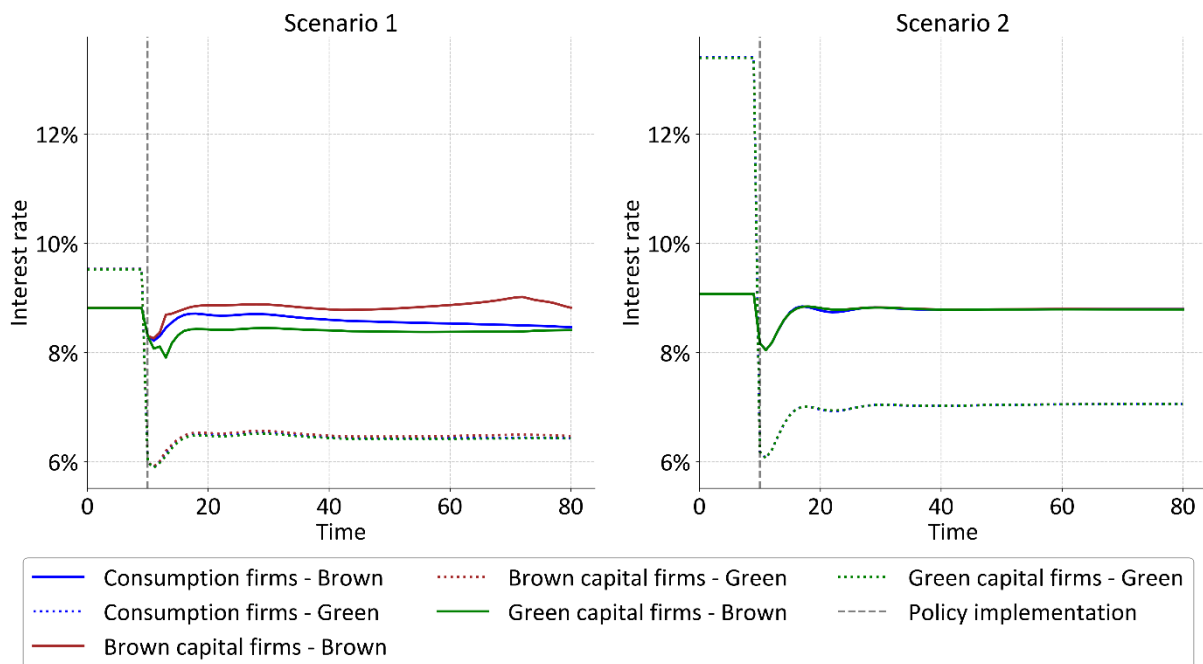


Figure 16: Firms' loan interest rates across scenarios with a guarantee. Solid lines represent firms' brown loan interest rates, and dotted lines represent firms' green loan interest rates. Note that the baseline of scenario 1 and the baseline of scenario 2 are not the same (see Appendix 2).

In scenario 1, the reduction in the financing cost of green capital leads to a sharp decline in firms' demand for brown capital (Figure 17). In scenario 2, the reduction in green capital financing costs is insufficient to offset firms' high perceived risk, so they continue to invest in brown capital (Figure 17).

Decomposition of the Share of Brown Investment by Consumption Goods Firms - Guarantees

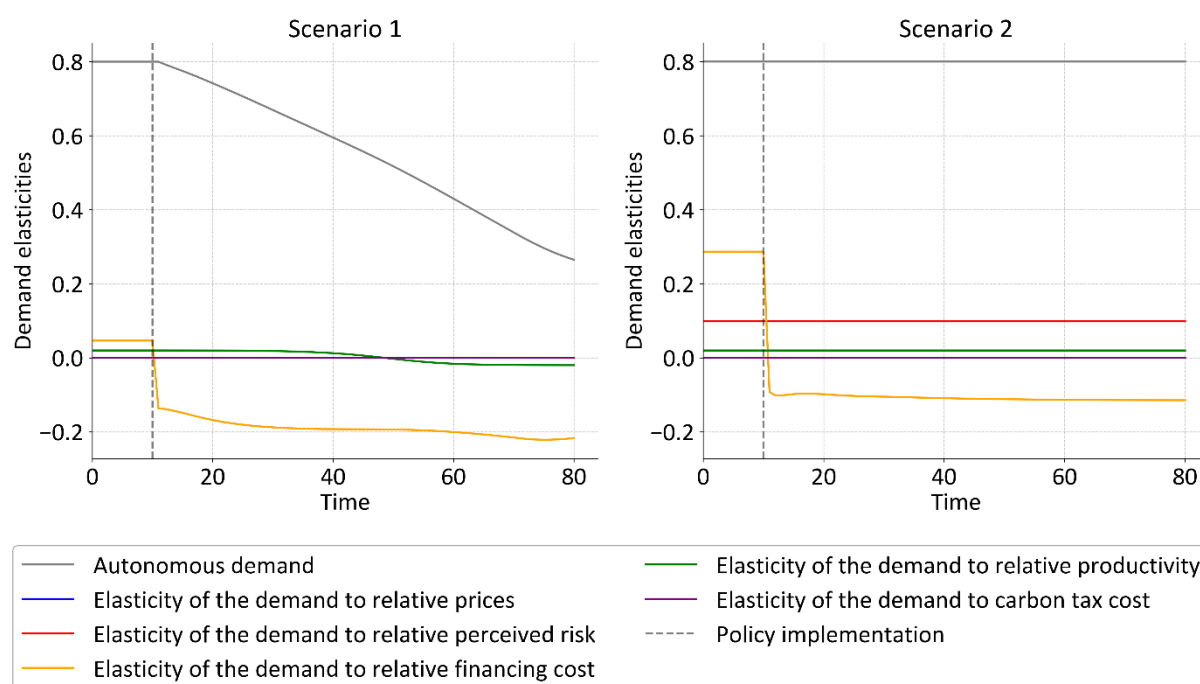


Figure 17: Decomposition of consumption goods firms' investment decision in brown capital relative to green capital with a guarantee. Positive values indicate positive demand for brown capital, leading to a higher share of brown capital; negative values reflect a negative demand for brown capital, leading to a lower share of brown capital.

Interestingly, in scenario 1, the share of investment allocated to brown capital by green firms declines more slowly than that of brown firms and consumption goods firms (Figure 18). This comes from the growing demand for green capital that eases the financing constraints faced by green capital producers. Specifically, the interest rates on their brown loans fall as their improved repayment capacity, driven by higher demand, reduces lenders' risk exposure. As a result, the spread between green and brown loan rates is smaller for green capital producers than for other firms (Figure 16). Consequently, green firms have a smaller incentive to invest in green capital. By contrast, brown capital producers experience a relative decline in demand for their output. This weakens their debt-servicing capacity, which translates into higher interest rates on their brown loans. Thanks to the guarantee, investment in green capital becomes comparatively more attractive, providing brown capital producers with a strong incentive to shift towards green capital.

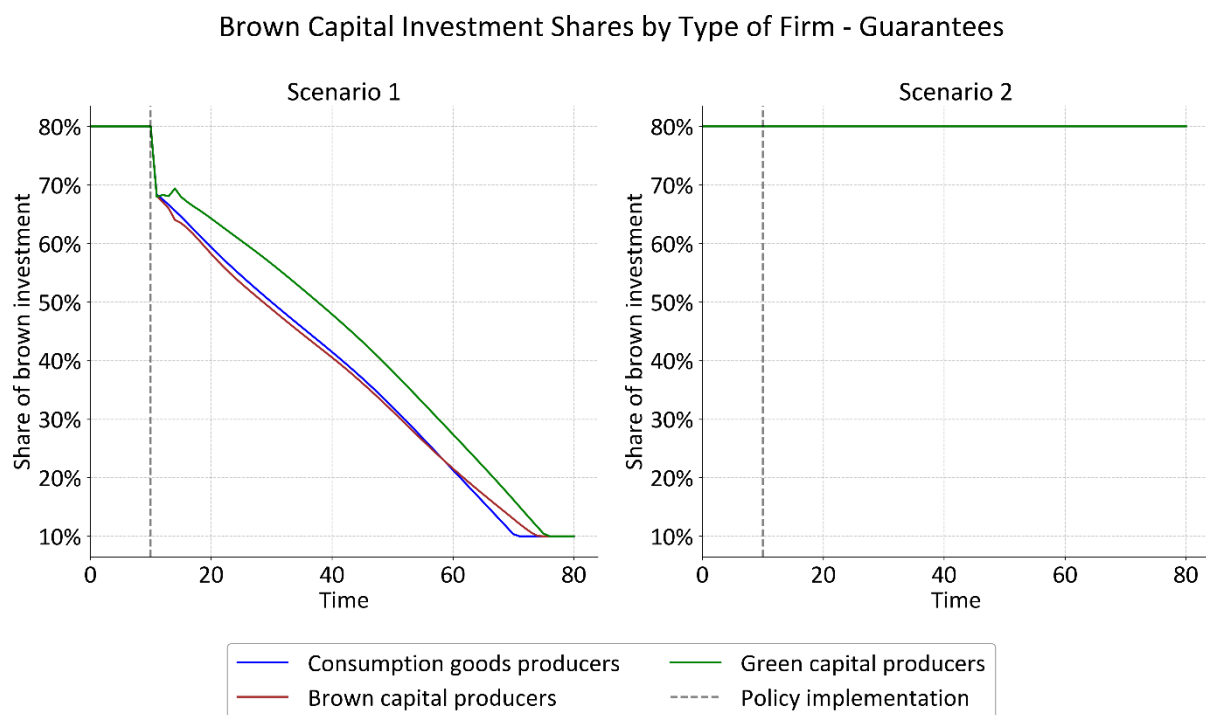


Figure 18: Share of investment going to brown capital by type of firm with a guarantee across scenarios

In scenario 1, the guarantee affects households' and the government's investment decisions by altering the productivity of green and brown capital, while these agents also adjust their behavior in response to capital trends in the broader economy (Appendix 1.3 Figure 32).

4.1.4. Green public expenditure

The green public expenditure policy redirects public investment toward green capital, with the government's share of green investment rising to 80% over the 20 years following implementation (Figure 19). As this is insufficient to achieve the overall target for green capital in the economy, the government also increases its green investment following an increasing share of GDP. Indeed, green public procurement is not a stand-alone policy to decarbonize the economy, since it targets only the public sector (OECD, 2003). In this paper, we focus on the impacts of each policy individually, although in practice, green public procurement should be implemented as part of an integrated policy package.

Green Public Expenditure Implementation

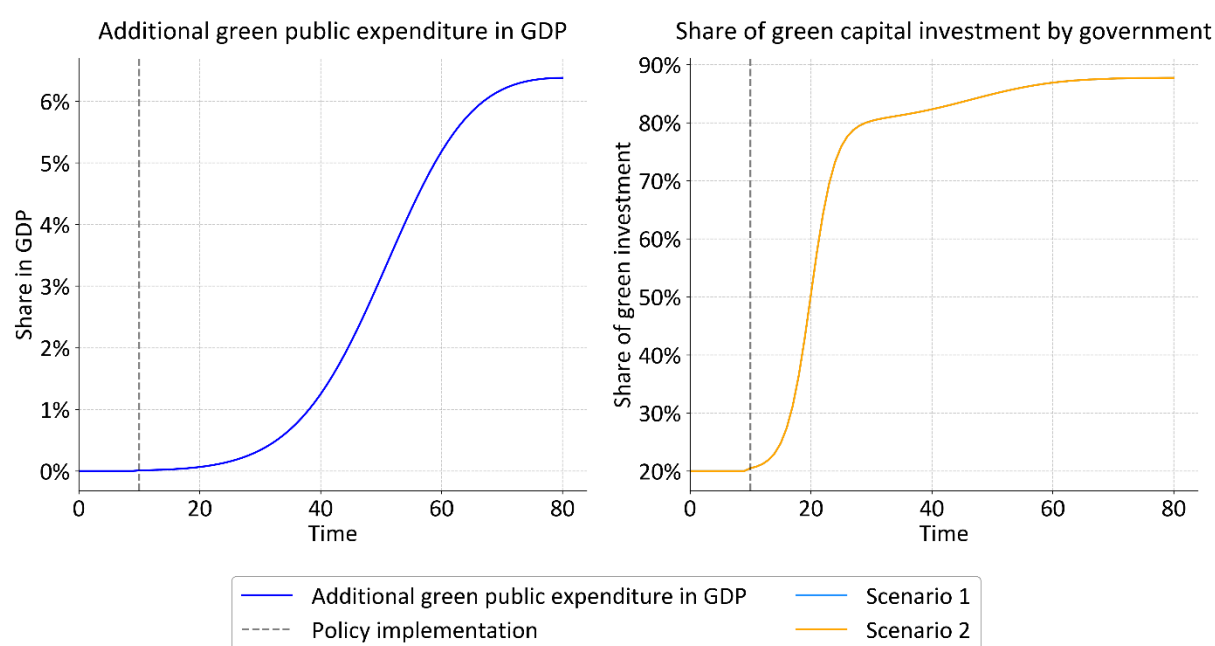


Figure 19: Implementation of the green public expenditure policy with a redirection of the investment of the government towards green capital and additional green public expenditure.

As firms and households respond to trends in the broader economy and capital productivity variations, their share of investment allocated to brown capital declines (Figure 20 and Figure 34 in Appendix 1). This takes time due to path dependency (the autonomous demand of brown capital decreases with delay) and because other factors are limiting agents' willingness to invest in green capital. For instance, in scenario 2, high financing costs and risks associated with green capital prevent firms from increasing their green investment in the short run, even though their autonomous demand rises as they observe the broader economy transitioning (Figure 20 and Figure 21). It's only when the share of green capital in the economy becomes sufficiently large that firms start to redirect their investment towards green capital, as financing costs and risks decline and productivity improves.

Brown Capital Investment Shares by Type of Firm - Green public expenditure

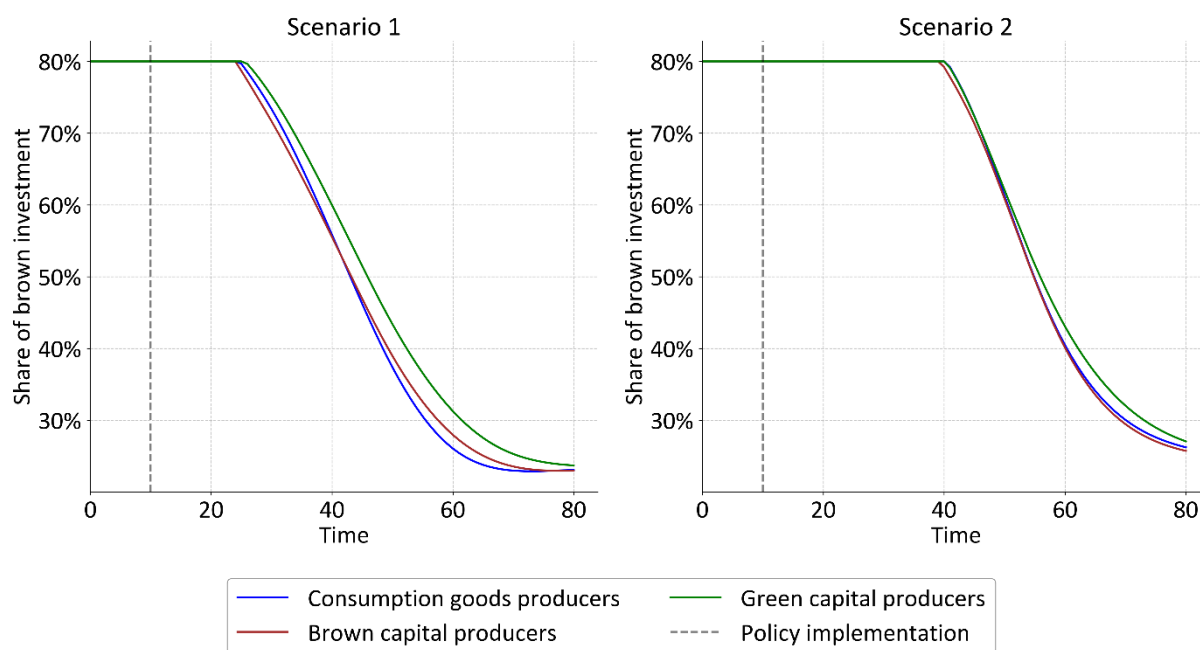


Figure 20: Share of investment going to brown capital by type of firm with green public expenditure across scenarios

Decomposition of the Share of Brown Investment by Consumption Goods Firms - Green public expenditure

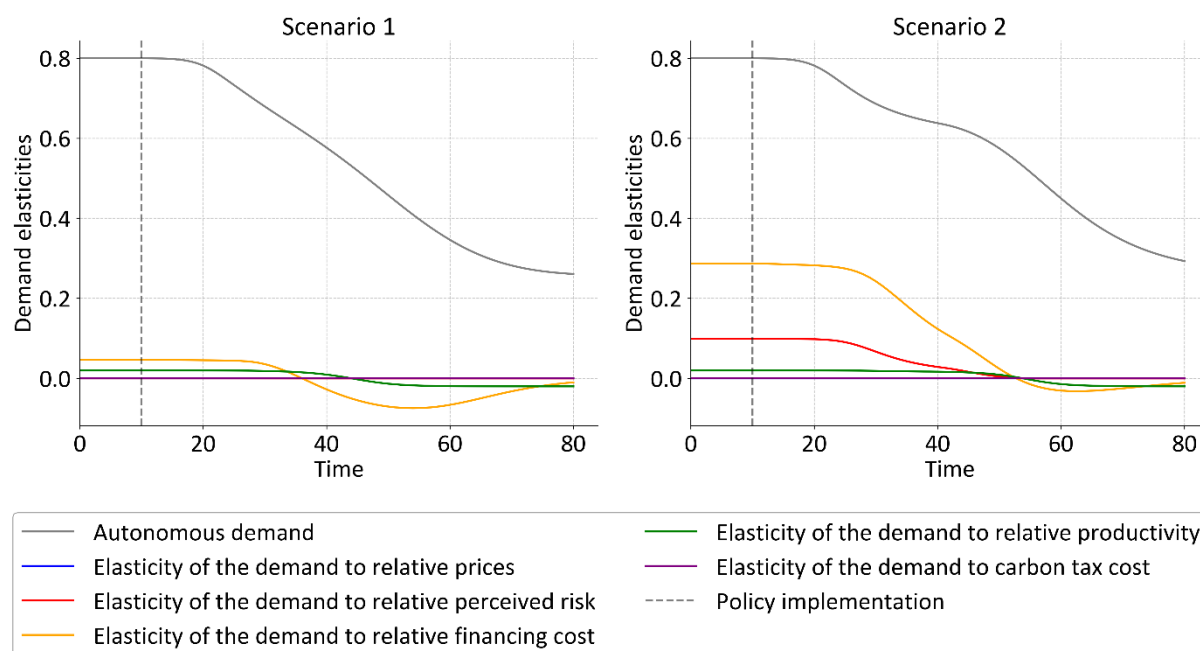


Figure 21: Decomposition of consumption goods firms' investment decision in brown capital relative to green capital with green public expenditure. Positive values indicate positive demand for brown capital,

leading to a higher share of brown capital; negative values reflect a negative demand for brown capital, leading to a lower share of brown capital.

We now look in more detail at the evolution of firms' capital financing costs as they play a key role in firms' investment decisions. In both scenarios, the greening of the economy triggers learning effects, reducing the default probability on firms' green loans and thereby lowering their interest rates (Figure 22). However, brown loan interest rates increase slightly for all firms as banks need to balance their capital adequacy ratios, which are decreasing due to higher lending (see Section 4.2). On the side of bond interest rates, they tend to fall in the long run in both scenarios as firms' external financial needs decrease, leading to a decrease in bond supply in the market and higher bond prices. Indeed, firms need less external finance as their profits increase strongly due to higher global demand.

Firms' Financing Costs - Green public expenditure

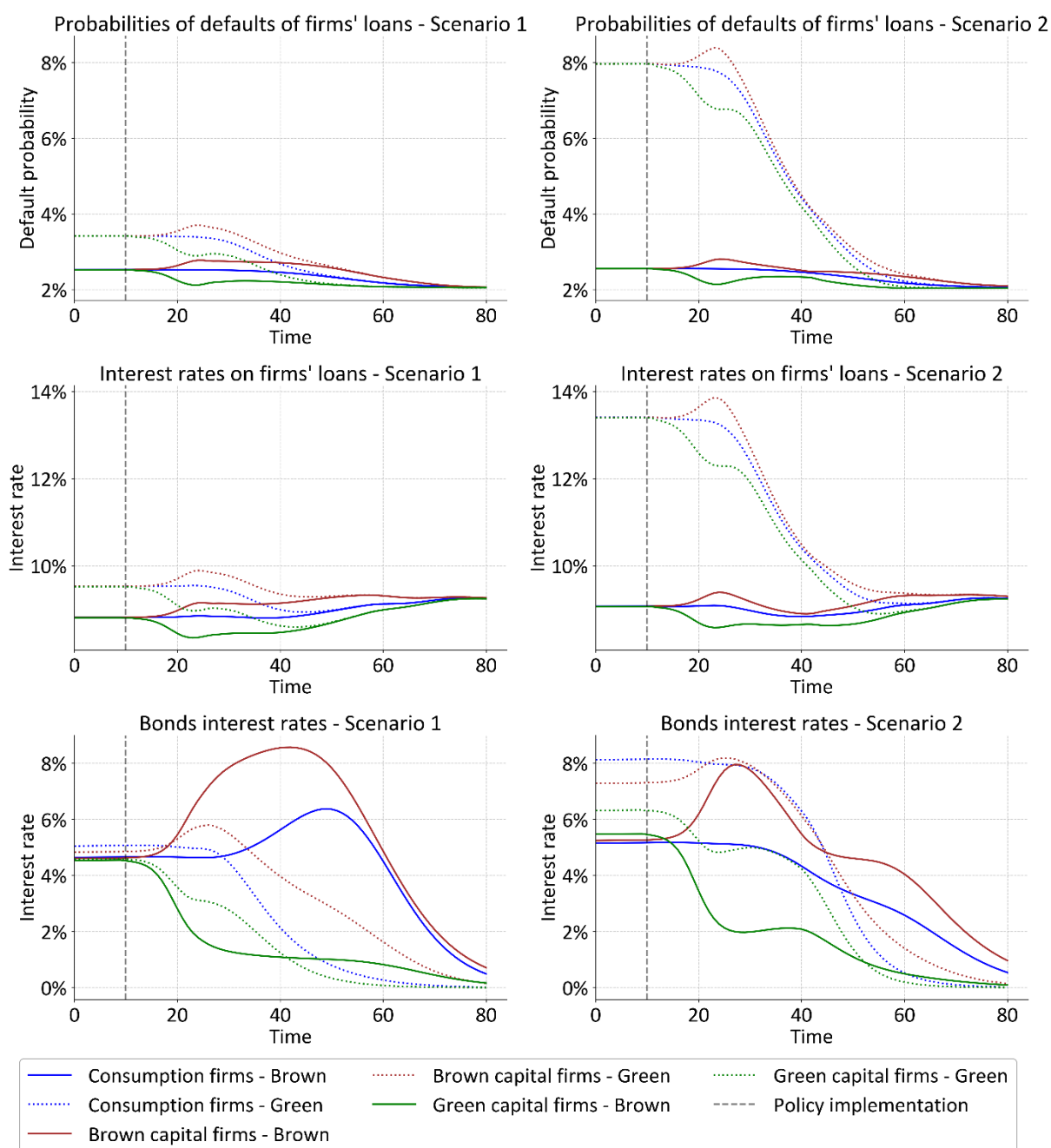


Figure 22: Evolution of firms' probabilities of loan default and financing costs with green public expenditure across scenarios. Solid lines represent firms' probabilities of brown loan default/brown interest rates, and dotted lines represent firms' probabilities of green loan default/green interest rates. Note that the baseline of scenario 1 and the baseline of scenario 2 are not the same (see Appendix 2).

Beyond the share of green capital, which signals the effectiveness of policies in fostering technological change, the stock of brown capital represents a critical ecological indicator that must also be considered. Indeed, what matters is not only the shift toward a green capital economy but, more importantly, the reduction of GHG emissions through a decline in the stock of brown capital.

In scenario 1, all policies reduce the amount of brown capital compared to the baseline (Figure 23). However, green public expenditure sharply increases economic growth, which in turn stimulates investment in brown capital, since the share of brown investment does not fall to zero. Hence, the amount of brown capital does not decrease strongly compared to the baseline in the long run. This result arises from our simplified representation of government capital, which is non-productive in the model: increases in the government's green capital stock do not substitute for firms' capital stock. Green public expenditure influences firms' investment decisions primarily through changes in autonomous demand (firms adjust their behavior based on broader economic trends), rather than directly augmenting their capital stock with green capital. As a result, green public expenditure must rise substantially to support the transition. This suggests a potential avenue for model refinement: if government-owned capital was productive and accessible to firms, the necessary level of green public investment could be lower, and the associated impacts on overall economic growth would be more moderate. Nonetheless, even this simplified representation provides useful insights about the potential impacts of increased green public procurement.

In scenario 2, green mandates are the most effective instrument to reduce the amount of brown capital. The carbon tax also starts to reduce it at the end of the period as firms begin their transition. The guarantee tends to increase the amount of brown capital due to the increase in GDP growth (Section 4.3), combined with firms' decision to keep investing in brown capital. While green public expenditure initially lowers brown capital through redirected public investment, long-term economic growth eventually increases the brown capital stock beyond its baseline level.

Stock of Brown Capital in the Economy

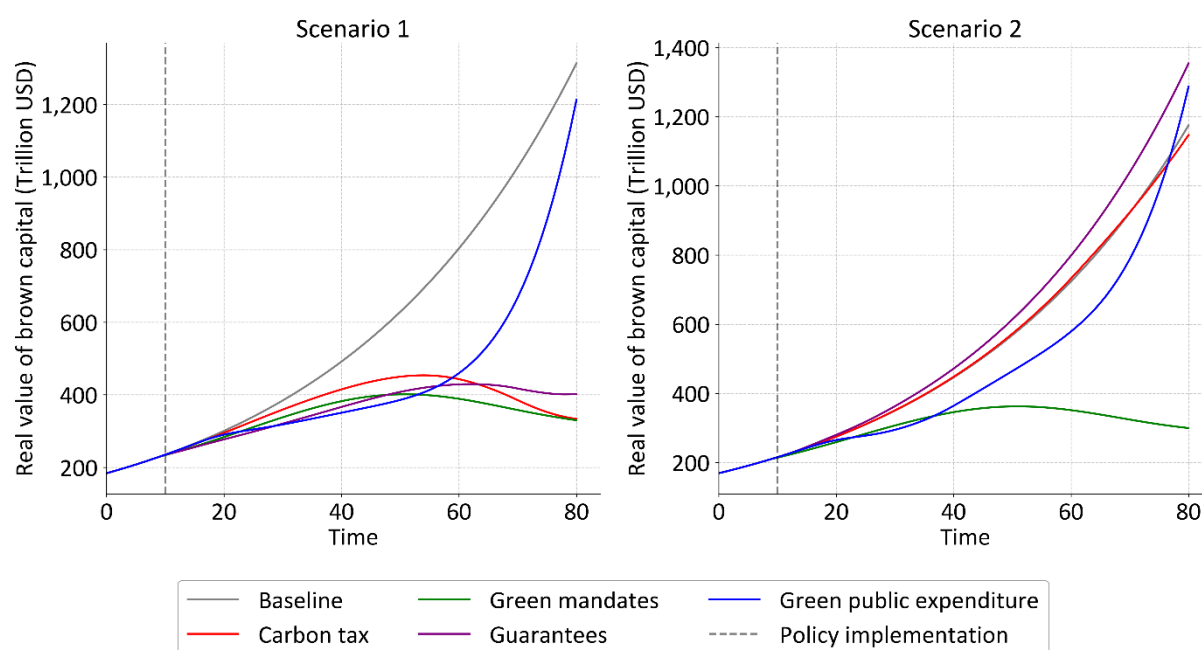


Figure 23: Evolution of the stock of brown capital in the economy across scenarios. Note that the baseline of scenario 1 and the baseline of scenario 2 are not the same (see Appendix 2).

4.2. Financial indicators

To assess the impact of climate policies on firms' financial stability, we examine their average loan default rate (Figure 24). In scenario 1, the transition to a low-carbon economy is accompanied by an expansion of green loans, which initially exhibit higher default rates than brown loans. Consequently, the average default rate of firms increases in the short run. It declines in the long run, driven by the reduction in green loan defaults, resulting from learning effects associated with the large-scale deployment of green capital. In scenario 2, the introduction of a carbon tax increases firms' default rates in the short run by exerting downward pressure on profits. This occurs because firms continue to invest in brown capital and are therefore subject to carbon taxation. In the long run, as firms start to invest in green capital, the amount of green loans increases. In scenario 2, the rate of default on green loans is high. As the transition is still in its early stages, learning effects have not yet materialized. Consequently, firms' financial stability deteriorates.

Green mandates also induce short-run financial instability for firms. The transition to a low-carbon economy involves an expansion of green loans, which initially exhibit higher default rates than brown loans. As a result, the average default rate of firms rises in the short run. The increase is more pronounced in scenario 2 due to the higher probability of defaults on green loans compared to scenario 1. In the long run, the average default rate of firms declines in both scenarios as investments in green capital expand, with learning effects gradually reducing the default rates of green loans.

The guarantee on green loans lowers the average default rate by improving firms’ profitability through reduced interest rates. This effect is more pronounced in scenario 1, as the guarantee positively supports the transition, encouraging firms to invest in green capital, which benefits from lower financing costs due to the guarantee.

Finally, green public expenditure has a strong positive impact on firms’ defaults in both scenarios as it increases demand for firms’ production, leading to higher profits. The reduction in the average default rate of firms is even more pronounced in scenario 2, as the initially high financing costs of green capital decline over the course of the transition.

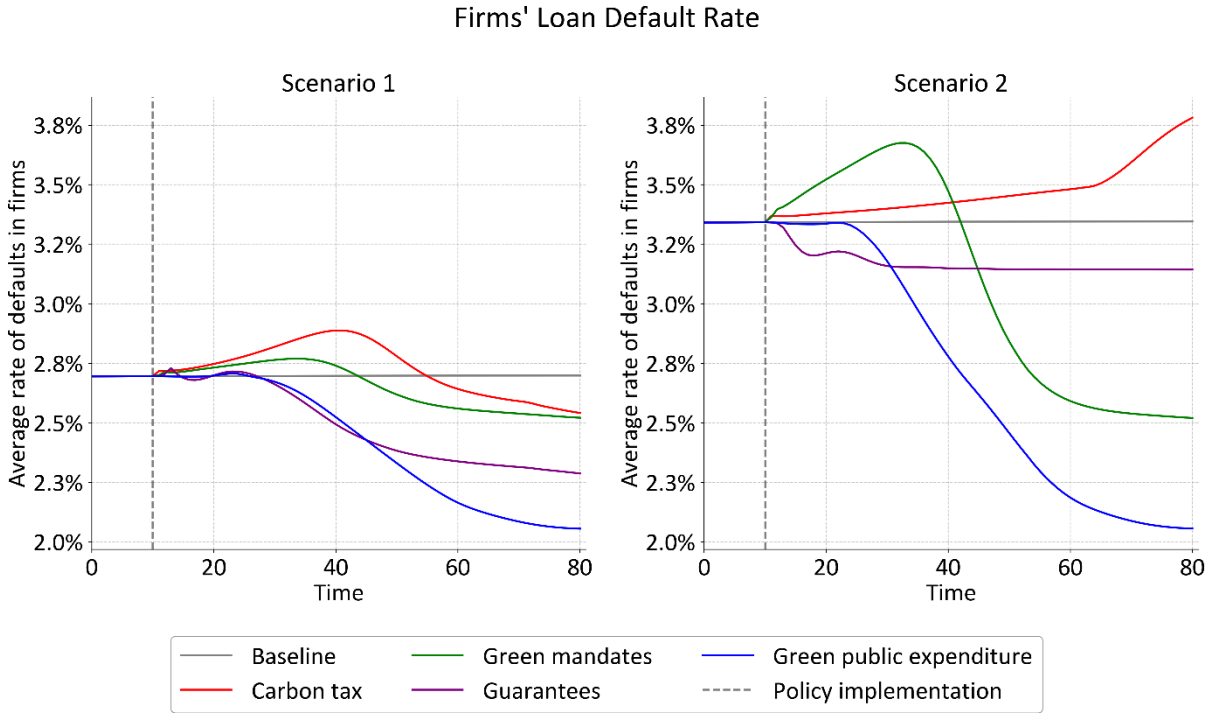


Figure 24: Impact of the policies on the average rate of loan defaults in firms across scenarios. Note that the baseline of scenario 1 and the baseline of scenario 2 are not the same (see Appendix 2).

To evaluate the impact of the policies on banks’ financial stability, we look at the evolution of their capital adequacy ratio²⁶ (Figure 25). Note that these policies do not threaten banks’ financial stability as the CAR variations are small in these simulations²⁷. In scenario 1, the carbon tax and green mandates have a modest negative impact on the CAR in the short run, as the expansion of green loans initially results in higher defaults. In the long run, defaults on firms’ green loans decline, leading to an increase in the CAR. In scenario 2, the carbon tax lowers the CAR because it negatively impacts firms’ defaults in the short run as it decreases firms’ profits. When the transition starts to happen, the CAR of banks decreases because green loans have a higher rate of defaults. Green mandates lower banks’ financial stability in the short run in scenario 2, due to the increase in green loans, which are subject to high default

²⁶ The capital adequacy ratio (CAR) is an indicator used to assess whether banks hold sufficient capital to absorb a reasonable level of losses and avoid insolvency.
²⁷ Larger variations in firms’ defaults could lead to stronger variations of the CAR.

rates. In the long run, the rate of defaults on green loans decreases, leading to an increase in the CAR.

In scenario 1, guarantees slightly reduce banks’ capital adequacy ratio because lower interest rates decrease their profits (Figure 16, Section 4.1.3). In scenario 2, however, guarantees increase the CAR by reducing the number of defaults, while interest income remains largely unchanged since the number of green loans does not grow in relative terms as the transition does not happen.

Green public expenditure has a small negative impact on the CAR due to the high growth rate of new loans to meet higher investment needs. The decline in the CAR arises from a timing mismatch between asset growth and income flow: the loan stock expands more rapidly than banks’ profits, as interest payments on newly issued loans are only received in the following period. In scenario 2, there is an increase in the CAR in the short run due to the decrease in the rate of defaults on green loans, thanks to learning effects.

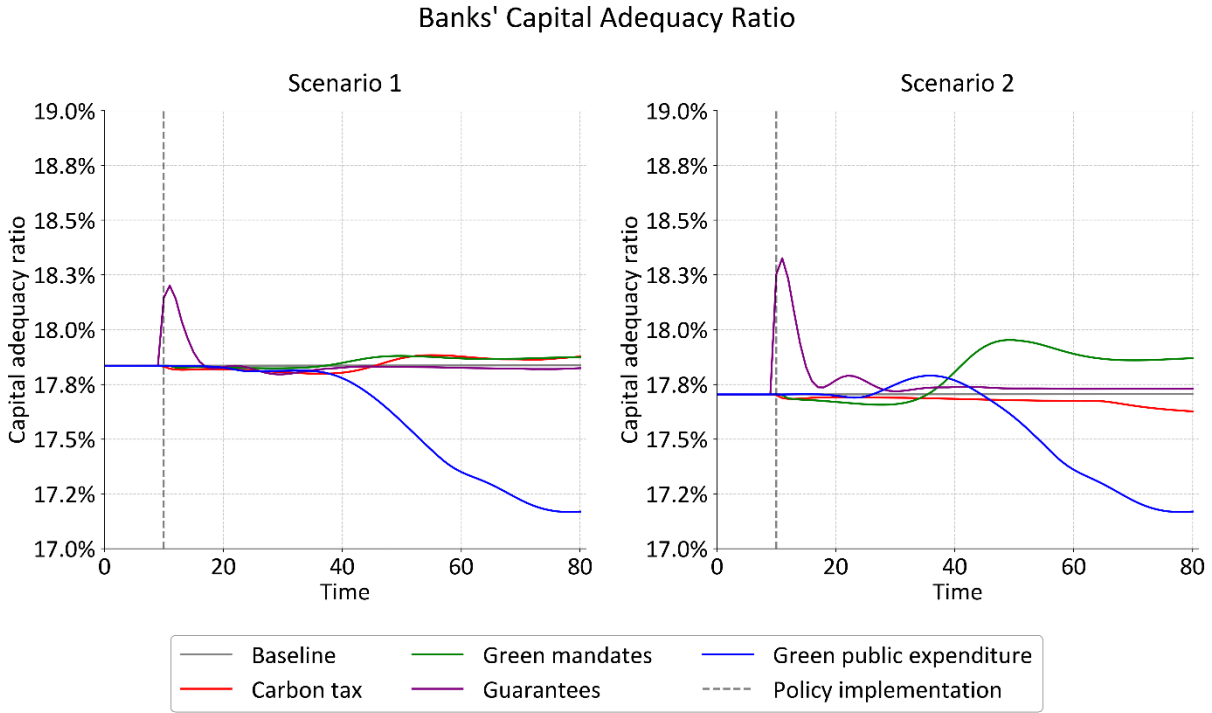


Figure 25: Impact of the policies on banks’ capital adequacy ratio across scenarios. Note that the baseline of scenario 1 and the baseline of scenario 2 are not the same (see Appendix 2).

4.3. Macroeconomic indicators

In this part, we analyze the macroeconomic impacts of each policy. The first indicator studied is output growth (Figure 26). The carbon tax has a small positive impact in both scenarios as it increases the government’s revenue, leading to higher government consumption and investment.

Green mandates have a small negative impact on output growth in the short run, as the expansion of green capital is associated with higher interest rates (Figure 31, Appendix 1.2). In

the long run, they have a small positive impact as the financing costs on green capital decrease thanks to learning effects.

Guarantees allow for increasing output growth as they strongly decrease capital financing costs (Figure 16, Section 4.1.3). They have a stronger positive impact in scenario 1 because they enable the low-carbon transition: firms invest in green capital, which benefits from lower financing costs thanks to the guarantee. In scenario 2, firms do not benefit as much from the strong decrease in green capital financing costs as they keep investing massively in brown capital (Figure 18, Section 4.1.3).

Finally, green public expenditure sharply increases output growth as public investment increases strongly in both scenarios (Figure 19, Section 4.1.4).

Note that these results on GDP growth are affected by two main simplistic modeling assumptions. First, firms' loan defaults do not directly impact firms' financial stability, as they only affect banks negatively. In reality, firms are negatively affected when a project that they are financing fails, sometimes leading to their bankruptcy. Second, increasing public debt does not have repercussions on government fiscal policies nor on the interest rate on government bonds, which is constant in the model. Consequently, output growth may be overestimated.

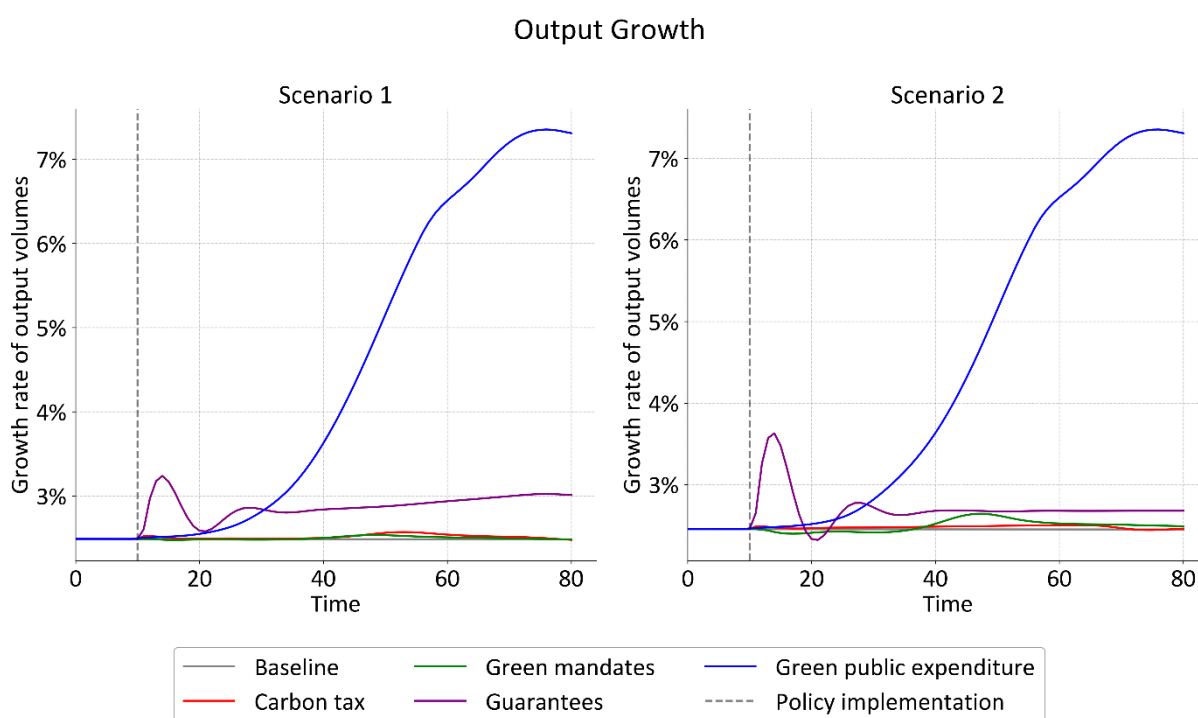


Figure 26: Impact of the policies on output growth across scenarios. Note that the baseline of scenario 1 and the baseline of scenario 2 are not the same (see Appendix 2).

Then, we study the impact of each policy on public debt in GDP (Figure 27). The carbon tax reduces government debt in both scenarios as it increases fiscal revenues.

Green mandates tend to have a positive impact on government debt in the long run as they increase GDP and thus fiscal revenues by lowering financing costs. However, in the short run,

they increase public debt to GDP, especially in scenario 2, due to higher interest rates on green loans (Figure 31, Appendix 1.2).

In scenario 1, the guarantee results in a significant rise in government debt to GDP, as guarantee payments escalate alongside the growing number of green loans taken out by firms during the transition. This increase in the debt-to-GDP ratio may be overestimated due to the assumption that loss given defaults are equal to defaults in our model. In scenario 2, guarantees also contribute to higher public debt, since increased economic growth encourages greater investment and loan uptake.

Green public expenditure has a positive impact on government debt to GDP in the short run, thanks to a stimulus effect of higher government spending. Over time, higher public spendings increase the debt-to-GDP ratio. In scenario 2, the reduction in financing costs boosts firms’ profits, allowing government debt-to-GDP to remain below its initial level in the long run.

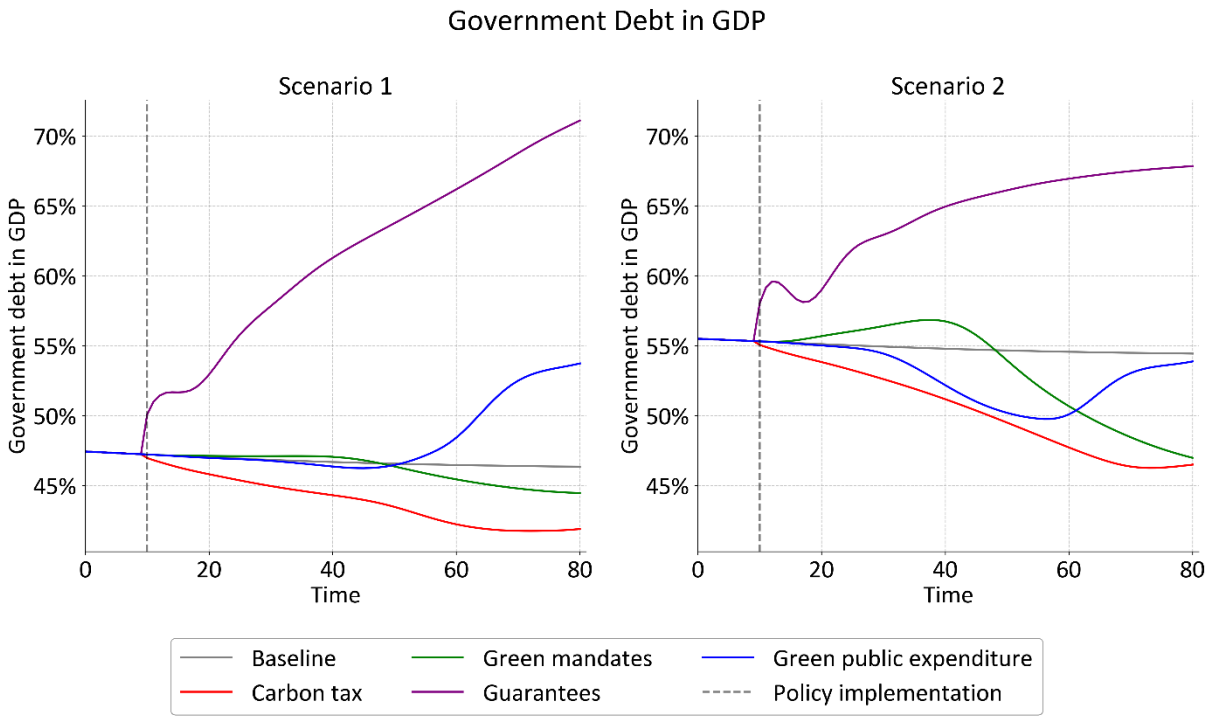


Figure 27: Impact of the policies on public debt in GDP across scenarios. Note that the baseline of scenario 1 and the baseline of scenario 2 are not the same (see Appendix 2).

5. Discussion

This analysis reveals that the impact of climate policies depends on the risks associated with green investment. In scenario 1, where risks are low, all policies reduce GHG emissions by decreasing the brown capital stock (Table 2). However, in scenario 2, high risks limit the effectiveness of all climate policies on the reduction of GHG emissions, except green mandates (Table 3). Indeed, when green investment risk is high, investors perceive greater risk and banks increase their lending rates, discouraging investment in green capital. These results underline the need to consider the perception of risks by investors and banks when implementing

climate policies, as they can be important barriers to the transition. Moreover, the actual level of green investment risk critically affects macro-financial stability, as higher default rates amplify transition risks (Table 3).

Our results highlight the importance of reducing risks before implementing a carbon tax. Indeed, in scenario 2, the carbon tax has little effect on the stock of brown capital, as firms keep investing in brown capital because the cost of the carbon tax is insufficient relative to the risks and the financing costs of investing in green capital. While increasing the carbon tax could address this issue, it would also exacerbate short-run financial instability for firms and banks due to the high default rates on green loans. This underscores the need for complementary policies that reduce risks. These results are consistent with the literature. For instance, Mercure et al. (2014) and Wieners et al. (2022) show that carbon pricing alone is insufficient to break the fossil fuel technology lock-in. Moreover, Wieners et al. (2022) and Dafermos and Nikolaidi (2022) also find that a carbon tax leads to transition risks by lowering firms' profits.

Table 2: Summary of results in scenario 1. Green/red colors represent positive/negative impacts and symbols indicate the magnitude of the impacts.

Scenario 1	Green transition		Macroeconomic impact				Firms' financial stability		Banks' financial stability	
	Green capital share	Brown capital stock	Public debt in GDP		GDP growth		Rate of defaults		CAR	
			Short run	Long run	Short run	Long run	Short run	Long run	Short run	Long run
Carbon tax	+++	---	---		+		++	-	-	+
Guarantees	+++	--	+++		++		--		+	-
Green mandates	+++	---	+	-	-	+	+	-	-	+
Green public exp.	+++	-	-	++	+++		---		-	

Green public guarantees reduce financing costs but do not mitigate investment risks for firms. In scenario 2, they could support the transition if the perceived risks of green capital for firms were also lowered. Indeed, while guarantees lower green capital financing costs by transferring the risk for banks to the government, the risk is high in scenario 2 and becomes

the primary barrier to green investment for firms. In this context, guarantees result in high government debt, as default rates on green loans are high. To reduce risks, public guarantees could be complemented with additional derisking instruments, such as streamlined licensing processes, standards and labels, awareness campaigns, and skills development initiatives (Glemarec, 2011; Waissbein et al., 2013).

Green mandates are effective in both scenarios, as agents comply with the regulation (Table 2 and Table 3). However, their macroeconomic and financial impacts are less favorable in scenario 2 than in scenario 1. In scenario 2, higher default rates and elevated interest rates on green loans amplify financial instability and public debt in the short run. In the long run, however, mandates help reduce risks and thereby lower financing costs.

While green public expenditure promotes the transition to green capital in both scenarios, its impact is more limited in scenario 2. Indeed, the transition of firms is delayed in scenario 2, as high financing costs and risks associated with green capital prevent them from expanding green investment in the short run. Moreover, the stimulus effect of higher public spending drives stronger economic growth, which limits the reduction of brown capital and even contributes to its increase in scenario 2 compared to the baseline.

Table 3: Summary of results in scenario 2. Green/red colors represent positive/negative impacts and symbols indicate the magnitude of the impacts.

Scenario 2	Green transition		Macroeconomic impact				Firms' financial stability		Banks' financial stability	
	Green capital share	Brown capital stock	Public debt in GDP		GDP growth		Rate of defaults		CAR	
			Short run	Long run	Short run	Long run	Short run	Long run	Short run	Long run
Carbon tax	+	–	---		+		+	++	–	
Guarantees	No impact	+	+++		++		–		+	
Green mandates	+++	---	++	---	–	+	++	--	–	+
Green public exp.	++	+	–		+++		---		–	

These results highlight that each instrument entails trade-offs between environmental effectiveness and macro-financial stability. For instance, a carbon tax increases firms' financial instability but reduces public debt, whereas guarantees improve firms' financial stability but raise public debt. This suggests scope for policy complementarity, and future research could explore the design of policy mixes.

Several limitations of our analysis should be noted and could be the subject of additional research. First, we assume that the policies considered are fully applicable and enforceable. For example, we assume both the availability of green substitutes and the existence of a clear green taxonomy, allowing agents to effectively identify green projects. We abstract from political economy challenges such as social acceptability and regressivity (Douenne & Fabre, 2022; IMF, 2023). This analysis does not account for implementation challenges, such as the complexity of application and reporting processes for guarantees (Garbacz et al., 2021; CPI, 2025), or the constrained capacity and expertise of public administrations required for effective green procurement (Baron, 2016) (see Section 2). Besides, we assume that agents possess sufficient financing capacity to comply with green mandates. In practice, however, financial constraints may limit compliance and thereby reduce the effectiveness of mandates in cutting emissions. This limitation stems from the absence of credit rationing in our model: banks are assumed to always supply the requested loans, adjusting interest rates according to borrowers' financial conditions rather than restricting credit altogether. Moreover, we do not consider regulatory costs, including those incurred by the government in administering and enforcing regulations, or the administrative costs borne by agents when providing information to the government (OECD, 2014).

Second, we do not account for project failures, focusing only on loan defaults. As a result, the impact of riskier investments on firms' financial stability is underestimated. Similarly, we assume that all government investment projects succeed. In practice, high-risk contexts could lead to project failures, increasing costs, and discouraging further investment. Besides, guarantees only reduce risks for banks, not for bondholders or equity investors. In a high-risk environment, these investors may withdraw, limiting firms' access to capital and thereby weakening the effectiveness of guarantees.

Third, our simulations do not consider price differences between green and brown capital goods, except for the adjustment induced by carbon pricing. While it is clear that they play a key role in agents' investment decisions, we focus on the investment risks as the main barrier to green investment in this paper, but price differences could be integrated in future work.

Fourth, our representation of macroeconomic risks is simplified. For instance, we do not account for the impact of country risk, which is likely to influence banks' lending interest rates, sovereign borrowing costs, and credit ratings. For example, while we assume that the interest rate on government debt remains constant over time, rising debt levels could trigger a repricing of risk, thereby amplifying macroeconomic risks. Similarly, in the case of guarantees,

we assume that the guarantor maintains a high credit rating and therefore does not need to allocate substantial reserves to reassure banks.

Fifth, the stock of capital of the government is treated as non-productive in the model. This simplification overstates the level of public expenditure required to achieve the transition, as productive public capital could directly complement firms' investment. This represents a potential avenue for future research.

Sixth, further work could improve both the calibration and validation of the model. CIREF is a stylized model designed to provide insights into policy outcomes under various scenarios. The results are based on a specific calibration of parameters, which enables the model to replicate a wide range of stylized facts (Appendix 4.6) and are subject to a preliminary sensitivity analysis (Appendix 3.1). Nevertheless, a more detailed global sensitivity analysis would strengthen the robustness of our findings.

Lastly, our analysis underlines that the instruments examined here appear to be promising candidates to develop policy mixes, as they exhibit complementary effects: green public procurement supports pilot projects and learning effects; green mandates foster the transition and derisk investment; guarantees lower financing costs; and a carbon tax provides incentives while generating fiscal revenues. Future work could explore which combinations of policy instruments can foster the low-carbon transition while maintaining macroeconomic stability within a defined 'safe operating space' (SOS) (Daumas et al., 2025). The study of policy mixes could complement the current literature on the subject (Dafermos & Nikolaidi, 2022; Wieners et al., 2022) by considering different scenarios of investment risks.

Bibliography

- Abraham, F., & Schmukler, S. L. (2017). Are Public Credit Guarantees Worth the Hype? (SSRN Scholarly Paper 3249563). Social Science Research Network. <https://papers.ssrn.com/abstract=3249563>
- Acemoglu, D., Aghion, P., Bursztyn, L., & Hémous, D. (2012). The Environment and Directed Technical Change. *The American Economic Review*, 102(1), 131–166.
- Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., & Van Reenen, J. (2016). Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry. *Journal of Political Economy*, 124(1), 1–51.
- Anderson, D., Clark, C., Foxon, T., Gross, R., & Jacobs, M. (2001). Innovation and the Environment: Challenges and Policy Options for the UK. Imperial College Centre for Energy Policy and Technology & the Fabian Society. <https://www.imperial.ac.uk/media/imperial-college/research-centres-and-groups/icept/7294721.PDF>
- Arping, S., Lóránth, G., & Morrison, A. D. (2010). Public initiatives to support entrepreneurs: Credit guarantees versus co-funding. *Journal of Financial Stability*, 6(1), 26–35. <https://doi.org/10.1016/j.jfs.2009.05.009>
- Baron, R. (2016). The Role of Public Procurement in Low-carbon Innovation. Unpublished. <https://doi.org/10.13140/RG.2.2.10325.22245>
- Bauer, N., Bosetti, V., Hamdi-Cherif, M., Kitous, A., McCollum, D., Méjean, A., Rao, S., Turton, H., Paroussos, L., Ashina, S., Calvin, K., Wada, K., & van Vuuren, D. (2015). CO2 emission mitigation and fossil fuel markets: Dynamic and international aspects of climate policies. *Technological Forecasting and Social Change*, 90, 243–256. <https://doi.org/10.1016/j.techfore.2013.09.009>
- Best, R., & Burke, P. J. (2018). Adoption of solar and wind energy: The roles of carbon pricing and aggregate policy support. *Energy Policy*, 118, 404–417. <https://doi.org/10.1016/j.enpol.2018.03.050>
- BIS. (2019). Credit to the non-financial sector dashboard [Dataset]. https://data.bis.org/topics/TOTAL_CREDIT/tables-and-dashboards
- Blanchard, O., Gollier, C., & Tirole, J. (2023). The Portfolio of Economic Policies Needed to Fight Climate Change. *Annual Review of Economics*, 15(Volume 15, 2023), 689–722. <https://doi.org/10.1146/annurev-economics-051520-015113>
- Böhringer, C., Rutherford, T. F., & Tol, R. S. J. (2009). The EU 20/20/2020 Targets: An Overview of the EMF22 Assessment (WP325). Economic and Social Research Institute (ESRI). <https://ideas.repec.org//p/esr/wpaper/wp325.html>

Botte, F. (2020). Estimating normal rates of capacity utilisation and their tolerable ranges: A comment on Mark Setterfield. *Cambridge Journal of Economics*, 44(2), 475–482. <https://doi.org/10.1093/cje/bez043>

Brammer, S., & Walker, H. (2011). Sustainable procurement in the public sector: An international comparative study. *International Journal of Operations & Production Management*, 31(4), 452–476. <https://doi.org/10.1108/01443571111119551>

Brett, C. (2024). *The Price Is Wrong: Why Capitalism Won't Save the Planet*. Verso Books.

Brunner, S., Flachsland, C., & Marschinski, R. (2012). Credible commitment in carbon policy. *Climate Policy*, 12(2), 255–271.

Buchetti, B., Miquel-Flores, I., Perdichizzi, S., & Reghezza, A. (2024). Greening the Economy: How Public-Guaranteed Loans Influence Firm-Level Resource Allocation. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.4759852>

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. <https://doi.org/10.1016/j.ecolecon.2015.03.020>

Campiglio, E., Daumas, L., Monnin, P., & von Jagow, A. (2023). Climate-related risks in financial assets. *Journal of Economic Surveys*, 37(3), 950–992. <https://doi.org/10.1111/joes.12525>

Carney, P. (2015). *Breaking the Tragedy of the Horizon – climate change and financial stability* [Speech].

Chateau, J., Jaumotte, F., & Schwerhoff, G. (2024). Climate policy options: A comparison of economic performance. *Energy Policy*, 192, 114232. <https://doi.org/10.1016/j.enpol.2024.114232>

Chiani, L., Borgonovo, E., Plischke, E., & Tavoni, M. (2025). gsaot: An R package for Optimal Transport-based sensitivity analysis (Version 1). *arXiv*. <https://doi.org/10.48550/ARXIV.2507.18588>

CPI. (2024). *Global Landscape of Climate Finance 2024: Insights for COP 29*. Climate Policy Initiative. <https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2024/>

CPI. (2025). *Energizing Private Capital: Innovations in Guarantee Offerings for Climate Finance*. Climate Policy Initiative. <https://www.climatepolicyinitiative.org/publication/energizing-private-capital-innovations-in-guarantee-offerings-for-climate-finance/>

Cuturi, M. (2013). Sinkhorn Distances: Lightspeed Computation of Optimal Transport. *Advances in Neural Information Processing Systems*, 26. https://papers.nips.cc/paper_files/paper/2013/hash/af21d0c97db2e27e13572cbf59eb343d-Abstract.html

Dafermos, Y., & Nikolaidi, M. (2021). How can green differentiated capital requirements affect climate risks? A dynamic macrofinancial analysis. *Journal of Financial Stability*, 54, 100871. <https://doi.org/10.1016/j.jfs.2021.100871>

Dafermos, Y., & Nikolaidi, M. (2022). Assessing climate policies: An ecological stock–flow consistent perspective. *European Journal of Economics and Economic Policies: Intervention*, 3. <https://doi.org/10.4337/ejeep.2022.0095>

Daumas, L., Godin, A., Guivarch, C., & Yilmaz, S. D. (2025). Robust financing mixes for Colombia’s climate strategy—A Robust Decision-Making Application of the GEMMES-Colombia model. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.5327551>

de la Torre, A., Gozzi, J. C., & Schmukler, S. L. (2007). Innovative Experiences in Access to Finance: Market Friendly Roles for the Visible Hand? (SSRN Scholarly Paper 1008404). Social Science Research Network. <https://papers.ssrn.com/abstract=1008404>

Douenne, T., & Fabre, A. (2022). Yellow Vests, Pessimistic Beliefs, and Carbon Tax Aversion. *American Economic Journal: Economic Policy*, 14(1), 81–110. <https://doi.org/10.1257/pol.20200092>

Dunz, N., Naqvi, A., & Monasterolo, I. (2021). Climate sentiments, transition risk, and financial stability in a stock-flow consistent model. *Journal of Financial Stability*, 54, 100872. <https://doi.org/10.1016/j.jfs.2021.100872>

ECB. (2020). ECB publishes supervisory banking statistics for the first quarter of 2020 (Supervisory Banking Statistics). European Central Bank. <https://www.bankingsupervision.europa.eu/press/pr/date/2020/html/ssm.pr200724~08068ccfbd.en.html>

Egli, F., Steffen, B., & Schmidt, T. S. (2018). A dynamic analysis of financing conditions for renewable energy technologies. *Nature Energy*, 3(12), Article 12. <https://doi.org/10.1038/s41560-018-0277-y>

Egorova, T., Sedlacek, J., Sukhodolov, T., Karagodin-Doyennel, A., Zilker, F., & Rozanov, E. (2023). Montreal Protocol’s impact on the ozone layer and climate. *Atmospheric Chemistry and Physics*, 23(9), 5135–5147. <https://doi.org/10.5194/acp-23-5135-2023>

European Banking Authority. (2019). EBA report on Non-Performing Loans. European Banking Authority. <https://data.europa.eu/data/datasets/eba-report-on-non-performing-loans?locale=en>

Funke, F., Mattauch, L., Douenne, T., Fabre, A., & Stiglitz, J. (2024). Supporting carbon pricing when interest rates are higher. *Nature Climate Change*, 14(7), 665–667. <https://doi.org/10.1038/s41558-024-02040-z>

Garbacz, W., Vilalta, D., & Moller, L. (2021). The role of guarantees in blended finance (OECD Development Co-Operation Working Papers 97; OECD Development Co-Operation Working Papers, Vol. 97). OECD. <https://doi.org/10.1787/730e1498-en>

Glemarec, Y. (2011). Catalysing Climate Finance: A Guidebook on Policy and Financing Options to Support Green, Low-Emission and Climate-Resilient Development. United Nations Development Programme. https://www.undp.org/sites/g/files/zskgke326/files/migration/in/catalysing_climate_finance_a_guidebook_on_policy_and_financing_options_to_support_green_low_emission_and_climate_resilient_development.pdf

Gloaguen, O., & Alberola. (2013). Assessing the Factors behind CO2 Emissions Changes Over the Phases 1 and 2 of the EU ETS: An Econometric Analysis. <https://www.i4ce.org/wp-content/uploads/13-10-CDC-Climat-R-WP-13-15-Assessing-the-factors-behing-CO2-emissions-changes.pdf>

Godley, W., & Lavoie, M. (2012). Monetary Economics. Palgrave Macmillan UK. <https://doi.org/10.1007/978-1-137-08599-3>

Goldstein, A., Turner, W. R., Gladstone, J., & Hole, D. G. (2019). The private sector's climate change risk and adaptation blind spots. *Nature Climate Change*, 9(1), 18–25. <https://doi.org/10.1038/s41558-018-0340-5>

Goulder, L. H., & Parry, I. W. H. (2008). Instrument Choice in Environmental Policy (SSRN Scholarly Paper 1117566). Social Science Research Network. <https://doi.org/10.2139/ssrn.1117566>

Granoff, I., Hogarth, J. R., & Miller, A. (2016). Nested barriers to low-carbon infrastructure investment. *Nature Climate Change*, 6(12), 1065–1071. <https://doi.org/10.1038/nclimate3142>

Grubb, M., Drummond, P., Poncia, A., McDowall, W., Popp, D., Samadi, S., Penasco, C., Gillingham, K. T., Smulders, S., Glachant, M., Hassall, G., Mizuno, E., Rubin, E. S., Dechezleprêtre, A., & Pavan, G. (2021). Induced innovation in energy technologies and systems: A review of evidence and potential implications for CO2 mitigation. *Environmental Research Letters*, 16(4), 043007. <https://doi.org/10.1088/1748-9326/abde07>

Haas, C., & Kempa, K. (2023). Low-Carbon Investment and Credit Rationing. *Environmental and Resource Economics*, 86(1), 109–145. <https://doi.org/10.1007/s10640-023-00789-z>

Hansen, H., Rand, J., & Andersen, O. W. (2020). Guarantees and Incentives in Development Aid. Danida. https://um.dk/en/danida/results/eval/eval_reports/guaranties-and-incentives-in-development-aid-20200527t133339

Hirth, L., & Steckel, J. C. (2016). The role of capital costs in decarbonizing the electricity sector. *Environmental Research Letters*, 11(11), 114010. <https://doi.org/10.1088/1748-9326/11/11/114010>

- Honohan, P. (2010). Partial credit guarantees: Principles and practice. *Journal of Financial Stability*, 6(1), 1–9. <https://doi.org/10.1016/j.jfs.2009.05.008>
- Hourcade, J.-C., Dasgupta, D., & Gherzi, F. (2021). Accelerating the speed and scale of climate finance in the post-pandemic context. *Climate Policy*, 21(10), 1383–1397. <https://doi.org/10.1080/14693062.2021.1977599>
- IEA. (2014). IEA's Policies and Measures Database [Dataset]. <https://www.iea.org/policies>
- IEA. (2024). Strategies for Affordable and Fair Clean Energy Transitions – Analysis—IEA [Special report]. IEA. <https://www.iea.org/reports/strategies-for-affordable-and-fair-clean-energy-transitions>
- IEA, & IFC. (2023). Scaling Up Private Finance for Clean Energy in Emerging and Developing Economies. IEA. <https://www.iea.org/reports/scaling-up-private-finance-for-clean-energy-in-emerging-and-developing-economies>
- IMF. (2020a). Fiscal Monitor: Policies for the Recovery. International Monetary Fund. <https://www.imf.org/en/Publications/FM/Issues/2020/09/30/october-2020-fiscal-monitor>
- IMF. (2020b). World Economic Outlook: A Long and Difficult Ascent. International Monetary Fund. <https://www.imf.org/en/Publications/WEO/Issues/2020/09/30/world-economic-outlook-october-2020>
- IMF. (2022). Global Financial Stability Report, October 2022: Navigating the High-Inflation Environment. IMF. <https://www.imf.org/en/Publications/GFSR/Issues/2022/10/11/global-financial-stability-report-october-2022>
- IMF. (2023). Fiscal Monitor: Climate Crossroads: Fiscal Policies in a Warming World. IMF. <https://www.imf.org/en/Publications/FM/Issues/2023/10/10/fiscal-monitor-october-2023>
- International Monetary Fund (IMF). (2019). Fiscal Monitor: How to Mitigate Climate Change. IMF. <https://www.imf.org/en/Publications/FM/Issues/2019/09/12/fiscal-monitor-october-2019>
- IPCC. (2014). AR5 Synthesis Report: Climate Change 2014 (p. 151). IPCC. <https://www.ipcc.ch/report/ar5/syr/>
- IPCC (Ed.). (2022). Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. <https://doi.org/10.1017/9781009157926>
- IRENA. (2023). Low-cost finance for the energy transition. International Renewable Energy Agency. <https://www.irena.org/Publications/2023/May/Low-cost-finance-for-the-energy-transition>

- Isoard, S., & Soria, A. (2001). Technical change dynamics: Evidence from the emerging renewable energy technologies. *Energy Economics*, 23(6), 619–636. [https://doi.org/10.1016/S0140-9883\(01\)00072-X](https://doi.org/10.1016/S0140-9883(01)00072-X)
- Jaffe, A. B., Newell, R. G., & Stavins, R. N. (2005). A tale of two market failures: Technology and environmental policy. *Ecological Economics*, 54(2), 164–174. <https://doi.org/10.1016/j.ecolecon.2004.12.027>
- Jimenez, G., Laeven, L. A., Martinez Miera, D., & Peydro, J.-L. (2024). Public Guarantees, Private Banks' Incentives, and Corporate Outcomes: Evidence from the COVID-19 Crisis. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.4756098>
- Joas, F., & Flachsland, C. (2016). The (ir)relevance of transaction costs in climate policy instrument choice: An analysis of the EU and the US. *Climate Policy*, 16(1), 26–49. <https://doi.org/10.1080/14693062.2014.968762>
- Juselius, M., & Drehmann, M. (2020). Leverage Dynamics and the Burden of Debt. *Oxford Bulletin of Economics and Statistics*, 82(2), 347–364.
- Känzig, D. R. (2023). The Unequal Economic Consequences of Carbon Pricing (SSRN Scholarly Paper 4440716). Social Science Research Network. <https://papers.ssrn.com/abstract=4440716>
- Kemp-Benedict, E., & Godin, A. (2017). Introducing risk into a Tobin asset-allocation model. Working Papers, Article PKWP1713. <https://ideas.repec.org//p/pke/wpaper/pkwp1713.html>
- Kotilainen, K., Aalto, P., Valta, J., Rautiainen, A., Kojo, M., & Sovacool, B. K. (2019). From path dependence to policy mixes for Nordic electric mobility: Lessons for accelerating future transport transitions. *Policy Sciences*, 52(4), 573–600. <https://doi.org/10.1007/s11077-019-09361-3>
- Krieger, B., & Zipperer, V. (2022). Does green public procurement trigger environmental innovations? *Research Policy*, 51(6), 104516. <https://doi.org/10.1016/j.respol.2022.104516>
- Lamperti, F., Bosetti, V., Roventini, A., Tavoni, M., & Treibich, T. (2021). Three green financial policies to address climate risks. *Journal of Financial Stability*, 54, 100875. <https://doi.org/10.1016/j.jfs.2021.100875>
- Lamperti, F., Napoletano, M., & Roventini, A. (2020). GREEN TRANSITIONS AND THE PREVENTION OF ENVIRONMENTAL DISASTERS: MARKET-BASED VS. COMMAND-AND-CONTROL POLICIES. *Macroeconomic Dynamics*, 24(7), 1861–1880. <https://doi.org/10.1017/S1365100518001001>
- Lamperti, F., & Roventini, A. (2022). Beyond climate economics orthodoxy: Impacts and policies in the agent-based integrated-assessment DSK model*. <https://doi.org/10.4337/ejeep.2022.0096>

- Levinson, A. (2019). Energy Efficiency Standards Are More Regressive Than Energy Taxes: Theory and Evidence. *Journal of the Association of Environmental and Resource Economists*, 6(S1), S7–S36. <https://doi.org/10.1086/701186>
- Lilliestam, J., Patt, A., & Bersalli, G. (2021). The effect of carbon pricing on technological change for full energy decarbonization: A review of empirical ex-post evidence. *WIREs Climate Change*, 12(1), e681. <https://doi.org/10.1002/wcc.681>
- Magacho, G., Godin, A., Yilmaz, S., & Spinola, D. (2024). Recycling carbon taxes for reindustrialisation: Addressing structural rigidity and financialisation in natural resource exporting countries (p. 52). AFD. <https://www.afd.fr/en/ressources/recycling-carbon-taxes-reindustrialisation-addressing-structural-rigidity-and-financialisation-natural-resource-exporting-countries>
- Mazzucato, M., & Semieniuk, G. (2018). Financing renewable energy: Who is financing what and why it matters. *Technological Forecasting and Social Change*, 127, 8–22. <https://doi.org/10.1016/j.techfore.2017.05.021>
- Mercure, J.-F., Pollitt, H., Bassi, Andrea. M., Viñuales, Jorge. E., & Edwards, N. R. (2016). Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. *Global Environmental Change*, 37, 102–115. <https://doi.org/10.1016/j.gloenvcha.2016.02.003>
- Mercure, J.-F., Pollitt, H., Chewprecha, U., Salas, P., Foley, A. M., Holden, P. B., & Edwards, N. R. (2014). The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector. *Energy Policy*, 73, 686–700. <https://doi.org/10.1016/j.enpol.2014.06.029>
- Mercure, J.-F., Sharpe, S., Vinuales, J. E., Ives, M., Grubb, M., Lam, A., Drummond, P., Pollitt, H., Knobloch, F., & Nijse, F. J. M. M. (2021). Risk-opportunity analysis for transformative policy design and appraisal. *Global Environmental Change*, 70, 102359. <https://doi.org/10.1016/j.gloenvcha.2021.102359>
- Monasterolo, I., Mandel, A., Battiston, S., Mazzocchi, A., Oppermann, K., Coony, J. D., Stretton, S. J., Stewart, F. E., & Dunz, N. M. F. (2022). The Role of Green Financial Sector Initiatives in the Low-Carbon Transition: A Theory of Change (Policy Research Working Paper Series 10181). The World Bank. <https://econpapers.repec.org/paper/wbkwbrwps/10181.htm>
- Monasterolo, I., Roventini, A., & Foxon, T. J. (2019). Uncertainty of climate policies and implications for economics and finance: An evolutionary economics approach. *Ecological Economics*, 163, 177–182. <https://doi.org/10.1016/j.ecolecon.2019.05.012>
- Negro, S. O., Alkemade, F., & Hekkert, M. P. (2012). Why does renewable energy diffuse so slowly? A review of innovation system problems. *Renewable and Sustainable Energy Reviews*, 16(6), 3836–3846. <https://doi.org/10.1016/j.rser.2012.03.043>

Nicolas, T., Ungaro, S., & Vansteenberghe, É. (2023). Public-Guaranteed Loans, Bank Risk-Taking and Regulatory Capital Windfall
[Prêts garantis par l'État, prise de risque bancaire et effet d'aubaine sur le capital réglementaire]. *Débats Économiques et Financiers*, Article 41. <https://ideas.repec.org//p/bfr/decfin/41.html>

Nikiforos, M., & Zezza, G. (2017). STOCK-FLOW CONSISTENT MACROECONOMIC MODELS: A SURVEY. *Journal of Economic Surveys*, 31(5), 1204–1239. <https://doi.org/10.1111/joes.12221>

OECD. (2003). The Environmental Performance of Public Procurement: Issues of Policy Coherence. OECD. <https://doi.org/10.1787/9789264101562-en>

OECD. (2014). Regulatory Compliance Cost Assessment Guidance. OECD. <https://doi.org/10.1787/9789264209657-en>

OECD. (2019). Annual balance sheets for non-financial assets [Dataset].

OECD. (2025). Government at a Glance 2025. OECD Publishing. <https://doi.org/10.1787/0efd0bcd-en>

Pahle, M., Burtraw, D., Flachsland, C., Kelsey, N., Biber, E., Meckling, J., Edenhofer, O., & Zysman, J. (2018). Sequencing to ratchet up climate policy stringency. *Nature Climate Change*, 8(10), 861–867. <https://doi.org/10.1038/s41558-018-0287-6>

Pan, H., & Köhler, J. (2007). Technological change in energy systems: Learning curves, logistic curves and input–output coefficients. *Ecological Economics*, 63(4), 749–758. <https://doi.org/10.1016/j.ecolecon.2007.01.013>

Peñasco, C., Anadón, L., & Verdolini, E. (2021). Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments. <https://doi.org/10.17863/CAM.63272>

Pigou, A., Cecil. (1920). The Economics of Welfare. Palgrave Macmillan London. <https://link.springer.com/book/9780230249318>

Polzin, F., Egli, F., Steffen, B., & Schmidt, T. S. (2019). How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective. *Applied Energy*, 236, 1249–1268. <https://doi.org/10.1016/j.apenergy.2018.11.098>

Rogers, E. M. (2010). Diffusion of Innovations, 4th Edition. Simon and Schuster. <https://teddykw2.wordpress.com/wp-content/uploads/2012/07/everett-m-rogers-diffusion-of-innovations.pdf>

Romer, P. M. (1990). Endogenous Technological Change. *Journal of Political Economy*, 98(5), S71–S102.

Rozenberg, J., Vogt-Schilb, A., & Hallegatte, S. (2020). Instrument choice and stranded assets in the transition to clean capital. *Journal of Environmental Economics and Management*, 100, 102183. <https://doi.org/10.1016/j.jeem.2018.10.005>

- Shapiro, J. S., & Walker, R. (2018). Why Is Pollution from US Manufacturing Declining? The Roles of Environmental Regulation, Productivity, and Trade. *American Economic Review*, 108(12), 3814–3854. <https://doi.org/10.1257/aer.20151272>
- Shapiro, N., & Sawyer, M. (2003). Post Keynesian price theory. *Journal of Post Keynesian Economics*, 25(3), 355–365. <https://doi.org/10.1080/01603477.2003.11051365>
- Söderholm, P. (2020). The green economy transition: The challenges of technological change for sustainability. *Sustainable Earth*, 3(1), 6. <https://doi.org/10.1186/s42055-020-00029-y>
- Souffron, C., & Jacques, P. (2024). A Successful Assessment of the Economic Impacts of Ecological Transition Policies in the EU Requires the European Commission to Broaden the Range of Its Modelling Tools (SSRN Scholarly Paper 4640677). Social Science Research Network. <https://doi.org/10.2139/ssrn.4640677>
- Steckel, J., & Jakob, M. (2018). The role of financing cost and de-risking strategies for clean energy investment. *International Economics*, 155(C), 19–28.
- Steffen, B. (2020). Estimating the cost of capital for renewable energy projects. *Energy Economics*, 88, 104783. <https://doi.org/10.1016/j.eneco.2020.104783>
- Stiglitz, J., Stern, N., Duan, M., Edenhofer, O., Giraud, G., & Heal, G., Lèbre la Rovere, E., Morris, A., Moyer, E., Pangestu, M., Shukla, P., Sokona, Y., Winkler, H. (2017). Report of the High-Level Commission on Carbon Prices. World Bank. <https://www.carbonpricingleadership.org/report-of-the-highlevel-commission-on-carbon-prices>
- Stiglitz, J., & Weiss, A. (1981). Credit Rationing in Markets with Imperfect Information. *The American Economic Review*, 71(3), 393–410.
- TCFD. (2023). 2023 Status Report. Task Force on Climate-related Financial Disclosures. <https://www.fsb-tcfd.org/publications/>
- Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., & de Vries, G. J. (2015). An Illustrated User Guide to the World Input–Output Database: The Case of Global Automotive Production. *Review of International Economics*, 23(3), 575–605. <https://doi.org/10.1111/roie.12178>
- Tobin, J. (1969). A General Equilibrium Approach To Monetary Theory. *Journal of Money, Credit and Banking*, 1(1), 15–29. <https://doi.org/10.2307/1991374>
- Tvinnereim, E., & Mehling, M. (2018). Carbon pricing and deep decarbonisation. *Energy Policy*, 121, 185–189. <https://doi.org/10.1016/j.enpol.2018.06.020>
- Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*, 28(12), 817–830. [https://doi.org/10.1016/S0301-4215\(00\)00070-7](https://doi.org/10.1016/S0301-4215(00)00070-7)
- Vesa, J., Gronow, A., & Ylä-Anttila, T. (2020). The quiet opposition: How the pro-economy lobby influences climate policy. *Global Environmental Change*, 63, 102117. <https://doi.org/10.1016/j.gloenvcha.2020.102117>

Waidelich, P., Krug, J., & Steffen, B. (2023). Mobilizing Credit for Clean Energy: De-Risking and Public Loan Provision Under Learning Spillovers (SSRN Scholarly Paper 4610182). <https://doi.org/10.2139/ssrn.4610182>

Waissbein, O., Glemarec, Y., Bayraktar, H., & Schmidt, T. (2013). Derisking Renewable Energy Investment (p. 156). UNDP. <https://www.undp.org/publications/derisking-renewable-energy-investment>

Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. *Joule*, 6(9), 2057–2082. <https://doi.org/10.1016/j.joule.2022.08.009>

Wieners, C., Lamperti, F., Buizza, R., Dosi, G., & Roventini, A. (2022). Macroeconomic policies to stay below 2°C with sustainable growth. https://www.anpec.org.br/encontro/2022/submissao/files_l/i11-4c05fb8bd6e38c7f95d7e9d26cba6086.pdf

World Bank. (2023). Scaling Up to Phase Down: Financing Energy Transitions in the Power Sector. World Bank. <http://hdl.handle.net/10986/39689>

World Bank. (2025a). State and Trends of Carbon Pricing 2025. World Bank. <https://www.worldbank.org/en/publication/state-and-trends-of-carbon-pricing>

World Bank. (2025b). World Bank Open Data (NE.CON.GOV.T.ZS) [Dataset]. <https://data.worldbank.org>

Appendix 1 Supplementary results

Appendix 1.1 Carbon tax

The carbon tax rate is calibrated in scenario 1 to reach the transition target and applied in both scenarios (Figure 28). The carbon tax revenues in GDP increase more in scenario 2 than in scenario 1, as the transition occurs later in scenario 2.

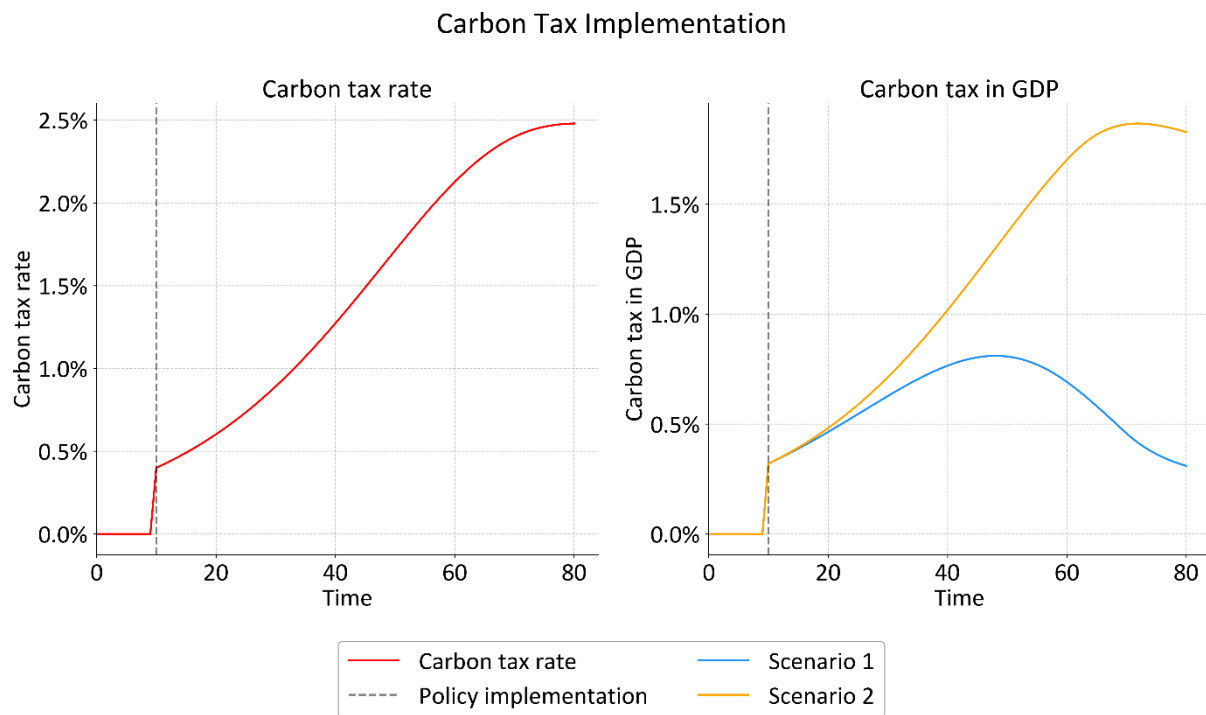


Figure 28: Carbon tax rate (same across scenarios) and carbon tax revenues in GDP across scenarios.

Brown Capital Investment Shares of Households and the Government - Carbon tax

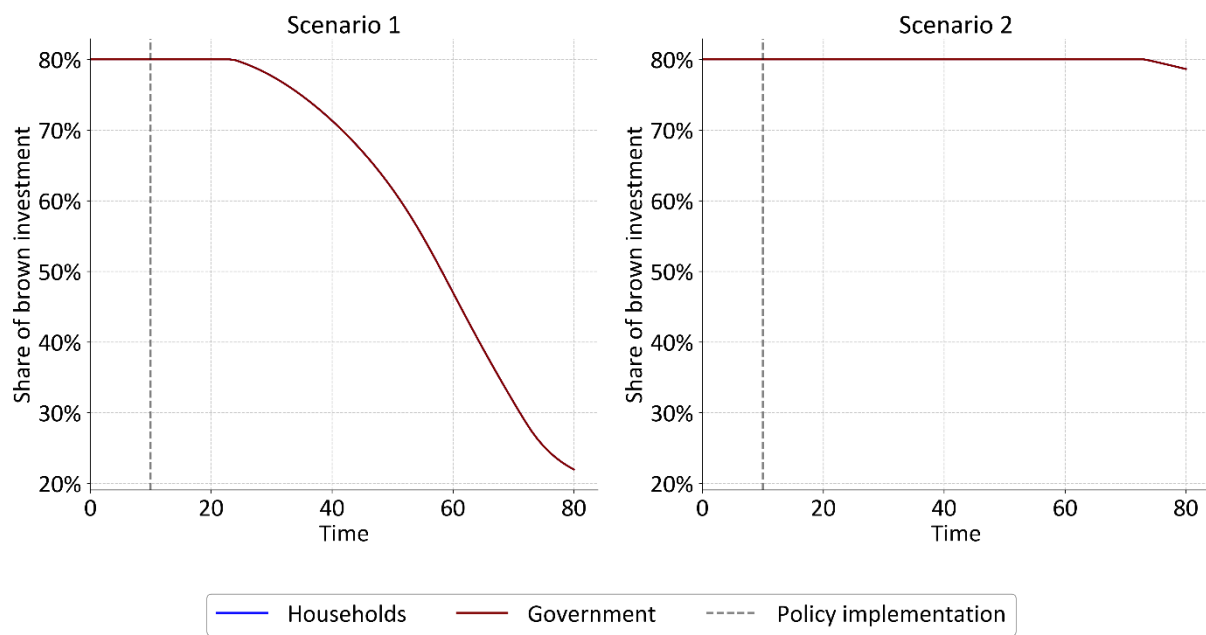


Figure 29: Share of investment going to brown capital by households and the government with a carbon tax across scenarios.

Appendix 1.2 Green mandates

In both scenarios, the “unconstrained” share of brown investment by firms declines over time, as the mandate supports the transition by lowering financing costs and perceived risks for green capital, boosting its productivity, and reducing the autonomous demand for brown capital (Figure 30).

Decomposition of the Share of Brown Investment by Consumption Goods Firms - Green mandates

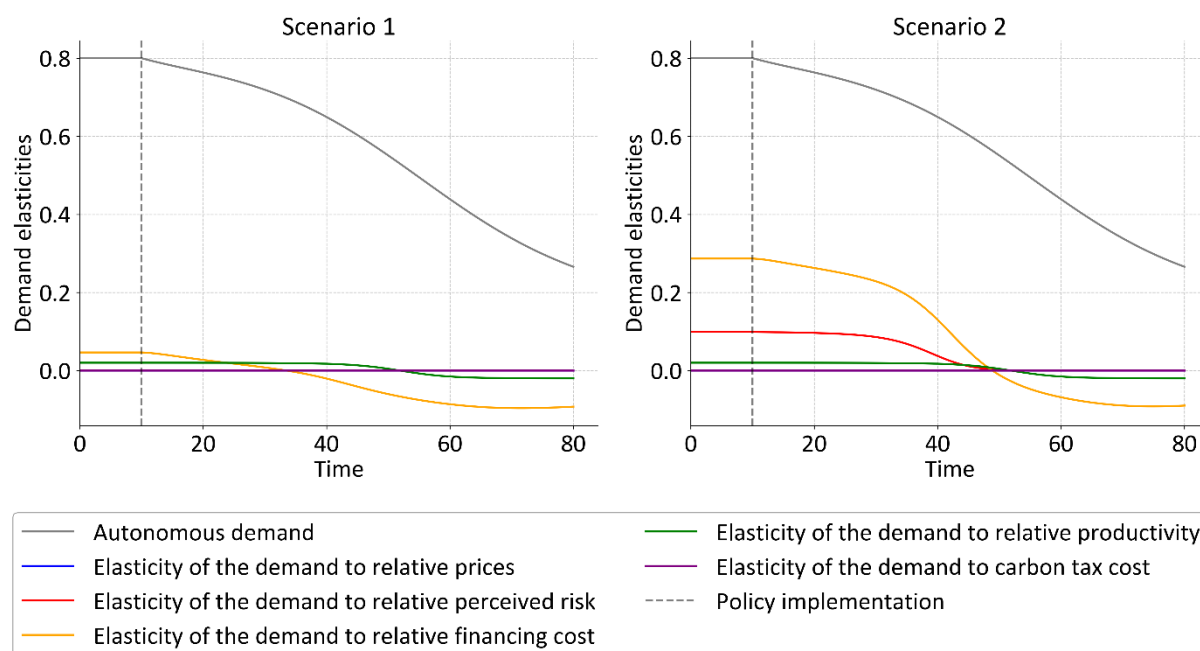


Figure 30: Decomposition of consumption goods firms' investment decision in brown capital relative to green capital with green mandates. Positive values indicate positive demand for brown capital, leading to a higher share of brown capital; negative values reflect a negative demand for brown capital, leading to a lower share of brown capital.

Firms' Financing Costs - Green mandates

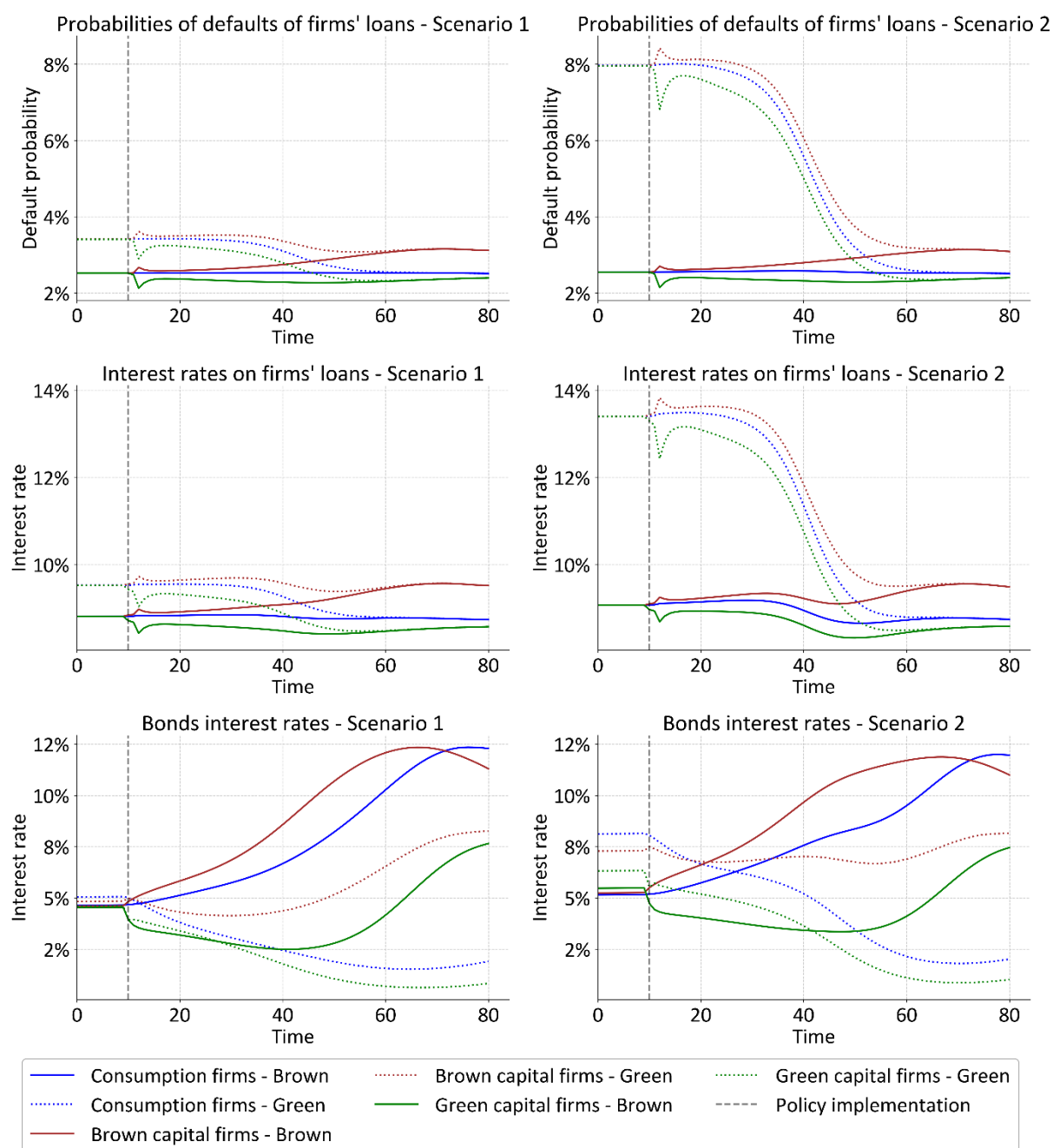


Figure 31: Evolution of firms' probabilities of loan default and financing costs with green mandates across scenarios. Solid lines represent firms' probabilities of brown loan default/brown interest rates,

and dotted lines represent firms’ probabilities of green loan default/green interest rates. Note that the baseline of scenario 1 and the baseline of scenario 2 are not the same (see Appendix 2).

Appendix 1.3 Guarantees

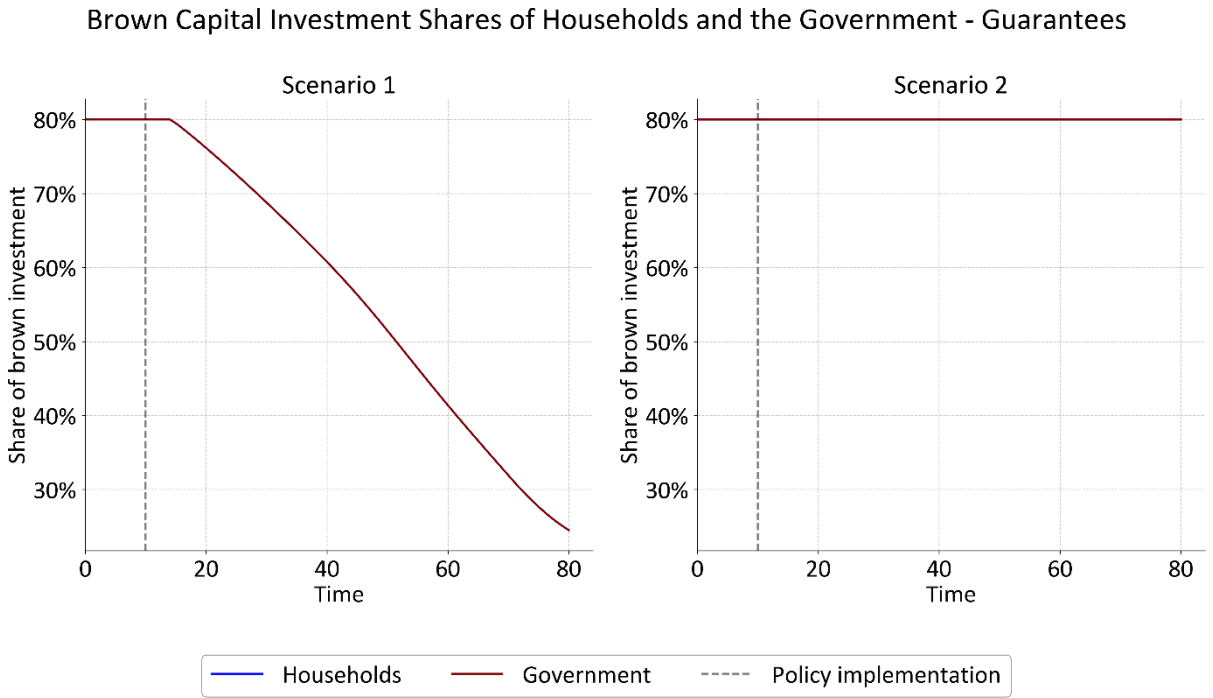


Figure 32: Share of investment going to brown capital by households and the government with guarantees across scenarios.

When guarantees are implemented, the probabilities of defaults on green loans decrease over time, thanks to learning effects as the transition occurs in scenario 1 (Figure 33). In scenario 2, the probabilities of default on green loans decrease slightly, as lower financing costs from the guarantee reduce the firms’ debt-service ratio.

Examining bond dynamics in more detail, interest rates on green bonds decrease relative to brown bonds for all firms in scenario 1 (Figure 33). Producers of brown capital face a substantial rise in interest rates on their brown bonds as households gradually shift their preferences toward green bonds during the transition. In contrast, green firms initially put lower interest rates on both green and brown bonds, due to increased household demand for their bonds. Over time, as green firms expand their market share, demand for bonds issued by brown firms declines, leading to rising interest rates—even on the green bonds of brown firms—thereby tightening their financing conditions. In scenario 2, the reduction in interest rates on green loans encourages firms to meet more of their external financing needs through bank loans rather than bond issuance, which increases bond prices and lowers bond interest rates.

Firms' Financing Costs - Guarantees

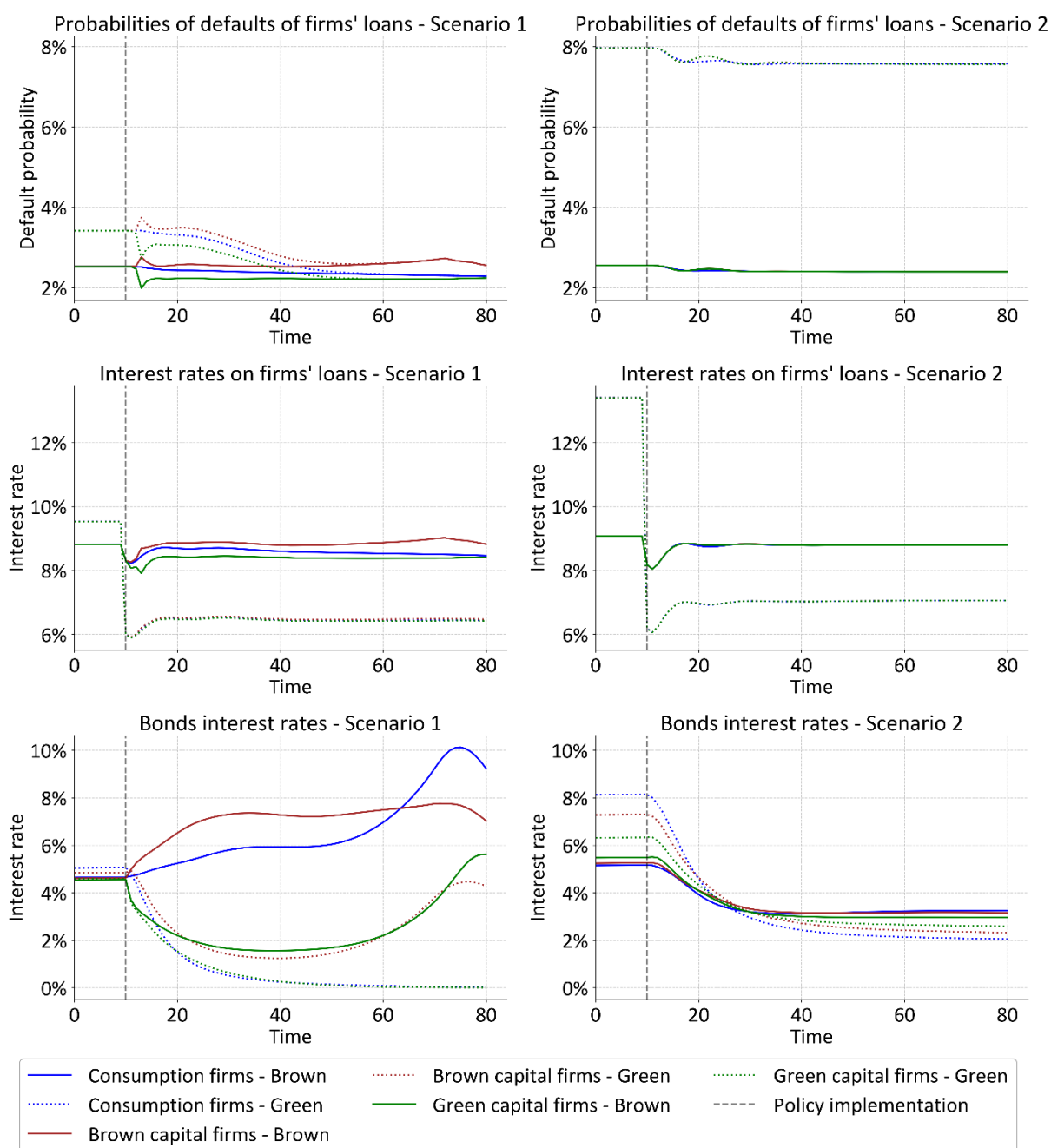


Figure 33: Evolution of firms' probabilities of loan default and financing costs with guarantees across scenarios. Solid lines represent firms' probabilities of brown loan default/brown interest rates, and

dotted lines represent firms' probabilities of green loan default/green interest rates. Note that the baseline of scenario 1 and the baseline of scenario 2 are not the same (see Appendix 2).

Appendix 1.4 Green public expenditure

Brown Capital Investment Shares of Households and the Government - Green public expenditure

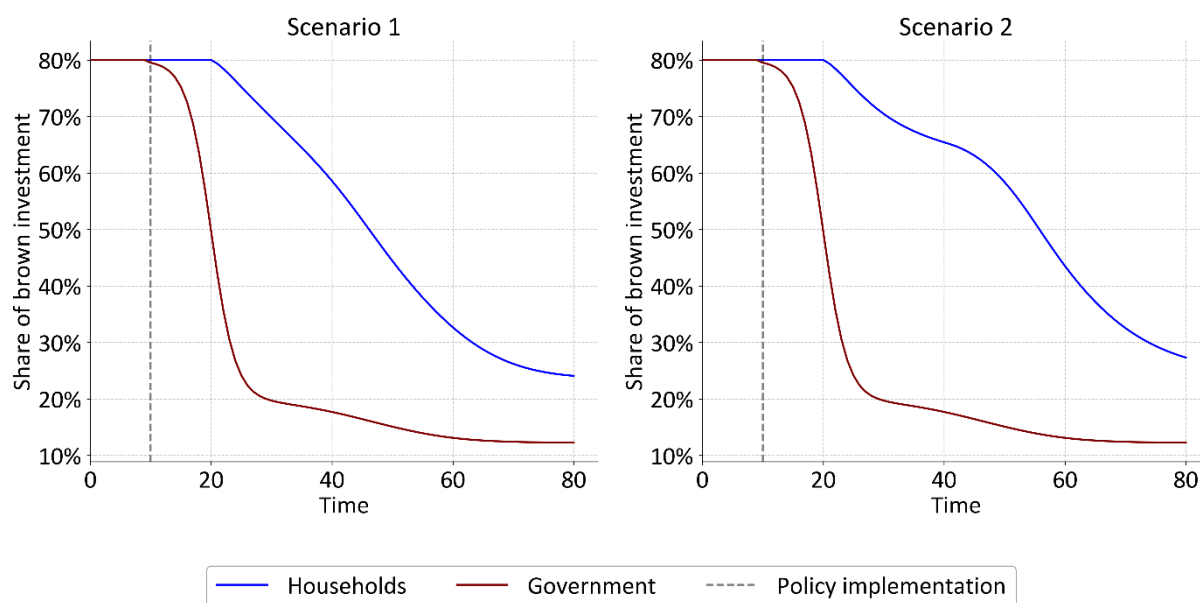


Figure 34: Share of investment going to brown capital by households and government with green public expenditure across scenarios.

Appendix 2 Baselines

As explained in Section 3.4, our scenario analysis uses two different baselines, reflecting different probabilities of default (Figure 35). Nonetheless, the share of firms' green investment is the same across both baselines.

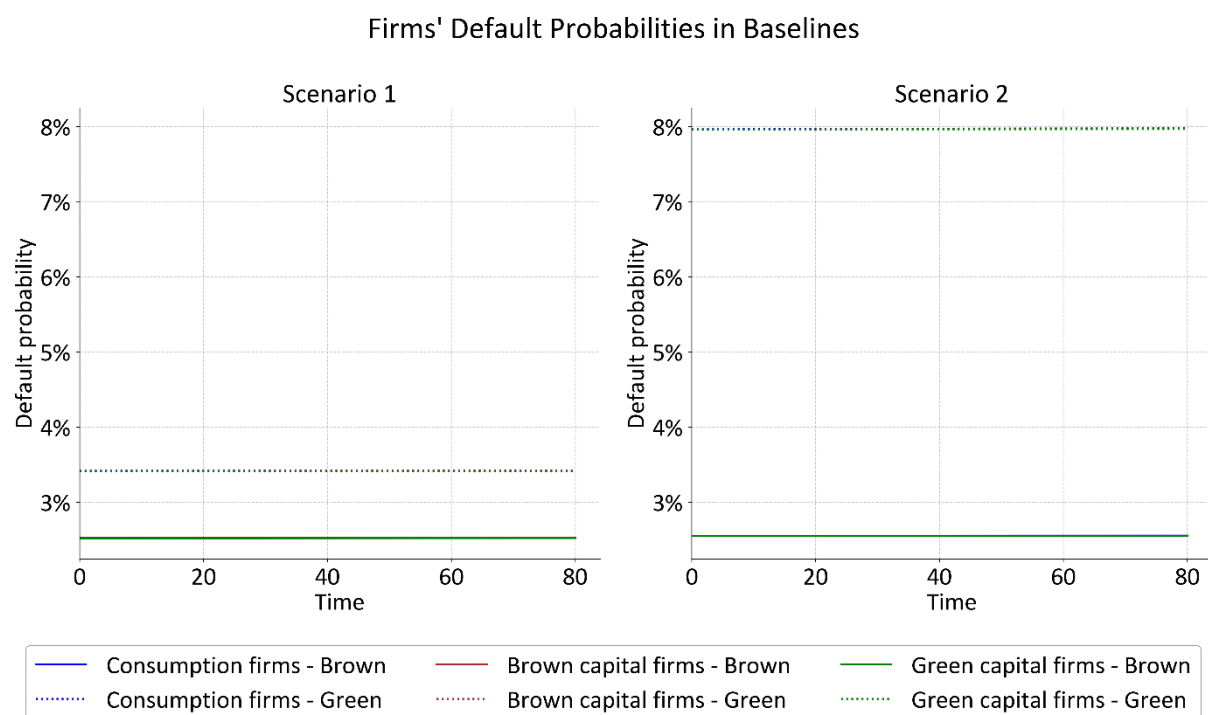


Figure 35: Average probability of defaults of firms in the two baselines.

The lower default rate in scenario 1 increases banks' capital adequacy (Figure 36), leading to lower lending interest rates compared to scenario 2 (Figure 37).

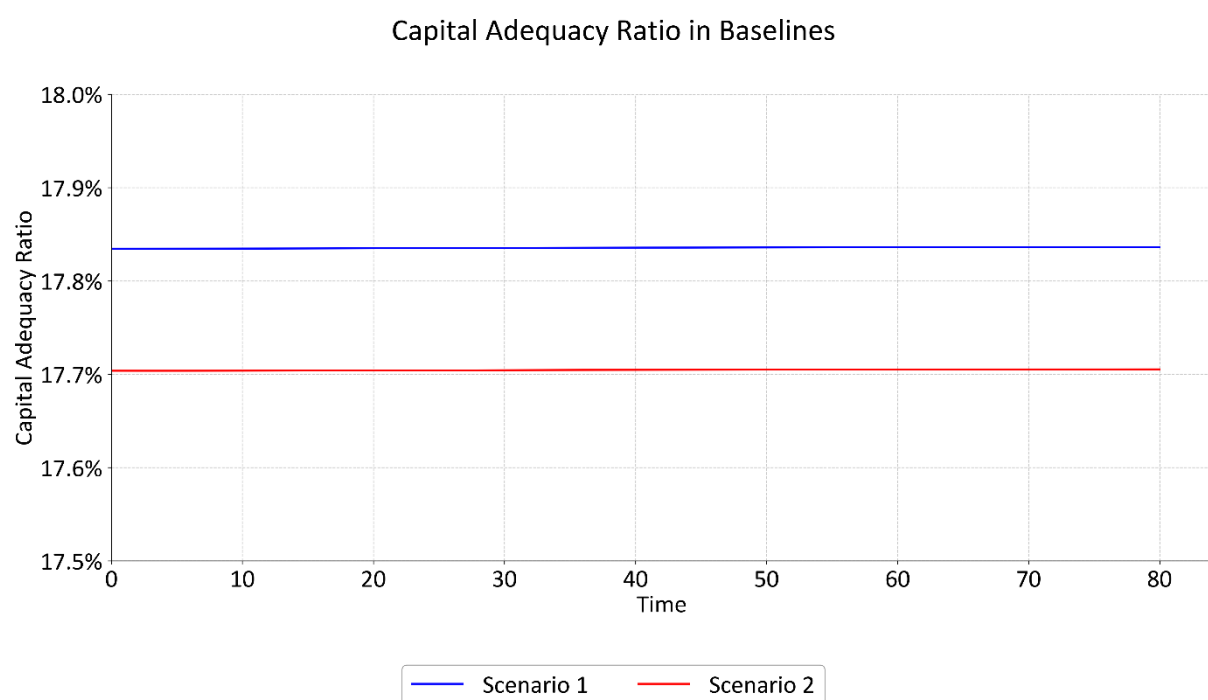


Figure 36: Banks' capital adequacy ratios in baselines.

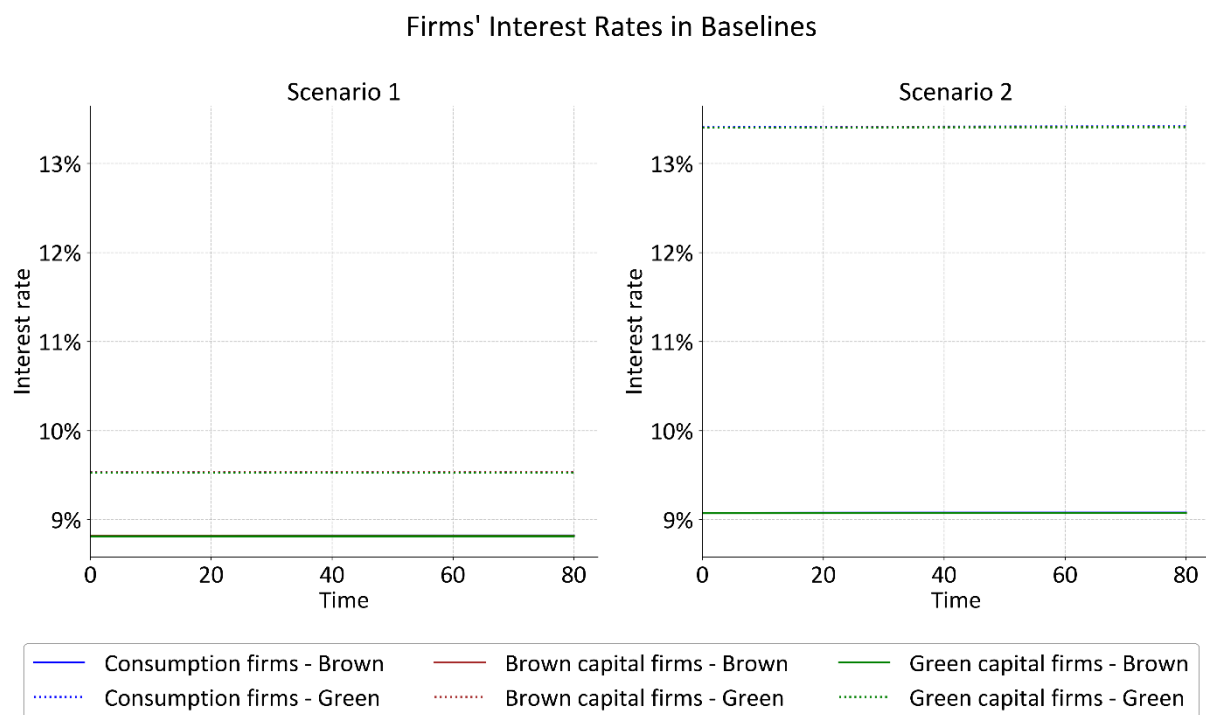


Figure 37: Interest rates on green and brown loans by firm type in baselines.

Lower financing costs and default probabilities lead to higher real GDP growth in scenario 1 compared to scenario 2 (Figure 38). This, in turn, positively affects other macroeconomic indicators, such as reducing the government debt-to-GDP ratio.

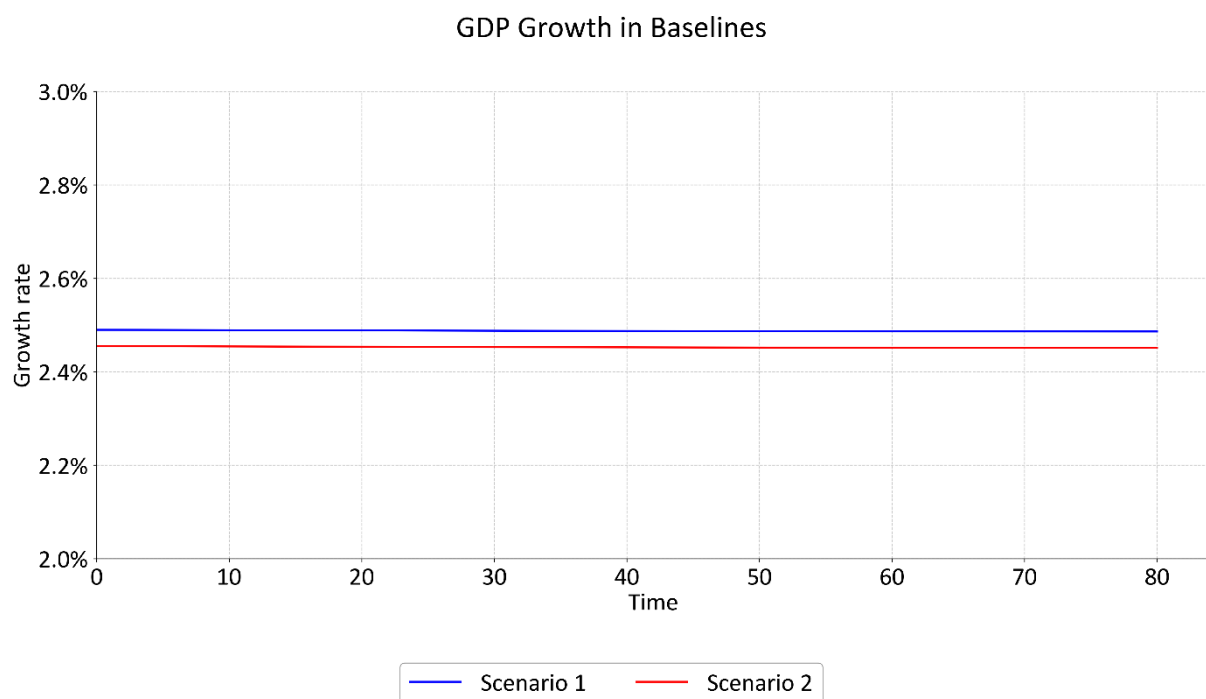


Figure 38: Real GDP growth in baselines.

Appendix 3 Sensitivity analyses

Appendix 3.1 Global sensitivity analysis

Given the high number of uncertain parameters in CIREF, we perform a global sensitivity analysis to identify the main drivers of the results. The sensitivity analysis is conducted on 32 selected parameters (Table 4). We generate 15,000 vectors of these parameters using Latin Hypercube Sampling and run the model in the absence of climate policy in scenario 1 until the calibration year. The range of variation for each parameter is constrained between -5% and +5% of its baseline value.

Table 4: Parameters for the global sensitivity analysis

Parameter	Description
τ^F	Consumption goods firms' profits tax rate
τ^B	Brown capital producers' profits tax rate
τ^G	Green capital producers' profits tax rate
τ^{Bk}	Banks' profits tax rate
γ_i	Adjustment factor of investment to the capacity utilization rate
π^H	Share of firms' profits going to households as distributed profits
π^{HBk}	Share of banks' profits going to households as distributed profits
π^{Gov}	Share of firms' profits going to the government as distributed profits
η	Share of firms' profits going to investment
$\mu_{b,1}$	Sensitivity of the share of bonds in firms' external finance needs relative to the bond interest rate
$\mu_{b,2}$	Sensitivity of the share of bonds in firms' external finance needs relative to the loan interest rate
τ^H	Households' tax rate
α_1	Propensity to consume out of disposable income
α_2	Propensity to consume out of wealth
α_3	Propensity to invest out of disposable income
α_4	Propensity to invest out of wealth
ζ^H	Share of households' investment target financed through loans
$\bar{G}$	Government running cost
κ_0^D	Capital adequacy ratio adjustment rate for deposit interest rate

κ_0^L	Capital adequacy ratio adjustment rate for loans interest rate
κ_1	Firms' sectoral interest rate adjustment rate related to green/brown defaults
κ_1^H	Households' interest rate adjustment rate
κ_2	Firms' sectoral interest rate adjustment rate related to firms' debt service ratio
v_{w1}	Sensitivity of nominal wage growth to past inflation
v_{w2}	Sensitivity of nominal wage growth to past growth
d^T	Target ratio of government deposits to government bonds
def_0	Parameter of the default rate function
def_1	Parameter of the default rate function
def_2	Parameter of the default rate function
$\lambda_0^{D^H}$	Autonomous demand of deposits in the portfolio allocation model of the financial wealth of households
λ_1^{AH}	Elasticity of the demand of AH relative to the interest rate on deposits in the portfolio allocation model of financial wealth of households ($AH = D^H, B^{H_{FG}}, B^{H_{FB}}, B^{H_{BG}}, B^{H_{BB}}, B^{H_{GG}}, B^{H_{GB}}$).
λ_2^{AH}	Elasticity of the demand of AH relative to the interest rate on brown bonds of consumption goods producers in the portfolio allocation model of financial wealth of households

After excluding runs that did not converge, we retain 9,132 parameter vectors, indicating that the model exhibits a certain degree of instability. We then correct for outliers by restricting the range of the main output values to those closer to the baseline, resulting in a final sample of 8,722 vectors (Table 5).

Table 5: Range of main outputs in the sensitivity analysis at calibration year

Variable	Minimal value	Calibration value	Maximal value
Nominal GDP	1E+13	9E+13	1E+15
CAR	15%	18%	21%
Average probability of firm loan defaults	1.6%	2.7%	5.3%
Government deficit in GDP	-0.3%	2%	7%

In future work, we need to increase the sample size and add some constraints to the Latin Hypercube Sampling, such as reaching a steady state close to the calibration, to have a large sample, allowing a more robust analysis.

We use an Optimal Transport-based sensitivity analysis to measure how much the output distribution changes when conditioning on a given input. This method computes the distance between the conditional distribution of the output given a fixed input and the unconditional distribution of the output. To do so, we use the R package *gsaot* developed by Chiani et al. (2025). This package has the advantage of offering a post-processing sensitivity analysis for a given input-output dataset. It allows us to compute entropic Optimal Transport-based sensitivity (OT) indices (Cuturi, 2013). These indices provide an ordinal measure of the sensitivity of outputs to a given input, but do not indicate the direction of this sensitivity. We present the results for the five parameters that have the greatest impact on each output (Figure 39). To obtain information on the direction of sensitivity, we compute Pearson correlation coefficients (Table 6).

The OT indices for nominal GDP are the highest for the sensitivity of nominal wage growth to past inflation and the default rate function parameter related to firms' illiquidity ratio, meaning that these parameters have the strongest impact on nominal GDP. However, the differences between the indices are relatively small, suggesting that no single input dominates.

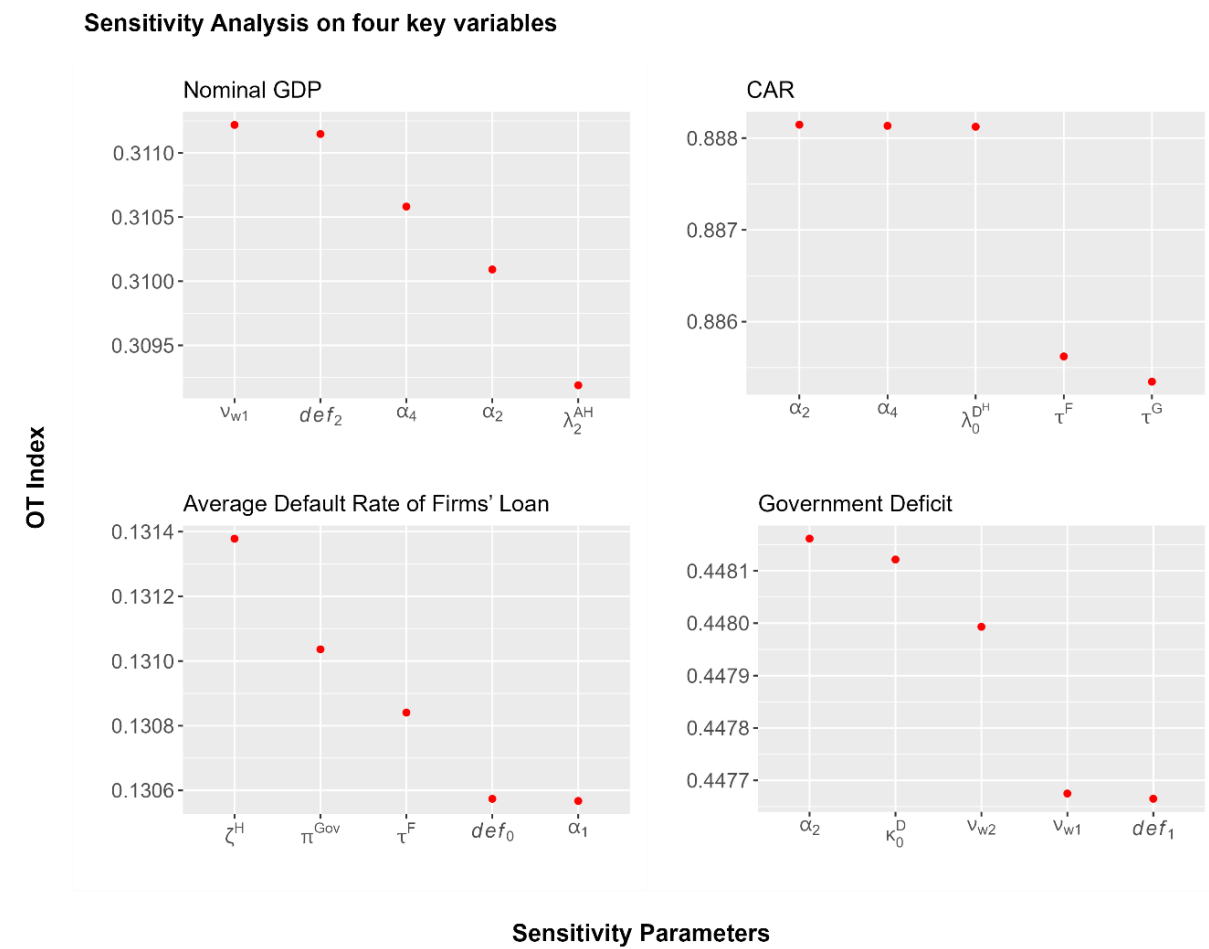


Figure 39: OT indices for the five parameters playing the most on four key variables.

The correlation coefficients for the sensitivity of nominal wage growth to past inflation and the default rate function parameter related to firms' illiquidity ratio are, respectively, positive and negative. Greater sensitivity of nominal wage growth to past inflation implies that an increase in inflation triggers a stronger rise in wages, boosting household consumption through higher disposable income. An increase in the default rate function parameter related to firms' illiquidity ratio raises the probability of defaults, adversely affecting banks, which may respond by raising interest rates, thereby reducing firms' profits and negatively affecting the economy.

Table 6: Correlation coefficients for the five parameters with the highest OT indices on four key variables.

Outputs	Inputs	Pearson Correlation
Nominal GDP	v_{w1}	0.019
	def_2	-0.024
	α_4	-0.006
	α_2	0.006
	λ_2^{AH}	-0.021
CAR	α_2	0.005
	α_4	-0.002
	λ_0^{DH}	0.004
	τ^F	-0.014
	τ^G	0.014
Average Default Rate of Firms' Loan	ζ^H	-0.022
	π^{Gov}	-0.014
	τ^F	0.013
	def_0	0.002
	α_1	-0.002
Government Deficit in GDP	α_2	0.001
	κ_0^D	0.018
	v_{w2}	0.005
	v_{w1}	-0.031
	def_1	-0.005

These results are preliminary. A larger sample is needed to draw robust conclusions about the impact of the parameters on model outcomes. Future research could perform a global sensitivity analysis of scenarios with climate policies. This would help us understand how model parameters influence the results of such policies.

Appendix 3.2 Change of scenarios variables values

To analyze the robustness of our results, we undertake a sensitivity analysis on the initial values of the variables used to construct scenario 2. We test lower (Case 1) and higher values (Case 2) for variables in scenario 2, and compare the results to the central case. This allows us to study the impact of lower/higher risks (and hence financing costs) on green investment on

modelling results. The sensitivity analysis presented in this paper is limited to a narrow range of values and future work should extend this analysis to a broader set of values.

Table 7: Initial variable shocks for sensitivity analysis in scenario 2

Scenario	Case 1	Central Case	Case 2
2	$\varphi_{0,0}^{n_G} = 5\%$ $\omega_0^G = 0.7$	$\varphi_{0,0}^{n_G} = 8\%$ $\omega_0^G = 1$	$\varphi_{0,0}^{n_G} = 12\%$ $\omega_0^G = 1.3$

With $\varphi_{0,0}^{n_G}$, the initial probability of defaults on firms' green loans calculated with the initial values of φ_0^{illiqn} , φ_{t-v}^V and φ_v^ϵ ; ω_0^G , the initial risk on green investment for firms.

First, we analyze the impact of the shock of the initial variables values on the baselines (Table 8). The increase of the probabilities of defaults on firms' green loans leads to higher interest rates on green and brown loans as banks' CAR decreases. This increase of financing costs has a negative macroeconomic impact (higher government deficit in GDP and lower GDP growth), and it reduces the stock of brown capital due to lower investment.

Table 8: Sensitivity analysis: effects of scenario variables shocks on selected outcomes in baseline in $t=0$.

Scenario 2 - Baseline	t = 0		
Variable	Case 1	Central Case	Case 2
Green capital share (%)	20	20	20
Government deficit in GDP (%)	2.3	2.4	2.6
Real GDP growth (%)	2.5	2.5	2.4
Stock of brown capital (trillion USD)	177	169	164
Average firms' default rate (%)	3.0	3.3	3.7
Capital adequacy ratio (%)	17.8	17.7	17.6
Brown loans interest rate for consumption goods firms (%)	8.9	9.1	9.2
Green loans interest rate for consumption goods firms (%)	11.0	13.4	16.6

Second, we examine how shocks to the initial values of scenario variables affect policy performance in scenario 2. To this end, we compare the differences in outcomes relative to their respective baselines across the sensitivity analysis cases (Table 9). Altering scenario parameters shows that the effectiveness of the policies decreases across all cases when green investment risks rise, except for green mandates. These changes also modify policies' economic and financial impacts.

In the case of the carbon tax, higher green investment risks raise financing costs, while stronger risk perceptions by firms reduce their willingness to invest in green capital (Table 8). Consequently, the share of green capital increases less when risks increase, and it even stays constant in case 2 (Table 9). In case 1, the carbon tax has a positive impact on the economy compared to the baseline as the transition allows for a reduction in financing costs (lower green and brown loan interest rates). It increases the CAR of banks by reducing the average

firms' default rate compared to the baseline. In the central case, firms' start to redirect their investment towards green capital at the end of the simulation period, so the financing costs do not have time to decrease. In fact, financing costs increase relative to the baseline, driven by higher default rates resulting from reduced firms' profits under the carbon tax. Higher defaults conducts to a decrease of banks' financial stability compared to the baseline (lower CAR). The carbon tax still has a positive impact on GDP growth compared to the baseline in the central case, as it increases government fiscal revenues (lower government deficit in GDP), leading to higher consumption and investment. But this positive effect on growth is smaller than in case 1, as financing costs increase in the central case (higher green and brown loans interest rates). In case 2, the carbon tax fails to initiate the transition, so financing costs remain high and even increase due to lower firms' profits compared to the baseline. On average, financing costs increase less than in the central case, where defaults rates increase more as firms start to invest in risky green capital. Consequently, the decrease of the CAR is smaller in case 2 than in the central case. In case 2, the increase of government revenues from carbon taxation leads to higher investment and consumption, fostering higher GDP growth compared to the baseline. GDP growth is stronger than in the central case because the increase of government revenues is stronger in case 2 as firms' do not start to invest in green capital, and hence pay higher carbon taxes. The stock of brown capital decreases more in case 1, as the transition occurs, than in other cases. Brown capital stock increases in case 2 due to higher GDP growth compared to the baseline and the absence of transition towards green capital investment.

Green mandates allow to reach the transition target in all scenarios independently of financings costs and risk (Table 9). The higher the risk, the stronger the positive impact on the economy compared to baselines, as mandates indirectly decrease higher financing costs over time. Besides, the decrease of higher defaults has a stronger positive impact on the CAR. As financing costs are higher in case 2, the increase of GDP growth compared to the baseline is stronger than in the other cases. However, in the short run, mandates conduct to a stronger increase in defaults rate in case 2 than in other cases, as green investment increases more (higher GDP growth) and is subject to higher probabilities of defaults in the short run. This leads to a stronger increase of government deficit in GDP in case 2 than in the other cases in the short run. In the long run, the stock of brown capital decreases less in case 2 than in other cases, as higher GDP growth leads to a stronger increase in total investment, and so, in brown capital investment.

When risks are sufficiently low, guarantees allow to foster the transition (case 1, Table 9). However, higher risks conduct the guarantees to not have any effect on the share of green capital in the economy as firms' perception of risk on green capital is too high (central case and case 2). By reducing financing costs, the guarantee has a positive effect on GDP growth but it increases government deficit in GDP. The increase in GDP growth is stronger in case 1 than in other cases, because the increase of the share of green capital in the economy leads to an increase of green loans, which are subject to lower interest rates. Besides, thanks to

learning effects, the average rate of defaults in firms decreases more in case 1 than in the other cases. Hence, banks' capital adequacy ratio increases more than in the central case. The guarantee has a stronger positive impact on GDP growth in case 2 compared to the central case, because it allows a stronger reduction in financing costs, as financing costs are higher in case 2 than in the central case (Table 8). The CAR increases more in case 2 than in the central case as the guarantee allows a stronger reduction of defaults rate for banks as they are initially higher in case 2 (Table 8). The stock of brown capital decreases compared to the baseline in case 1 thanks to the transition. In the central case and in case 2, it increases compared to their baselines as the guarantee does not activate the transition and leads to stronger GDP growth.

Green public expenditure is more effective, the lower the investment risks (Table 9). The share of green capital increases slightly more in case 1 than in the central case or case 2. Firms are more willing to invest in green capital in case 1 (lower risk and financing costs) than in the other cases. Consequently, when the government starts to invest more in green capital, they follow the trend more rapidly, leading to faster learning effects. Green public expenditure leads to lower green loans interest rates thanks to learning effects, and to higher brown loans interest rates due to a lower CAR over time. Indeed, the rise of investment increases the amount of loans, decreasing the CAR. The default rate and the green lending interest rate decrease less in case 1 than in other cases as they are initially lower²⁸ (Table 8). Case 1 experiences the largest decline in CAR, reflecting its initially higher level compared to the other cases. As financing costs decrease less, the increase in GDP growth is lower in case 1 and the increase in government deficit in GDP is higher in case 1 than in the other cases. The stock of brown capital increases more in the central case and in case 2 compared to their baselines, as higher growth favors higher total investment than in case 1.

Table 9: Sensitivity analysis: difference between policy and baseline outcomes for scenario variables shocks in t=40 and in t=80.

Scenario 2		t = 40			t = 80		
Variable	Policy	Case 1	Central Case	Case 2	Case 1	Central Case	Case 2
Green capital share (ppt)	Carbon tax	1	0	0	44	3	0
	Green mandates	18	18	18	60	60	60
	Guarantees	13	0	0	42	0	0
	Green public expenditure	20	18	18	59	57	55
Government deficit in GDP (ppt)	Carbon tax	-0.25	-0.26	-0.26	-0.32	-0.29	-0.45
	Green mandates	0.04	0.08	0.11	-0.24	-0.4	-0.52
	Guarantees	1.33	0.85	1	1.51	0.88	1.04

²⁸ For example, the initial rate of green loan default in case 1 is lower than in the central case, so, when the transition occurs, the rate of green loan default in case 1 decreases less than in the central case to reach the rate of default on brown loans.

	Green public expenditure	0.66	0.56	0.48	4.18	4	3.88
Real GDP growth (ppt)	Carbon tax	0.03	0.03	0.03	0.07	0.01	0.06
	Green mandates	0.04	0.07	0.1	0.02	0.04	0.06
	Guarantees	0.32	0.23	0.26	0.47	0.23	0.26
	Green public expenditure	1.15	1.18	1.2	4.84	4.86	4.87
Stock of brown capital (% change)	Carbon tax	-0.54	0.45	0.45	-54.8	-2.39	2.23
	Green mandates	-22.32	-22.47	-22.6	-74.7	-74.5	-74.37
	Guarantees	-10.99	5.76	6.67	-43.17	15.23	17.79
	Green public expenditure	-21.12	-18.35	-18.23	0.01	9.52	17.54
Average firms' default rate (ppt)	Carbon tax	0.1	0.08	0.08	-0.29	0.44	0.17
	Green mandates	0.08	0.13	0.19	-0.45	-0.82	-1.16
	Guarantees	0.03	-0.2	-0.24	-0.64	-0.2	-0.24
	Green public expenditure	-0.33	-0.57	-0.77	-0.92	-1.29	-1.63
Capital adequacy ratio (ppt)	Carbon tax	-0.03	-0.02	-0.02	0.11	-0.08	-0.03
	Green mandates	0.05	0.1	0.15	0.09	0.16	0.23
	Guarantees	-0.02	0.03	0.05	0.04	0.02	0.04
	Green public expenditure	-0.01	0.06	0.13	-0.61	-0.54	-0.47
Brown loans interest rate for consumption goods firms (ppt)	Carbon tax	0.09	0.09	0.09	-0.15	0.26	0.16
	Green mandates	-0.05	-0.13	-0.19	-0.19	-0.33	-0.46
	Guarantees	-0.21	-0.29	-0.37	-0.4	-0.28	-0.36
	Green public expenditure	-0.11	-0.24	-0.36	0.32	0.18	0.04
Green loans interest rate for consumption goods firms (ppt)	Carbon tax	0.15	0.21	0.3	-2.11	0.5	0.6
	Green mandates	-0.87	-2.06	-3.83	-2.22	-4.67	-7.87
	Guarantees	-4.25	-6.39	-9.22	-4.52	-6.36	-9.18
	Green public expenditure	-1.38	-3.01	-5.41	-1.71	-4.16	-7.37

Appendix 4 Model documentation

In this documentation, lowercase letters represent volumes, while uppercase letters denote nominal values. The model CIREF is fully recursive (following Dafermos & Nikolaidi, 2022). In the following equations, subscripts F , B , G , H , Bk , CB and Gov are used to denote consumption goods firms, brown capital firms, green capital firms, households, banks, the central bank, and the government, respectively.

Appendix 4.1 Model equations

Appendix 4.1.1 Firms

Total production of firms:

$$Y_t = Y_t^F + Y_t^G + Y_t^B \quad (33)$$

Total investment:

$$I_t = I_t^F + I_t^G + I_t^B + I_t^H + I_t^{Gov} \quad (34)$$

The production of consumption goods firms is equal to the demand of households and the government:

$$Y_t^F = C_t^H + C_t^{Gov} \quad (35)$$

The production of green firms is equal to the demand for green capital. Firms, households, and the government can invest in the two types of capital, green and brown:

$$Y_t^G = \phi_t^{BG} I_t^B + \phi_t^{GG} I_t^G + \phi_t^{FG} I_t^F + \phi_t^{GovG} I_t^{Gov} + \phi_t^{HG} I_t^H \quad (36)$$

where ϕ_t^{BG} , ϕ_t^{GG} , ϕ_t^{FG} , ϕ_t^{GovG} and ϕ_t^{HG} are respectively the shares of green investment in total investment of brown firms, green firms, consumption goods firms, the government, and households. They are determined through a portfolio allocation model for each type of agent (see (1), (6), (136)).

Production of brown firms:

$$Y_t^B = \phi_t^{BB} I_t^B + \phi_t^{GB} I_t^G + \phi_t^{FB} I_t^F + \phi_t^{GovB} I_t^{Gov} + \phi_t^{HB} I_t^H \quad (37)$$

where ϕ_t^{BB} , ϕ_t^{GB} , ϕ_t^{FB} , ϕ_t^{GovB} and ϕ_t^{HB} are respectively the shares of brown investment in total investment of brown firms, green firms, consumption goods firms, the government, and households.

The shares of brown and green capital investment are determined through a portfolio allocation choice model²⁹ for each types of firm (1). In their investment decisions, firms consider the user cost of capital, the perceived risks associated with each type of investment (ω^B and ω^G), and the productivity of each type of capital (ϵ_t^B and ϵ_t^G). The user cost of capital is the cost borne by the firm for the utilization of capital assets. It is equal to the sum of the unit cost of buying capital (prices: p_t^B and p_t^G); the financing cost of capital, approximated here with the interest rates on loans (r_t^{nB} and r_t^{nG}) and bonds ($r_{b,t}^{nB}$ and $r_{b,t}^{nG}$) multiplied by their

²⁹ Tobin's asset-allocation model (Tobin, 1969) has become a standard component in SFC models (Kemp-Benedict & Godin, 2017). It relates financial asset returns to wealth allocation: if an asset offers a higher return compared to other assets, more wealth is allocated to it. Here, we follow Dunz et al. (2021) and apply it to firms' investment allocation.

shares in external financial needs ($\sigma_{L,t}^{nB}$ and $\sigma_{L,t}^{nG}$, the shares of external financial needs covered by brown and green loans respectively); and the unit cost of capital depreciation (depreciation rates: δ^B and δ^G). In this modelling exercise, depreciation rates are assumed to be identical across capital types, so they do not affect firms' investment decisions. Likewise, initial prices are also set equal for simplification. Moreover, in the case where a carbon tax policy is implemented, the carbon tax will increase the cost of using brown capital to produce, so firms take this into account by considering the ratio between the cost of producing with brown capital and the cost of producing with green capital. The estimated cost of producing with brown capital is equal to sum of the unit cost of labor (UC_{t-1}^n) and the unit cost of carbon taxation, whereas, the cost of producing with green capital is simply the unit cost of labor (UC_{t-1}^n). Note that the unit cost of carbon taxation consider the amount of carbon tax paid by the firm on its brown capital that the firm does not translate in higher consumer prices ($CT_{t-1}^n - \kappa_{CT}CT_{t-1}^n$). In the case where a green mandate is implemented, the share of brown capital is equal to the minimum between the one computed with the portfolio allocation model and the one allowing to comply with the regulation ($1 - \overline{\phi_t^{LG}}$).

For a given type of capital, the coefficients λ associated with its own user cost and risk are negative and the one associated with its own productivity is positive. Instead, the coefficients associated with the user cost and risk of the other type of capital are positive, and the one associated with the productivity of the other type of capital are negative.

The share of brown capital investment in total investment of firms $n = B, G, F$ is given by:

$$\begin{aligned} \phi_t^{nB} = \min \bigg(& \lambda_{0,t}^B + \lambda_1^B p_{t-1}^B + \lambda_2^B p_{t-1}^G + \lambda_3^B (\sigma_{L,t-1}^{nB} r_{t-1}^{nB} + (1 - \sigma_{L,t-1}^{nB}) r_{b,t-1}^{nB}) \\ & + \lambda_4^B (\sigma_{L,t-1}^{nG} r_{t-1}^{nG} + (1 - \sigma_{L,t-1}^{nG}) r_{b,t-1}^{nG}) + \lambda_5^B \delta^B + \lambda_6^B \delta^G + \lambda_7^B \omega^B + \lambda_8^B \omega_t^G \\ & + \lambda_9^B \epsilon_{t-1}^B + \lambda_{10}^B \epsilon_{t-1}^G + \lambda_{11}^B \left(UC_{t-1}^n + \frac{CT_{t-1}^n - \kappa_{CT}CT_{t-1}^n}{Y_{t-1}^n} \right) \\ & + \lambda_{12}^B UC_{t-1}^n; (1 - \overline{\phi_t^{LG}}) \bigg) \end{aligned} \quad (38)$$

with $\lambda_{0,t}^B$ the autonomous brown capital demand, λ_1^B the elasticity of the investment in brown capital relative to the price of brown capital (negative), λ_2^B the elasticity of the investment in brown capital relative to the price of green capital (positive), λ_3^B the elasticity of the investment in brown capital relative to the financing cost of brown capital (negative), λ_4^B the elasticity of the investment in brown capital relative to the financing cost of green capital (positive), λ_5^B the elasticity of the investment in brown capital relative to the depreciation rate of brown capital (negative), λ_6^B the elasticity of the investment in brown capital relative to the depreciation rate of green capital (positive), λ_7^B the elasticity of the investment in brown capital relative to the risk on brown capital investment (negative), λ_8^B the elasticity of the investment in brown capital relative to the risk on green capital investment (positive), λ_9^B the elasticity of the investment in brown capital relative to brown capital productivity (positive), λ_{10}^B the elasticity of the

investment in brown capital relative to green capital productivity (negative), λ_{11}^B the elasticity of the investment in brown capital relative to the unit production cost when using brown capital (negative), and λ_{12}^B the elasticity of the investment in brown capital relative to the unit production cost when using green capital (positive).

The share of green investment in total investment of firms is the opposite of the share of brown investment:

$$\phi_t^{n_G} = 1 - \phi_t^{n_B} \quad (39)$$

We make the assumption that the economy still needs a minimum amount of green/brown capital before/after the transition, such that the share of green/brown investment is bounded between ϕ_{MIN}^Z and ϕ_{MAX}^Z .

The autonomous brown capital demand, $\lambda_{0,t}^B$, depends on the evolution of brown capital in total capital in the economy. This reflects that firms adapt to the context in which they operate. However, it adjusts gradually to reflect path dependency. Indeed, firms' investment decision is path dependent due to technological, institutional, and behavioral lock-in effects (Kotilainen et al., 2019).

$$\lambda_{0,t}^B = \lambda_{0,t-1}^B + \kappa_I (sh_{t-1}^{k_B} - sh_{t-2}^{k_B}) \quad (40)$$

with $sh_{t-1}^{k_B}$ the share of brown capital in the economy and κ_I the sensitivity of the autonomous brown capital demand to changes in $sh_{t-1}^{k_B}$.

The share of green capital in the economy is the sum of the green capital held by all agents divided by the sum of all the capital held by all agents:

$$sh_t^{k_G} = \frac{k_t^{FG} + k_t^{BG} + k_t^{GG} + k_t^{HG} + k_t^{GovG}}{k_t^F + k_t^B + k_t^G + k_t^H + k_t^{Gov}} \quad (41)$$

Share of brown capital in the economy:

$$sh_t^{k_B} = 1 - sh_t^{k_G} \quad (42)$$

The perception of risks on green capital by firms ω_t^G is a logistic function of the share of green capital in the economy (Figure 40)³⁰. The assumption is that as the share of green capital in the economy grows, the socio-technical system (regulatory frameworks, infrastructures, workforce skills, etc.) evolves, becoming increasingly aligned with green capital production (Negro et al., 2012; Söderholm, 2020). Moreover, firms develop experience to produce green capital, so the risk decreases as the transition occurs³¹. Pan & Köhler (2007) argue that learning

³⁰ Firms do not consider the probability of defaults in their perception of risk, as they do not observe these probabilities of defaults compared to banks.

³¹ Note that we do not consider the impact of unsuccessful commercial precedents in our modelling exercise. However, unsuccessful commercial precedents might have a negative impact on firms' green investment decisions in the short run.

curves follow an S-shape due to the lifecycle of technologies, which go through various phases from laboratory-invention, to explosive take-off, continued high growth, slowdown, and maturity. Similarly, according to Rogers (2010), the adoption of a technology follows an S-shape as the diffusion of the technology increases information and reduces uncertainty.

$$\omega_t^G = \begin{cases} \omega_0^G, & \text{if } sh_{t-1}^{k_G} \leq sh_{MIN}^{k_G} \\ \omega_B + \frac{\omega_0^G - \omega_B}{1 + \exp\left(\text{par}_f(sh_{t-1}^{k_G} - \text{par}_g)\right)}, & \text{if } sh_{MIN}^{k_G} < sh_{t-1}^{k_G} < sh_{MID}^{k_G} \\ \omega_B, & \text{if } sh_{t-1}^{k_G} \geq sh_{MID}^{k_G} \end{cases} \quad (43)$$

with ω_0^G the initial level of risk of investing in green capital; ω_B the risk of investing in brown capital; $sh_{MIN}^{k_G}$ the threshold of the share of green capital in the economy above which the risk on green capital starts to decrease; $sh_{MID}^{k_G}$ the threshold of the share of green capital in the economy above which the risk on green capital becomes equal to the risk on brown capital; par_f controls the speed of the decrease; par_g is the midpoint (value of the share of green capital for which the decrease of the risk is the most significant). We adopt the conservative assumption that the risk associated with brown investment remains constant and does not increase during the transition.

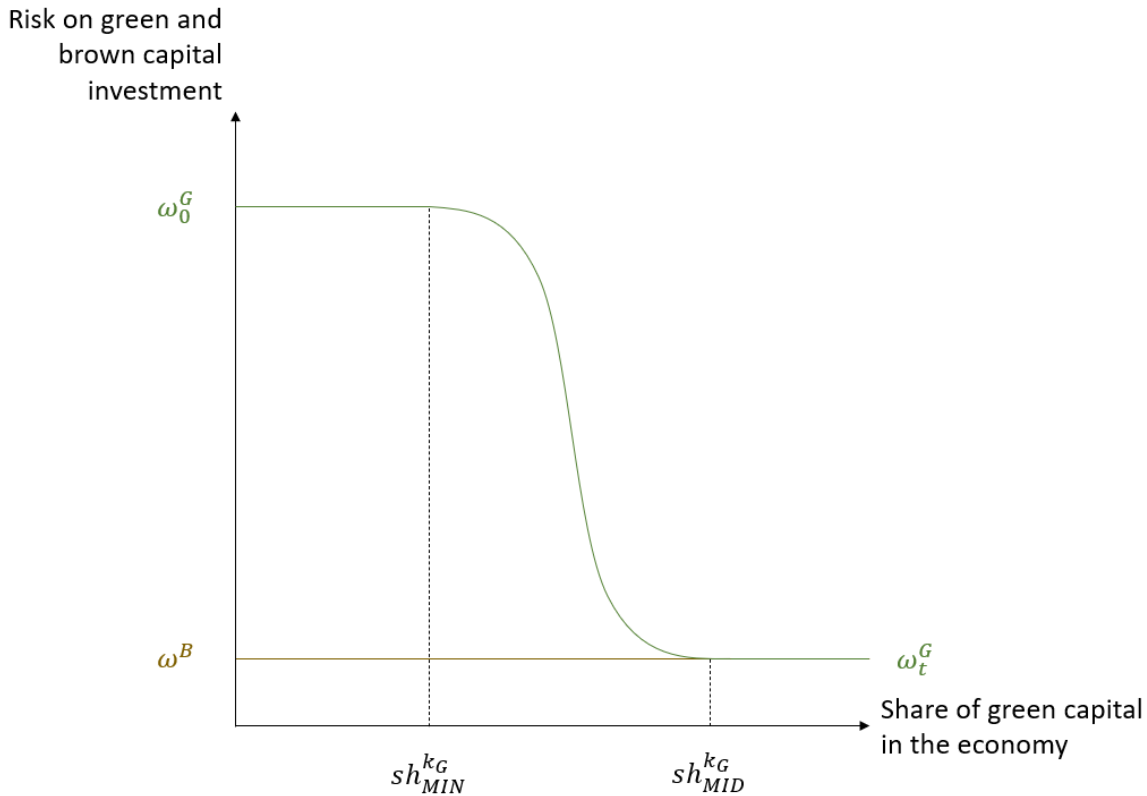


Figure 40: Evolution of perceived risks on green and brown capital investment for firms

The productivity of green capital is a logistic function of the share of green capital in the economy (Figure 41). The higher the share, the more it tends towards its maximal productivity (equals to the initial productivity of brown capital).

$$\epsilon_t^G = \begin{cases} \epsilon_0^G, & \text{if } sh_{t-1}^{k_G} \leq sh_{MIN}^{k_G} \\ \epsilon_0^B + \frac{\epsilon_0^B - \epsilon_0^G}{1 + \exp(par_a(sh_{t-1}^{k_G} - par_b))}, & \text{if } sh_{MIN}^{k_G} < sh_{t-1}^{k_G} < sh_{MAX}^{k_G} \\ \epsilon_0^B, & \text{if } sh_{t-1}^{k_G} \geq sh_{MAX}^{k_G} \end{cases} \quad (44)$$

with ϵ_0^B , the initial level of brown capital productivity, ϵ_0^G , the initial level of green capital productivity, and $sh_{MAX}^{k_G}$, the maximum value of the share of green capital in the economy at which green capital productivity becomes equal to its maximum value.

The productivity of brown capital varies in the opposite direction to green capital productivity. The assumption is that as the share of green capital in the economy grows, the socio-technical system (regulatory frameworks, infrastructures, workforce skills, etc.) evolves, becoming increasingly aligned with green capital production (Negro et al., 2012; Söderholm, 2020).

$$\epsilon_t^B = \begin{cases} \epsilon_0^B, & \text{if } sh_{t-1}^{k_G} \leq sh_{MIN}^{k_G} \\ \epsilon_0^B + \frac{\epsilon_0^B - \epsilon_0^G}{1 + \exp(-par_a(sh_{t-1}^{k_G} - par_b))}, & \text{if } sh_{MIN}^{k_G} < sh_{t-1}^{k_G} < sh_{MAX}^{k_G} \\ \epsilon_0^G, & \text{if } sh_{t-1}^{k_G} \geq sh_{MAX}^{k_G} \end{cases} \quad (45)$$

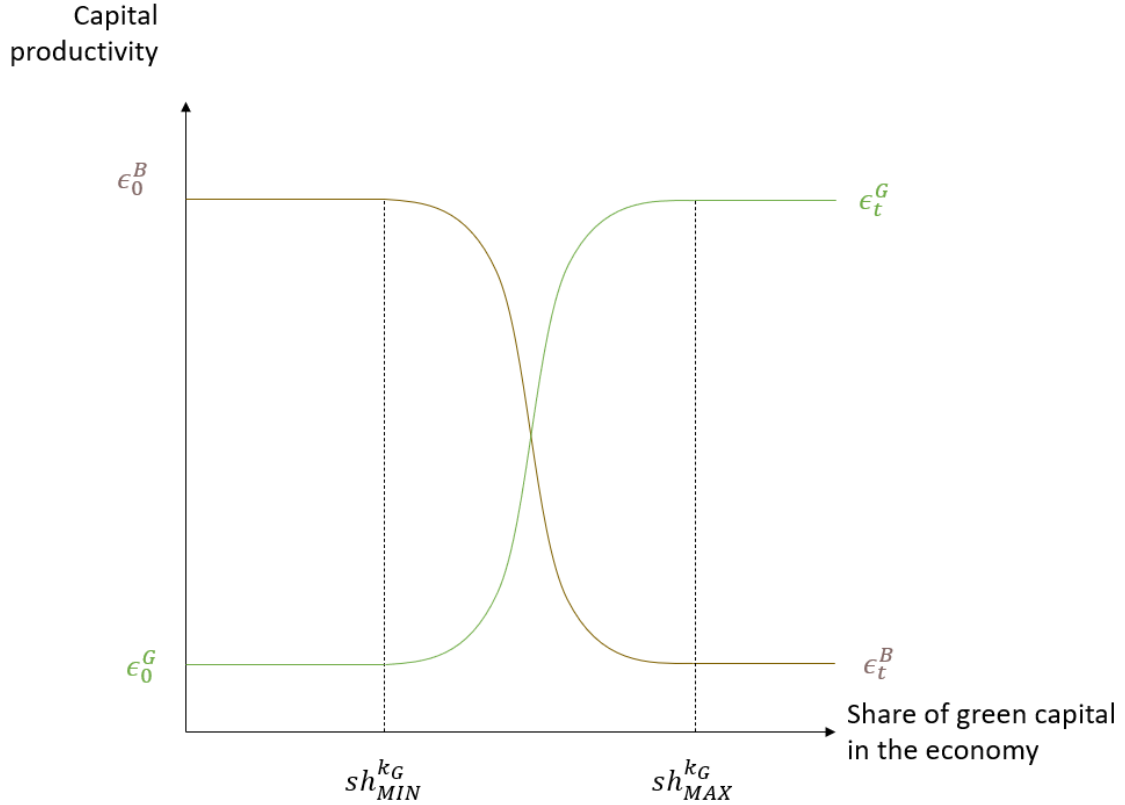


Figure 41: Evolution of green and brown capital productivities depending on the share of green capital in the economy

In case of the modelling of a green mandate, the allocation of firms', households' and government' investment depend on the share of green capital allowing to follow the regulation. If the allocation of investment towards green investment from the Tobin allocation model is smaller than the regulation, the share of green capital investment will be equal to $\overline{\phi}_t^{LG}$. Similarly, as long as the allocation of brown capital is higher than the regulation, the share of brown capital is equal to $(1 - \overline{\phi}_t^{LG})$. The share of green capital allowing to follow the regulation evolves through time at a constant rate $g_{\overline{\phi}^G}$ (hypothesis that the regulation will directly impact the investment linearly without time effect):

$$\overline{\phi}_t^G = \begin{cases} \overline{\phi}_t^G = \overline{\phi}_{t-1}^G + g_{\overline{\phi}^G}, & \text{if } \phi_{t-1}^{n_G} < \phi_{MAX}^{n_G} \\ \overline{\phi}_t^G = \overline{\phi}_{t-1}^G, & \text{if } \phi_{t-1}^{n_G} \geq \phi_{MAX}^{n_G} \end{cases} \quad (46)$$

with ϕ_{MAX}^G the maximum share of green capital investment³².

We then apply a logistic function to the share of green capital to limit the shocks when the share of green capital investment approaches its maximum value ϕ_{MAX}^G . It is this share of green capital which is used in the Tobin allocation model.

$$\overline{\phi}_t^{LG} = \phi_{MIN}^G + \frac{\phi_{MAX}^G - \phi_{MIN}^G}{1 + \exp(-par_j(\phi_t^G - par_k))} \quad (47)$$

with ϕ_{MAX}^G the maximum share of green capital investment; ϕ_{MIN}^G the minimum share of green investment; par_j the steepness of the approximated logistic function ; par_k the midpoint of the approximated logistic function.

The demand for inputs is given by a Leontief production function (note that this equation is not used in the code because the demand determines the production):

$$y_t^n = \text{Min}[N_t^n, k_t^n], n = B, G, F \quad (48)$$

where N_t^n and k_t^n are the labor (in working hours) and capital services that are lent by the firms.

Wage bill:

$$WB_t^n = w_t \frac{y_t^n}{\epsilon_t^N} \quad (49)$$

with w_t the wage rate, ϵ_t^N the labor productivity, and y_t^n the real output produced by firms n , as $y_t^n = \epsilon_t^N N_t^n$.

³² We assume that the economy still needs a minimum amount of brown capital after the transition such that the share of green/brown investment is bounded between ϕ_{MIN}^Z and ϕ_{MAX}^Z .

The labor productivity depends on past real output growth. This reflects the Kaldor-Verdoorn law: as production increases, firms tend to be more efficient (organization improvements, learning-by-doing, etc.), leading to labor productivity growth:

$$\epsilon_t^N = \epsilon_{t-1}^N (1 + v_\epsilon g_{y,t-1}) \quad (50)$$

with v_ϵ a parameter reflecting the sensitivity of productivity growth to real output growth.

Real output growth rate:

$$g_{y,t} = \frac{y_t - y_{t-1}}{y_{t-1}} \quad (51)$$

where $y_t = \frac{Y_t^G}{p_t^G} + \frac{Y_t^B}{p_t^B} + \frac{Y_t^F}{p_t^F}$.

The labor market is competitive with homogenous skills, such that the nominal wage rate is the same for all activities. Its growth depends on past inflation and output growth to mimic an expectation-augmented Phillips curve:

$$w_t = w_{t-1} (1 + v_{w1} g_{p_y,t-1} + v_{w2} g_{y,t-1}) \quad (52)$$

with v_{w1} the sensitivity of nominal wage growth to past inflation, and v_{w2} the sensitivity of nominal wage growth to past growth.

Inflation growth rate:

$$g_{p_y,t} = \frac{p_{y,t} - p_{y,t-1}}{p_{y,t-1}} \quad (53)$$

where $p_{y,t}$ is the average price of output in the economy at period t .

Average price of output:

$$p_{y,t} = \frac{Y_t}{y_t} \quad (54)$$

Price index used to compute real values (General Price Index):

$$GPI_t = \frac{p_t}{p_0} \quad (55)$$

The unit production cost at the firm level only depends on the cost of labor, as the cost of capital is financed with the firm's profits:

$$UC_t^n = \frac{w_t}{\epsilon_t^N} \quad (56)$$

Consumer prices depend on the unit production cost and the markup θ_t^n . Firms translate the increase in labor costs fully to consumers (100% pass-through). However, the markup allows firms to consider not only labor costs when fixing their prices. Indeed, prices are strategically

determined in the interests of the long-term growth and survival of firms (Shapiro & Sawyer, 2003).

$$p_t^n = UC_t^n(1 + \theta_t^n) \quad (57)$$

In our case, firms translate a part of the financing cost of capital and the profits' tax on consumer prices through a constant markup $\bar{\theta}$. In the case of the implementation of a carbon tax, firms translate a part of their increase in production cost due to the carbon tax to consumers by increasing their markup (we use the amount of carbon tax paid in the previous period for computational issues):

$$\theta_t^n = \bar{\theta} + \kappa_{CT} \frac{CT_{t-1}^n}{Y_{t-1}^n} \quad (58)$$

with κ_{CT} the sensitivity of the markup to carbon tax costs.

Capital cost of green capital for each type of firm:

$$KB_t^{nG} = Int_t^{nG} + c_{b,t-1}^{nG} b_{t-1}^{H_{nG}} \quad (59)$$

We assume that at the beginning of the period, firms pay interests Int_t^m to banks on the loan stock of the previous period, which is already decreased by the previous repayments and defaults, and firms pay interests to households on corporate bonds $c_{b,t-1}^m b_{t-1}^{H_m}$ ($m = B_G, B_B, G_G, G_B, F_G, F_B$).

Capital cost of brown capital for each type of firm:

$$KB_t^{nB} = Int_t^{nB} + c_{b,t-1}^{nB} b_{t-1}^{H_{nB}} \quad (60)$$

The interest payments from firms perceived by banks at period t are equal to the sum of all interest payments on loans at period t ($m = B_G, B_B, G_G, G_B, F_G, F_B$):

$$Int_t^m = \sum_{v=0}^{t-1} r_v^m L_{v,t-1}^m \quad (61)$$

where r_v^m is the interest rate at the time when the loan is contracted, and $L_{v,t-1}^m$ is the stock of the loan contracted at period v at the end of the previous period (86).

Capital bill at the firm level:

$$KB_t^n = KB_t^{nG} + KB_t^{nB} \quad (62)$$

Firms pay a carbon tax on their production depending on their share of brown capital in total capital used for production. The carbon tax is paid with firms' profits (20).

$$CT_t^n = \tau_t^{CT} Y_t^n \frac{K_t^{nB}}{K_t^n} \quad (63)$$

The carbon tax rate τ_t^{CT} increases over time, depending on a constant growth rate g_τ^{CT} and the difference between the targeted share of green capital and the actual share of green capital in the economy, such as the rate of carbon tax decreases when the economy approaches the targeted share of green capital:

$$\tau_t^{CT} = \tau_{t-1}^{CT} \left(1 + g_\tau^{CT} (\overline{sh}^{k_G} - sh_t^{k_G}) \right) \quad (64)$$

The profits net of taxes of firms n (they do not take into account the depreciation of capital):

$$\Pi_t^n = Y_t^n - WB_t^n - KB_t^n + r_{t-1}^D D_{t-1}^n - T_t^n - CT_t^n \quad (65)$$

Tax on firms' profits:

$$T_t^n = (Y_t^n - WB_t^n - KB_t^n + r_{t-1}^D D_{t-1}^n) \tau_t^n \quad (66)$$

Distributed profits to households and government (state-owned enterprises) are a constant share of profits:

$$DP_t^n = \pi^H \Pi_t^n + \pi^{Gov} \Pi_t^n \quad (67)$$

Retained profits:

$$RP_t^n = (1 - \pi^H - \pi^{Gov}) \Pi_t^n \quad (68)$$

Firms use their retained profits to meet their loan principal repayments:

$$REP_t^n = REP_t^{nG} + REP_t^{nB} \quad (69)$$

with REP_t^{nG} and REP_t^{nB} defined below.

The share of retained profits used for investment is equal to a share of the retained profits minus loan repayments:

$$\eta(RP_t^n - REP_t^n) \quad (70)$$

The rest goes to firms' deposits:

$$D_t^n = D_{t-1}^n + (1 - \eta)(RP_t^n - REP_t^n) \quad (71)$$

Capital stock in firms:

$$k_t^n = k_{t-1}^n (1 - \delta) + i_t^n \quad (72)$$

with $k_t^n = k_t^{nG} + k_t^{nB}$, reflecting that each firm possesses the two types of capital.

Investment in firms depends on the depreciation of capital, and on the difference between the previous period capacity utilization rate u_{t-1}^n and the targeted capacity utilization rate $\bar{u}$. This allows investment to decrease when firms are in a situation of under-utilization of capacities (the production is lower than the potential), and to increase when firms are in a situation of over-utilization of capacities (the production is higher than the potential).

$$i_t^n = \text{MAX}(0, \gamma_i(u_{t-1}^n - \bar{u})k_{t-1}^n + \delta k_{t-1}^n) \quad (73)$$

where $\bar{u}$ is the targeted capacity utilization rate, which is exogenously calibrated, and where γ_i is a parameter reflecting that desired investment targets are met over several periods.

Capacity utilization rate of firms n in the previous period:

$$u_{t-1}^n = \frac{y_{t-1}^n}{\epsilon_{t-1}^B k_{t-1}^{nB} + \epsilon_{t-1}^G k_{t-1}^{nG}} \quad (74)$$

where $\epsilon_{t-1}^B k_{t-1}^{nB} + \epsilon_{t-1}^G k_{t-1}^{nG}$ represents the average productivity of capital in firms n .

Total investment of firms n in nominal terms is equal to:

$$I_t^n = \frac{i_t^n}{\frac{\phi_t^{nG}}{p_t^G} + \frac{\phi_t^{nB}}{p_t^B}} \quad (75)$$

$$\text{As : } \frac{\phi_t^{nG} I_t^n}{p_t^G} + \frac{\phi_t^{nB} I_t^n}{p_t^B} = i_t^n.$$

Investment in green capital in firms n :

$$i_t^{nG} = \frac{\phi_t^{nG} I_t^n}{p_t^G} \quad (76)$$

Investment in brown capital in firms n :

$$i_t^{nB} = \frac{\phi_t^{nB} I_t^n}{p_t^B} \quad (77)$$

Firms finance their financial needs firstly with retained profits (70), secondly with corporate bonds, and thirdly with loans.

Firms issue green bonds to cover their green investment and brown bonds to cover their brown investment. Firms' bonds are bought by households. For simplicity, these bonds are assumed to be one-year coupon bonds. The par value $\overline{p_{b,t}^m}$ of bonds evolves depending on the variation of the price of bonds with a time lag:

$$\overline{p_{b,t}^m} = \overline{p_{b,t-1}^m} + \mu_{p_b}(p_{b,t}^m - \overline{p_{b,t-1}^m}) \quad (78)$$

with $m = B_G, B_B, G_G, G_B, F_G, F_B$.

The share of external financial needs covered by corporate bonds depends negatively on the interest rate on bonds $r_{b,t}^m$: when it increases, firms use fewer bonds to cover their external financial needs as they become more costly (they will use more loans). On the opposite, it depends positively on the interest rate on loans $r_{v,t}^m$. We assume that at least 5% of external financing needs are covered by bonds.

$$\sigma_{b,t}^m = \text{MAX}(0.05; \mu_{b,0} - \mu_{b,1}r_{b,t-1}^m + \mu_{b,2}r_{v,t-1}^m) \quad (79)$$

with $\mu_{b,0}$, a constant term in the share of corporate bonds in the external financial needs, $\mu_{b,1}$ the sensitivity of the share of bonds relative to bonds' interest rate, and $\mu_{b,2}$ the sensitivity of the share of bonds relative to loans' interest rate.

The variation of the quantity of green bonds depends on the share of external financial needs divided by the par value of green bonds:

$$\Delta b_t^{n_G} = \sigma_{b,t}^{n_G} \frac{(I_t^{n_G} - \phi_t^{n_G} \eta(RP_t^n - REP_t^n))}{\overline{p_{b,t-1}^{n_G}}} \quad (80)$$

with $I_t^{B_G} = \phi_t^{B_G} I_t^B$, $I_t^{G_G} = \phi_t^{G_G} I_t^G$, and $I_t^{F_G} = \phi_t^{F_G} I_t^F$.

The variation of the quantity of brown bonds depends on the share of external financial needs divided by the par value of brown bonds:

$$\Delta b_t^{n_B} = \sigma_{b,t}^{n_B} \frac{(I_t^{n_B} - \phi_t^{n_B} \eta(RP_t^n - REP_t^n))}{\overline{p_{b,t-1}^{n_B}}} \quad (81)$$

with $I_t^{B_B} = \phi_t^{B_B} I_t^B$, $I_t^{G_B} = \phi_t^{G_B} I_t^G$, and $I_t^{F_B} = \phi_t^{F_B} I_t^F$.

The interest rate reflects the difference between the coupon rate (the interest rate that firms pay to households) and the market price. This reflects that when the price of bonds increases, reflecting a higher demand, firms can decrease the interest rate on bonds to lower their financing costs.

$$r_{b,t}^m = \frac{c_{b,t}^m}{\overline{p_{b,t}^m}} \quad (82)$$

The coupon rate depends on past interest rates, as when the market price of bonds increases, the interest rate decreases, so firms issue bonds at a lower coupon rate:

$$c_{b,t}^m = r_{b,t-1}^m \overline{p_{b,t-1}^m} \quad (83)$$

The market price for green bonds is determined by the confrontation between the supply of bonds from firms $b_t^{n_G}$, and the demand of bonds from households $B_t^{n_G}$ (which is determined by their portfolio allocation choice model) :

$$p_{b,t}^{n_G} = \frac{B_t^{n_G}}{b_t^{n_G}} \quad (84)$$

Market price for brown bonds:

$$p_{b,t}^{n_B} = \frac{B_t^{n_B}}{b_t^{n_B}} \quad (85)$$

Firms finance the rest of their investment needs with loans. As the loans belonging to separate generations have different probabilities of defaults (15), we need to keep track of what happens to each loan over time. Besides, loan vintages allow a better representation of the dynamics of principal repayments and interest changes. Consequently, we adopt a vintage loan structure described in Figure 42.

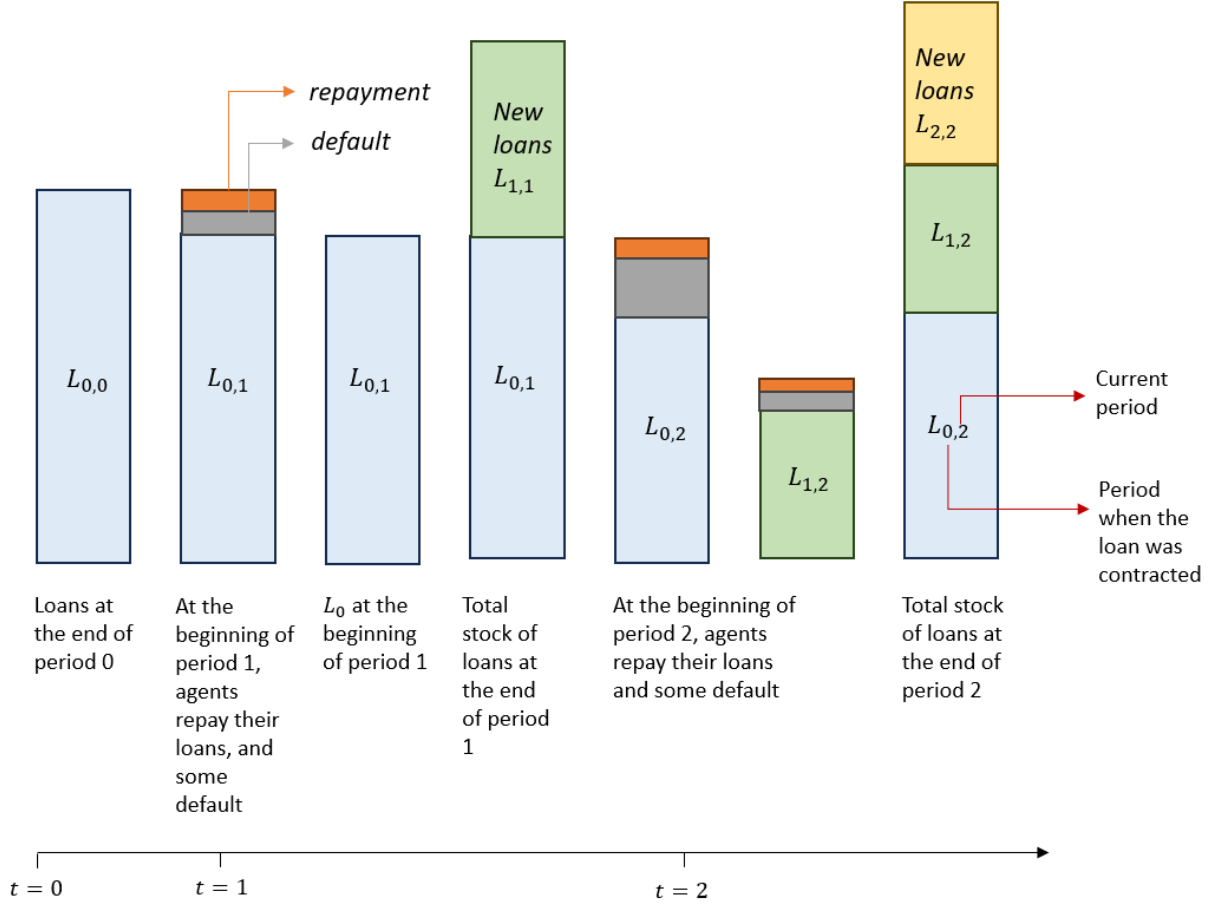


Figure 42: Presentation of the loan vintage structure

For a loan vintage contracted at period v , the loan stock at time t is equal to the loan stock of the previous period, minus the repayments and defaults that occurred at the beginning of the period t ($m = B_G, B_B, G_G, G_B, F_G, F_B$):

$$L_{v,t}^m = L_{v,t-1}^m - REP_{v,t}^m - \varphi_{v,t}^m L_{v,t-1}^m \quad (86)$$

with $REP_{v,t}^m$ the repayments (89) and $\varphi_{v,t}^m$ the probability of default at time t ((12) and (17)).

Loans of different vintages have the same maturity M . Following a well-established formula for loan repayment with a constant annuity, the annual capital cost corresponding to the vintage taken at time v , which includes both repayment and interest payments, is $AL_{v,t}^m$. The

annual capital cost is adjusted to take into account the defaults because past defaults decrease the annual capital cost ($m = B_G, B_B, G_G, G_B, F_G, F_B$):

$$AL_{v,t}^m = \frac{r_v^m(1+r_v^m)^M}{(1+r_v^m)^M - 1} L_{v,v}^m \prod_{s=v+1}^{t-1} (1 - \phi_{v,s}^m) \quad (87)$$

with $L_{v,v}^m$ the amount of loans m contracted at period v , and r_v^m the interest rate on this loan contract.

Note that if $L_{v,t-1}^m = 0$, $AL_{v,t}^m = 0$ to reflect that when the loan becomes zero because of the repayments and the defaults, the annual capital costs become null.

The interest payments on the vintage v at period t are done on the stock of loans of vintage v at the end of the previous period:

$$Int_{v,t}^m = r_v^m L_{v,t-1}^m \quad (88)$$

The repayments on the vintage v at period t , $REP_{v,t}^m$, is the residual between the annual capital cost and the interest payments. With this formula, the weight of interest payments in the annual capital cost decreases with time, as the loan stock decreases, while the repayment charge increases ($m = B_G, B_B, G_G, G_B, F_G, F_B$).

$$REP_{v,t}^m = AL_{v,t}^m - Int_{v,t}^m \quad (89)$$

If $t - v \geq M$, $REP_{v,t}^m = L_{v,t-1}^m (1 - \phi_{v,t}^m)$, reflecting that repayments equal the rest of the loan stock in the last period of life of the loan.

The total amount of repayments on loans m at period t is the sum of the repayments on all vintages ($m = B_G, B_B, G_G, G_B, F_G, F_B$):

$$REP_t^m = \sum_{v=0}^{t-1} REP_{v,t}^m \quad (90)$$

Note that the repayments of period t do not include the repayments on new loans as they start to be repaid in $t + 1$.

The total loan stock of m in period t is equal to the sum of the loan stock of all vintages in $t - 1$, minus the repayments and defaults that occurred at the beginning of the period t , and the new loan contracted at time t , $L_{t,t}^m$ ($m = B_G, B_B, G_G, G_B, F_G, F_B$):

$$L_t^m = \sum_{v=0}^{t-1} L_{v,t-1}^m - REP_t^m - DL_t^m + L_{t,t}^m \quad (91)$$

where $\sum_{v=0}^{t-1} L_{v,t-1}^m = L_{t-1}^m$.

New green loans at time t of firms n are equal to investment needs minus investment financed with retained profits and bonds (assumption that there is no credit rationing):

$$L_{t,t}^{n_G} = I_t^{n_G} - \phi_t^{n_G} \eta (RP_t^n - REP_t^n) - \overline{p_b^{n_G}} \Delta b_t^{n_G} \quad (92)$$

New brown loans at time t of firms n (assumption that there is no credit rationing):

$$L_{t,t}^{n_B} = I_t^{n_B} - \phi_t^{n_B} \eta (RP_t^n - REP_t^n) - \overline{p_b^{n_B}} \Delta b_t^{n_B} \quad (93)$$

The total amount of defaulted loans m is the sum of the defaults on all vintages (loans that default at the beginning of period t on the stock of each loan at period t – 1, which has been reduced by the previous defaults and repayments) ($m = B_G, B_B, G_G, G_B, F_G, F_B$):

$$DL_t^m = \sum_{v=0}^{t-1} \varphi_{v,t}^m L_{v,t-1}^m \quad (94)$$

with $\varphi_{v,t}$ the probability of default.

For brown loans, the probability of default at time t only depends on the evolution of the illiquidity ratio as the brown technology is mature (Dafermos & Nikolaidi, 2022). In further work, we could adopt a more detailed representation of this probability of default as we do for the one on green capital, but this will only add negative externalities to brown capital when the transition happens.

$$\varphi_{v,t}^{n_B} = \varphi_t^{illiq_n} \quad (95)$$

The probability of defaults related to firms' illiquidity ratio is equal to:

$$\varphi_t^{illiq_n} = \frac{1}{1 + def_0 e^{(def_1 - def_2 illiq_{t-1}^n)}} \quad (96)$$

with def_0, def_1 and def_2 parameters of the default rate function.

Firms' illiquidity ratio is an indicator of the ability of firms to repay their debt (Dafermos & Nikolaidi, 2022). It is the ratio of firms' cash outflows to cash inflows. The main difference between the debt-service ratio and the illiquidity ratio is that the latter considers the new flow of credit in cash inflows.

$$illiq_t^n = \frac{KB_t^n + REP_t^n + WB_t^n + T_t^n + CT_t^n}{Y_t^n + L_{t,t}^{n_B} + L_{t,t}^{n_G} + \overline{p_b^{n_B}} \Delta b_t^{n_B} + \overline{p_b^{n_G}} \Delta b_t^{n_G} + r_t^D \Delta D_t^n} \quad (97)$$

It reflects that when cash outflows increase compared to cash inflows, the probability of defaults increases. This allows representing that as the transition occurs, brown firms see a decrease in their profits, leading to a lower illiquidity ratio and thus a higher rate of defaults.

For green loans, the probability of default at time t depends on the evolution of the illiquidity ratio $\varphi_t^{illiq_n}$, but also on the age of the loan φ_{t-v}^V , and on the share of green capital in the economy when the loan was contracted φ_v^ϵ :

$$\varphi_{v,t}^{n_G} = \varphi_t^{illiqn} (1 + \varphi_{t-v}^V) (1 + \varphi_v^\epsilon) \quad (98)$$

The probability of default on green loans depends on the share of green capital in the economy in the period when the loan started to reflect the presence of learning-by-doing effects from firms as the technology becomes mature (Way et al., 2022), and from the financial sector as the more green investment projects are developed, the more banks can select the ones that will succeed (Egli et al., 2018). Consequently, new green loans will be subjected to a lower probability of default as the share of green capital increases. In this first version, we assume that the probability of default on green loans related to the share of green capital in the economy stays the same during the life of a vintage of loans. This reflects the assumption that a loan issued in period v is associated with a green investment project based on the conditions and technologies available at that time. We use a discrete approximation of a logistic function as it takes time to develop learning-by-doing effects (Pan & Köhler, 2007) (Figure 43).

$$\varphi_v^\epsilon = \begin{cases} \varphi_0^\epsilon, & \text{if } sh_v^{k_G} \leq sh_{MIN}^{k_G} \\ \frac{\varphi_0^\epsilon}{1 + \exp(par_e(sh_v^{k_G} - par_d))}, & \text{if } sh_{MIN}^{k_G} < sh_v^{k_G} < sh_{MID}^{k_G} \\ 0, & \text{if } sh_v^{k_G} \geq sh_{MID}^{k_G} \end{cases} \quad (99)$$

with $sh_v^{k_G}$ the share of green capital in the economy in the period when the loan vintage started v ; $sh_{MIN}^{k_G}$ the threshold of the share of green capital in the economy above which the probability of defaults on green loans starts to decrease; $sh_{MID}^{k_G}$ the threshold of the share of green capital in the economy above which φ_v^ϵ is equal to zero; par_e the steepness of the approximated logistic function; par_d represents the midpoint of the approximated logistic function.

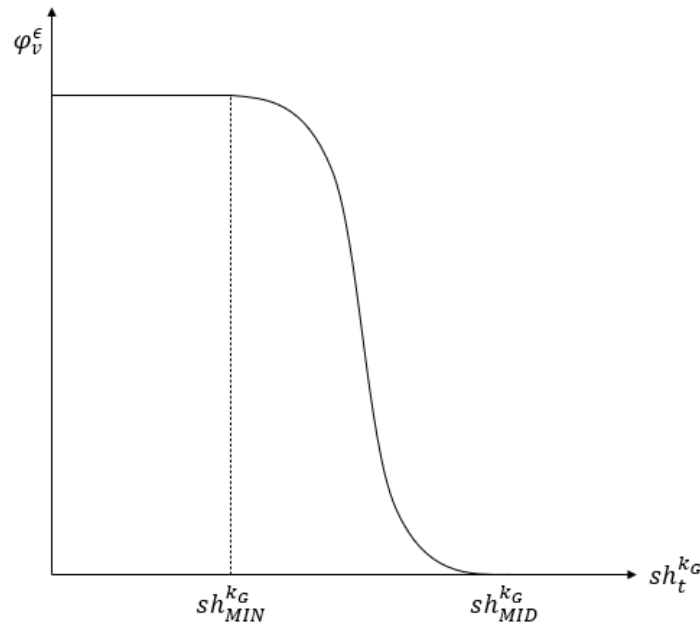


Figure 43: Probability of default on green loans related to the share of green capital in the economy

The probability of default on green loans depends on the age of the vintage of loans to reflect that the risk of default on green loans is higher in the first years of projects and that it tends to decrease once projects start operating. Indeed, low-carbon investment projects are often characterized by high CAPEX and low OPEX, leading to high upfront costs and long payback periods (IEA, 2024). This exposes investors to significant risks of substantial losses, as they must commit large investments to cover high upfront costs, while their future returns remain uncertain. Moreover, low-carbon technologies are less mature, leading to high risk in the construction period as surprises can occur on equipment costs and performance (Hourcade et al., 2021). Consequently, the risk of default on green loans is high at the beginning of the project, when the capital is still under construction, and it decreases once the project starts operating. This probability of default is an approximated logistic function. This probability of default depends on the share of green capital in the economy to reflect that as the transition occurs, the production ecosystem adapts, the technology becomes mature, and low-carbon investment projects become less risky.

$$\varphi_{v,t}^V = \frac{\varphi_v^\epsilon}{1 + \exp\left(\text{par}_s((t - v) - \text{par}_m)\right)} \quad (100)$$

where $t - v$ is equal to the age of the loan at period t where v is the period when the vintage of loans was contracted, φ_v^ϵ is the probability of defaults related to the share of green capital in the economy on the loan vintage contracted at the period v ; par_s is the steepness of the approximated logistic function; and par_m is the midpoint of the approximated logistic function.

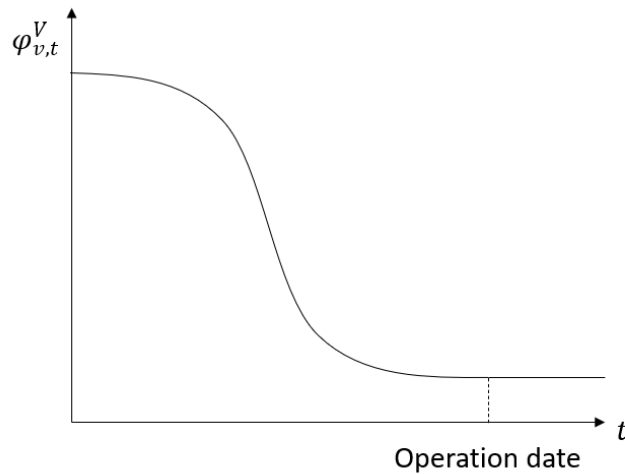


Figure 44: Probability of default related to the age of a vintage of loans

Appendix 4.1.2 Households

Households receive wages for their work WB_t^n , interests on deposits $r_{t-1}^D D_{t-1}^H$ and interests on green and brown corporate bonds $\sum_n c_{b,t-1}^{n_G} b_{t-1}^{H_{n_G}} + \sum_n c_{b,t-1}^{n_B} b_{t-1}^{H_{n_B}}$. They pay their loan interests payments Int_t^H and their income tax T_t^H with their disposable income. There is no carbon tax on households' brown capital. Banks distribute all their profits to households DP_t^{Bk} . Firms distribute a part of their profits to households $DP_t^H = \pi^H \Pi_t^n$ (the other part goes to the government).

Households disposable income ($n = B, G, F$):

$$YD_t = \sum_n WB_t^n - Int_t^H + \sum_n DP_t^{Hn} + DP_t^{Bk} + \sum_n c_{b,t-1}^{n_G} b_{t-1}^{H_{n_G}} + \sum_n c_{b,t-1}^{n_B} b_{t-1}^{H_{n_B}} + r_{t-1}^D D_{t-1}^H - T_t^H \quad (101)$$

The tax on households' primary income depends on their gross disposable income. In the case of a policy with a carbon tax on firms, the government can redistribute partly or entirely the carbon tax revenue to households in a reduction of their income tax, RED_t (133).

$$T_t^H = \tau^H \left(\sum_n WB_t^n - Int_t^H + \sum_n DP_t^{Hn} + DP_t^{Bk} + \sum_n c_{b,t-1}^{n_G} b_{t-1}^{H_{n_G}} + \sum_n c_{b,t-1}^{n_B} b_{t-1}^{H_{n_B}} + r_{t-1}^D D_{t-1}^H \right) - RED_t \quad (102)$$

Households' cost of capital is equal to the interest payments on their green and brown loans ($z = G, B$), which is the sum of the interest payments on all vintages in $t - 1$. Note that households have a loan vintage structure similar to firms, which is described in Figure 42.

$$Int_t^{H_z} = \sum_{v=0}^{t-1} r_v^{H_z} L_{v,t-1}^{H_z} \quad (103)$$

Total interest payments of households:

$$Int_t^H = Int_t^{H_G} + Int_t^{H_B} \quad (104)$$

Households' consumption depends on their disposable income and their wealth:

$$C_t^H = \alpha_1 YD_{t-1} + \alpha_2 V_{t-1}^H \quad (105)$$

To represent the way household savings are allocated to different financial assets, we use the Tobin portfolio allocation model with imperfect asset substitutability (106). In this equation, AH is the set of all financial assets owned by households, namely: $AH = D^H, B^{H_{FG}}, B^{H_{FB}}, B^{H_{BG}}, B^{H_{BB}}, B^{H_{GG}}, B^{H_{GB}}$. This is the most common formalization of portfolio

allocation in the SFC literature (Nikiforos & Zezza, 2017). The demand for corporate bonds and deposits depends on the interest rates on bonds and deposits. For a given asset, the coefficient associated with its own rate of return should be positive: $\lambda_{X,X} > 0$. Instead, the coefficients associated with the rates of return of the other assets should be negative: $\lambda_{X,Y} < 0$, $Y \neq X$.

Since the sum of asset shares in the portfolio must always be equal to 1, the sum of the first coefficients must be equal to 1 and any other sum of coefficients must be equal to 0: $\sum_{X \in AH} \lambda_X = 1$, $\sum_{X \in AH} \lambda_{X,Y} = 0$, $\sum_{X \in AH} \lambda_{X,DI} = 0$. This is known as the vertical condition. A horizontal condition also applies, according to which the sum of all coefficients on a line, except the first one, must be equal to 0: $\sum_{Y \in AH} \lambda_{X,Y} = 0$. This reflects the idea that a uniform change in the rates of return should not affect the shares of assets in the portfolio. We assume that the coefficients are symmetric, such that $\lambda_{X,Y} = \lambda_{Y,X}$. If the vertical condition is satisfied, this automatically ensures the horizontal condition as well. Finally, notice that in practice, the equation on the share of deposits is not used in the computer program, because the flow of new deposits is determined as a residual once all the other flows of assets have been deducted from household savings (118).

$$X_t = \left(\lambda_t^X + \sum_{Y \in AH} \lambda^{X,Y} r_{t-1}^Y \right) V_{F,t-1}^H, \forall X \in AH \quad (106)$$

The autonomous demand of corporate bonds evolves with the firms' share of green/brown capital in total firms' capital and with the market share of the firms $n = B, G, F$, to reflect the reshuffling of portfolios as the transition goes on:

$$\lambda_{0,t}^{Hn_B} = (1 - \lambda^{D^H}) \frac{Y_t^n}{\sum_n Y_t^n} \frac{K_t^{n_B}}{K_t^n} \quad (107)$$

$$\lambda_{0,t}^{Hn_G} = (1 - \lambda^{D^H}) \frac{Y_t^n}{\sum_n Y_t^n} \frac{K_t^{n_G}}{K_t^n} \quad (108)$$

The financial wealth of households is defined as the sum of their corporate bonds and deposits ($m = B_G, B_B, G_G, G_B, F_G, F_B$):

$$V_{F,t-1}^H = \sum_m B_{t-1}^{Hm} + D_{t-1}^H \quad (109)$$

where $B_{t-1}^{Hm} = b_{t-1}^{Hm} p_{b,t-1}^m$.

The financial wealth of households evolves with the disposable income after consumption, investment and loan repayments, and with the variation of the value of bonds they own (redundant equation):

$$\Delta V_{F,t}^H = YD_t - C_t^H - (I_t - L_{t,t}^{H_G} - L_{t,t}^{H_B}) - REP_t^{H_G} - REP_t^{H_B} + \sum_m b_{t-1}^{Hm} \Delta p_{b,t}^m \quad (110)$$

Households have an investment target depending on their past revenue and wealth (the richer they feel, the more they invest) and allowing to replace their depreciated capital:

$$I_t^T = \delta K_{t-1}^H + \alpha_3 YD_{t-1} + \alpha_4 V_{t-1}^H \quad (111)$$

Households' investment is constrained by how much they could have invested in the previous period. This constraint depends on their revenue after consumption, loan repayments, change in deposits, change in corporate bonds, and on the amount of new loans that financed their investment in the previous period. We use values of the previous period to circumvent endogeneity in our recursive model. This constraint reflects that households are cautious: they choose their level of investment by taking into account how much they could have invested in the previous period. However, this constraint is adjusted such that households constrain their level of investment depending on the gap between their past investment target and their realized investment: the higher the gap, the more they want to invest in the current period, and the less the constraint is strong.

$$I_t^C = \mu_t^H \left(YD_{t-1} - C_{t-1} - REP_{t-1}^{H_G} - REP_{t-1}^{H_B} - \Delta D_{t-1}^H - \sum_m \bar{p}_b^m \Delta b_{t-1}^{H_m} + L_{t-1,t-1}^{H_G} + L_{t-1,t-1}^{H_B} \right) \quad (112)$$

where $\mu_t^H = \mu_{t-1}^H + \kappa_H \left(\frac{I_{t-1}^T - I_{t-1}^H}{I_{t-1}^H} \right)$ is the ratio representing the sensitivity of the investment constraint of households relative to the investment of the previous period. This ratio depends on the gap between the past investment target of households and the investment that they made.

Actual households' investment is the minimum between their investment target and their investment constraint, meaning that households cannot invest more than their constrained investment:

$$I_t^H = \min(I_t^C, I_t^T) \quad (113)$$

The share of brown investment in total investment of households is done with a Tobin portfolio allocation model similar to firms. The decision of households depends on the price and the productivity of each type of capital. In the case where a green mandate is implemented, the share of households' brown investment is equal to the minimum between the share computed with the Tobin model and the share allowing to follow the regulation (25).

$$\phi_t^{H_B} = \min \left((\lambda_{0,t}^{H_B} + \lambda_1^{H_B} p_{t-1}^B + \lambda_2^{H_B} p_{t-1}^G + \lambda_3^{H_B} \epsilon_{t-1}^B + \lambda_4^{H_B} \epsilon_{t-1}^G); (1 - \phi_t^{L_G}) \right) \quad (114)$$

with $\lambda_{0,t}^{H_B}$ the autonomous brown capital demand, $\lambda_1^{H_B}$ the elasticity of the investment in brown capital relative to the price of brown capital (negative), $\lambda_2^{H_B}$ the elasticity of the investment in brown capital relative to the price of green capital (positive), $\lambda_3^{H_B}$ the elasticity of the

investment in brown capital relative to the productivity of brown capital (positive), $\lambda_4^{H_B}$ the elasticity of the investment in brown capital relative to the productivity of green capital (negative). Similarly to firms, the share of households' investment into green and brown capital is bounded between ϕ_{MIN}^Z and ϕ_{MAX}^Z .

Share of green investment in total investment for households:

$$\phi_t^{H_G} = 1 - \phi_t^{H_B} \quad (115)$$

Actual investment in green and brown capital ($z = G, B$):

$$I_t^{H_z} = \phi_t^{H_z} I_t^H \quad (116)$$

Households finance a constant share ζ^H of their investment with new loans (assumption that there is no credit rationing):

$$L_{t,t}^{H_z} = \zeta^H I_t^{H_z} \quad (117)$$

Households put the rest of their disposable income after consumption, investment, loan repayments, and bond purchases into a deposit account in banks:

$$D_t^H = D_{t-1}^H + YD_t - C_t - (I_t^{H_G} - L_{t,t}^{H_G}) - (I_t^{H_B} - L_{t,t}^{H_B}) - REP_t^{H_G} - REP_t^{H_B} - \sum_m \bar{p}_b^m \Delta b_t^{H_m} \quad (118)$$

Green and brown capital stock ($z = G, B$) of households:

$$K_t^{H_z} = K_{t-1}^{H_z} (1 - \delta) + I_t^{H_z} \quad (119)$$

Total capital stock:

$$K_t^H = K_t^{H_G} + K_t^{H_B} \quad (120)$$

Households' loan stock on the loan vintage contracted in the period v at time t is equal to the loan stock of the previous period minus the repayments and defaults that occurred at the beginning of the period t ($z = G, B$):

$$L_{v,t}^{H_z} = L_{v,t-1}^{H_z} - REP_{v,t}^{H_z} - \phi_{v,t}^{H_z} L_{v,t-1}^{H_z} \quad (121)$$

with $REP_{v,t}^{H_z}$ the repayments and $\phi_{v,t}^{H_z}$ the probability of default at time t .

Loans of different vintages have the same maturity M . Following a well-established formula for loan repayment with a constant annuity, the annual capital cost corresponding to the vintage taken at time v , including both repayment and interest, is $AL_{v,t}^{H_z}$ ($z = G, B$). Note that the initial stock of loan is decreased by past probabilities of defaults because defaults decrease the annual capital cost:

$$AL_{v,t}^{H_z} = \frac{r_v^{H_z} (1 + r_v^{H_z})^M}{(1 + r_v^{H_z})^M - 1} L_{v,v}^{H_z} \prod_{s=v+1}^{t-1} (1 - \phi_{v,s}^{H_z}) \quad (122)$$

with $L_{v,v}^{H_z}$ the amount of loans z contracted at period v , and $r_v^{H_z}$ the interest rate on this loan contract.

If $L_{v,t}^{H_z} = 0$, $AL_{v,t}^{H_z} = 0$ to reflect that when the loan becomes zero because of the repayments and the defaults, the annual capital costs become null.

The interest payment on the vintage v at period t is done on the stock of loans of vintage v at the end of the previous period:

$$Int_{v,t}^{H_z} = r_v^{H_z} L_{v,t-1}^{H_z} \quad (123)$$

The repayment on the vintage v at period t , $REP_{v,t}^{H_z}$ ($z = G, B$) is the residual between the annual capital cost and the interest payments:

$$REP_{v,t}^{H_z} = AL_{v,t}^{H_z} - Int_{v,t}^{H_z} \quad (124)$$

If the loan has reached maturity, the repayments are equal to the rest of the loan stock minus the defaults, to have a loan stock equal to zero:

$$\text{If } t - v \geq M, REP_{v,t}^{H_z} = L_{v,t-1}^{H_z} (1 - \phi_{v,t}^{H_z})$$

Consequently, the total amount of repayment on households' loans $z = G, B$ at period t is the sum of the repayments on all vintages:

$$REP_t^{H_z} = \sum_{v=0}^{t-1} REP_{v,t}^{H_z} \quad (125)$$

Note that the repayments of period t do not include the repayments on new loans as they start to be repaid in $t + 1$.

At time t , the loan stock of households is equal to the loan stock of the previous period (sum of vintages in $t - 1$) decreased by the repayments (125) and the defaults occurring at the beginning of period t (128), plus the new loans (117):

$$L_t^{H_z} = \sum_{v=0}^{t-1} L_{v,t-1}^{H_z} - REP_t^{H_z} - DL_t^{H_z} + L_{t,t}^{H_z} \quad (126)$$

Loan defaults on loans $z = G, B$ is the sum of defaults on all vintages at period t :

$$DL_t^{H_z} = \sum_{v=0}^{t-1} \phi_{v,t}^{H_z} L_{v,t-1}^{H_z} \quad (128)$$

For households, the probability of default on green and brown loans at time t only depends on the evolution of their disposable income:

$$\varphi_{v,t}^{H_z} = \varphi_{v,0}^{H_z} \left(1 - \frac{YD_t - YD_{t-1}}{YD_{t-1}} \right) \quad (129)$$

Appendix 4.1.3 Government

Government revenue comes from taxes, redistributed profits from state-owned enterprises, central bank profits, interests on its deposits in the central bank, and interests on its loan guarantee reserves in the central bank in case of the implementation of a guarantee scheme:

$$R_t^{Gov} = T_t^H + T_t^{Bk} + \sum_n T_t^n + \sum_n CT_t^n + DP_t^{Gov} + \Pi_t^{CB} + \bar{r}D_{t-1}^{Gov} + \bar{r}RES_{t-1}^{Gov} \quad (130)$$

with $DP_t^{Gov} = \pi^{Gov} \Pi_t^n$, $n = B, G, F$.

In case of the implementation of a guarantee system on green loans with funded guarantees, the government has to make reserves to reassure banks that it has enough money to compensate them. The reserves are equal to a percentage of the amount of green loans covered by the guarantee system. We make the hypothesis that the reserves go to a 'reserves account' of the government in the central bank, which remunerates the government at the same interest rate as government deposits.

$$RES_t^{Gov} = \rho_{RES} \rho_G \sum_n L_t^{nG} \quad (131)$$

Government consumption depends on its running costs and its revenue (following Dunz et al., 2021). In the case where a carbon tax is implemented without redistribution, we assume that carbon tax revenues are used to increase government consumption and investment, as they increase government revenues.

$$C_t^{Gov} = \bar{G} + g_1^{Gov} R_{t-1}^{Gov} \quad (132)$$

In case of the implementation of the carbon tax with redistribution, the government redistributes partly or fully the carbon tax revenues to households:

$$RED_t = \tau_{RED} \sum_n CT_t^n \quad (133)$$

with τ_{RED} the redistribution rate.

Total government spending is the sum of government consumption, interest payments on government bonds, and loan guarantee payments to banks ($n = B, G, F$):

$$G_t^{Gov} = C_t^{Gov} + r^{Gov}GB_{t-1} + \rho_G \sum_n DL_{t-1}^{n_G} \quad (134)$$

The rate of guarantee decreases over time following a constant rate g_{ρ_G} when the share of green capital in the economy approaches its target, as the rate of green loan defaults decreases. This decreases green loan interest rates such as the guarantee is less needed.

$$\rho_{G_t} = \rho_{G_{t-1}} \left(1 - g_{\rho_G} (\overline{sh^{k_G}} - sh_t^{k_G}) \right) \quad (135)$$

The share of brown investment in total investment of the government is determined through a portfolio allocation model, which is the same as households:

$$\phi_t^{Gov_B} = \min \left((\lambda_{0,t}^{Gov_B} + \lambda_1^{Gov_B} p_{t-1}^B + \lambda_2^{Gov_B} p_{t-1}^G + \lambda_3^{Gov_B} \epsilon_{t-1}^B + \lambda_4^{Gov_B} \epsilon_{t-1}^G); (1 - \overline{\phi_t^{L_G}}) \right) \quad (136)$$

Similarly to households, the share of the government's investment into green and brown capital is bounded between ϕ_{MIN}^Z and ϕ_{MAX}^Z .

In the case of the implementation of the green public expenditure policy, there is a redirection of public investment towards green capital, such as the share of brown investment by the government decreases following a logistic function to reach a given share $(1 - \overline{sh^{k_G}})$, some years after the start of the implementation of the policy:

$$\phi_t^{Gov_B} = \phi_0^{Gov_B} + \frac{(1 - \overline{sh^{k_G}}) - \phi_0^{Gov_B}}{1 + \exp(-par_l(t - par_n))} \quad (137)$$

with $\phi_0^{Gov_B}$, the initial share of brown capital investment of the government, par_l and par_n parameters of the logistic function.

Share of green investment in the total investment of the government:

$$\phi_t^{Gov_G} = 1 - \phi_t^{Gov_B} \quad (138)$$

The investment in brown capital by the government is done such as the government replaces its depreciated capital, and invest a constant share of its revenue g_2^{Gov} (following Dunz et al., 2021). In the case where a carbon tax is implemented without redistribution, we assume that carbon tax revenues are used to increase government consumption and investment, as they increase government revenues.

$$I_t^{Gov_B} = \phi_t^{Gov_B} (\delta K_{t-1}^{Gov} + g_2^{Gov} R_{t-1}^{Gov}) \quad (139)$$

Investment in green capital by government is similar to brown capital but in the case of a green public expenditure policy, it is augmented by $\overline{I_t^{Gov}}$, the supplementary amount of green public investment:

$$I_t^{Gov_G} = \phi_t^{Gov_G} (\delta K_{t-1}^{Gov} + g_2^{Gov} R_{t-1}^{Gov}) + \overline{I_t^{Gov}} \quad (140)$$

This supplementary amount of public green investment is a share of output (from the previous period, ensuring the model remains recursive):

$$\overline{I_t^{Gov}} = s_{I_{G,t}} Y_{t-1} \quad (141)$$

This share is determined by a logistic function, such that it decreases when the share of green capital in the economy approaches its target:

$$s_{I_{G,t}} = s_{I_{G,t-1}} \left(1 + g_{s_{I_G}} (\overline{sh^{k_G}} - sh_t^{k_G}) \right) \quad (142)$$

Total investment by the government is the sum of its green and brown investments:

$$I_t^{Gov} = I_t^{Gov_G} + I_t^{Gov_B} \quad (143)$$

Green and brown capital stock with $z = G, B$ of the government:

$$K_t^{Gov_z} = K_{t-1}^{Gov_z} (1 - \delta) + I_t^{Gov_z} \quad (144)$$

Total capital stock of the government:

$$K_t^{Gov} = K_t^{Gov_G} + K_t^{Gov_B} \quad (145)$$

The government targets a ratio of deposits to bonds with its deposits. This reflects that when the government emits bonds, it has to increase its deposits too, otherwise nobody will buy its bonds due to a lack of confidence:

$$D_t^{Gov} = D_{t-1}^{Gov} + \left(d^T - \frac{D_{t-1}^{Gov}}{GB_{t-1}} \right) GB_{t-1} \quad (146)$$

with d^T the targeted ratio of deposits relative to bonds.

The government finances its deficit by issuing bonds that are bought by the banks and the central bank:

$$\Delta GB_t = G_t^{Gov} + I_t^{Gov} - R_t^{Gov} + \Delta D_t^{Gov} + \Delta RES_t^{Gov} \quad (147)$$

If $\Delta GB_t < 0$, the government redeems the bonds to reduce its debt.

Appendix 4.1.4 Banks

Banks' profit is the difference between their revenue (interest payments on loans and government bonds, and guarantee payments on defaulted green loans) and their cost (taxes on profits, and interest payments on households' deposits and on advances). The payment of guarantees plays a role in their profits as it is a transfer from the government to the banks, which partly compensates the loss of repayments on defaulted loans.

$$\Pi_t^{Bk} = \sum_l \sum_{v=0}^{t-1} r_{t-1}^l L_{v,t-1}^l + r^{Gov} GB_{t-1}^{Bk} + \rho_G (DL_{t-1}^{B_G} + DL_{t-1}^{G_G} + DL_{t-1}^{F_G}) - T_t^{Bk} - r_{t-1}^D (D_{t-1}^H + D_{t-1}^B + D_{t-1}^G + D_{t-1}^F) - r^A A_{t-1} \quad (148)$$

with $l = B_B, B_G, G_G, G_B, F_B, F_G, H_B, H_G$.

Tax on banks' profits:

$$T_t^{Bk} = \left(\sum_l \sum_{v=0}^{t-1} r_{t-1}^l L_{v,t-1}^l + r^{Gov} GB_{t-1}^{Bk} - r_{t-1}^D (D_{t-1}^H + D_{t-1}^B + D_{t-1}^G + D_{t-1}^F) - r^A A_{t-1} \right) \tau^{Bk} \quad (149)$$

with τ^{Bk} banks' profits tax rate.

Households own the banks, which distribute their profits to them (Dunz et al., 2021):

$$DP_t^{Bk} = \pi^{H_{Bk}} \Pi_t^{Bk} \quad (150)$$

The retained profits of banks are the residual after the distribution of profits to households. Banks use their retained profits to finance their purchases of government bonds, their defaulted loans, and the new loans that they provide to other agents.

$$RP_t^{Bk} = (1 - \pi^{H_{Bk}}) \Pi_t^{Bk} \quad (151)$$

Banks are required to hold a constant fraction of their deposits as high-powered money in the central bank (Dafermos & Nikolaidi, 2022). As we assume that agents do not hold currencies (they do not have cash), high-powered money is equal to banks' mandatory reserves:

$$HPM_t^{Bk} = h_1 D_t^{Bk} \quad (152)$$

with the total amount of deposits of banks $D_t^{Bk} = D_t^H + D_t^B + D_t^G + D_t^F$.

Banks invest their retained profits and a constant share of the deposits of households and firms in government bonds to avoid accumulating dormant capital (Dafermos & Nikolaidi, 2022):

$$GB_t^{Bk} = h_2 D_t^{Bk} + RP_t^{Bk} \quad (153)$$

To impede banks from buying more government bonds than what is available, we add the following condition:

If $GB_t^{Bk} > GB_t$:

$$GB_t^{Bk} = GB_{t-1}^{Bk} + \Delta GB_t \quad (154)$$

Banks use advances from the central bank to balance their capital account:

$$\Delta A_t = \Delta L_t + \Delta HPM_t - \Delta D_t^{Bk} - RP_t^{Bk} + \Delta GB_t^{Bk} + DL_t \quad (155)$$

Banks determine the base interest rates on deposits and loans depending on their capital adequacy ratio, which reflects the risk of insolvency of banks from excessive loans. The capital adequacy ratio (CAR) of banks is the ratio of banks wealth to its risk-weighted loans ($l = B_G, B_G, G_G, G_B, F_B, F_G, H_B, H_G$):

$$CAR_t = \frac{V_t^{Bk}}{\sum_l \omega_L^l L_t^l} \quad (156)$$

where the capital of banks is equal to $V_t^{Bk} = V_{t-1}^{Bk} + RP_t^{Bk} - DL_t$ and ω_L^l is the risk weights on loans.

The base interest rate on deposits is given by (following Dunz et al., 2021):

$$r_t^D = \bar{r} \left(1 + \kappa_0 \frac{CAR_t - CAR^T}{CAR^T} \right) \quad (157)$$

where $\bar{r}$ is the interest rate fixed by the central bank, κ_0 is the CAR adjustment rate reflecting that when the CAR decreases compared to its target CAR^T , the bank tries to save money by decreasing the interest rate on deposits.

Banks determine their base interest rate, which applies to all loans, depending on their CAR, the interest rate of the central bank ($\bar{r}$), and a minimum profit markup on top of the risk-free interest rate (spr^L) (Dafermos & Nikolaidi, 2022):

$$r_t^L = (\bar{r} + spr^L) \left(1 - \kappa_0 \frac{CAR_t - CAR^T}{CAR^T} \right) \quad (158)$$

where $\bar{r}$ is the interest rate fixed by the central bank, spr^L is the bank markup, κ_0 is the CAR adjustment rate reflecting that when the CAR decreases compared to its target, the bank increases its interest rate to increase its profits.

The interest rate on brown loans for firms $n = B, G, F$ depends on banks' base interest rate and on the perception of risk by banks, which is reflected in the average rate of defaults on brown loans (following Dunz et al., 2021) and firms' debt service ratio (following Dafermos & Nikolaidi, 2022). The inclusion of the debt service ratio reflects that banks impose a higher interest rate when firms become more financially fragile (Juselius & Drehmann, 2020).

$$r_t^{nB} = r_t^L + \kappa_1 \frac{DL_t^{nB}}{L_{t-1}^{nB}} + \kappa_2 dsr_t^n \quad (159)$$

with DL_t^{nB} the defaults of firms n on their brown loans happening in period t on their brown loan stock of the previous period L_{t-1}^{nB} ; κ_1 the sectoral interest rate adjustment rate related to brown firms' defaults; and κ_2 the sectoral interest rate adjustment rate related to firms' debt service ratio dsr_t^n .

The interest rate on green loans for firms $n = B, G, F$ is extended compared to the interest rate on brown loans to include the rate of guarantees ρ_G and the potential overestimation of risk by banks χ_t^{Bk} . When a guarantee is implemented, banks consider the risk of default of the guarantor when determining their interest rates. In our modelling, when a 100% guarantee is implemented $r_t^{nG} = r_t^L$, meaning that banks do not charge higher interest rates as we assume that the guarantor has a low risk of defaults.

$$r_t^{nG} = r_t^L + (1 - \rho_G) \left(\kappa_1 \left(\frac{DL_t^{nG}}{L_{t-1}^{nG}} (1 + \chi_t^{Bk}) \right) + \kappa_2 dsr_t^n \right) \quad (160)$$

We add the possibility that banks can overestimate the probability of defaults on green loans due to unfamiliarity with green lending. This overestimation χ_t^{Bk} is a logistic function of the share of green capital in the economy. It reflects that when the share of green capital increases, banks develop learning effects (Egli et al., 2018) and actualize their perception of risks on green projects downwards. When banks do not overestimate the risks of defaults, χ_t^{Bk} is equal to zero (Figure 45).

$$\chi_t^{Bk} = \begin{cases} \chi_0^{Bk}, & \text{if } sh_{t-1}^{kG} \leq sh_{MIN}^{kG} \\ \frac{\chi_0^{Bk}}{1 + \exp(par_h(sh_{t-1}^{kG} - par_i))}, & \text{if } sh_{MIN}^{kG} < sh_{t-1}^{kG} < sh_{MID}^{kG} \\ 0, & \text{if } sh_{t-1}^{kG} \geq sh_{MID}^{kG} \end{cases} \quad (161)$$

with sh_{t-1}^{kG} the share of green capital in the economy in the previous period; χ_0^{Bk} the initial overestimation of risks by banks; sh_{MIN}^{kG} the threshold of the share of green capital in the economy above which the overestimation of risks by banks on green capital starts to decrease; sh_{MID}^{kG} the threshold of the share of green capital in the economy above which χ_t^{Bk} is equal to zero; par_h and par_i the steepness and the midpoint of the approximated logistic function.

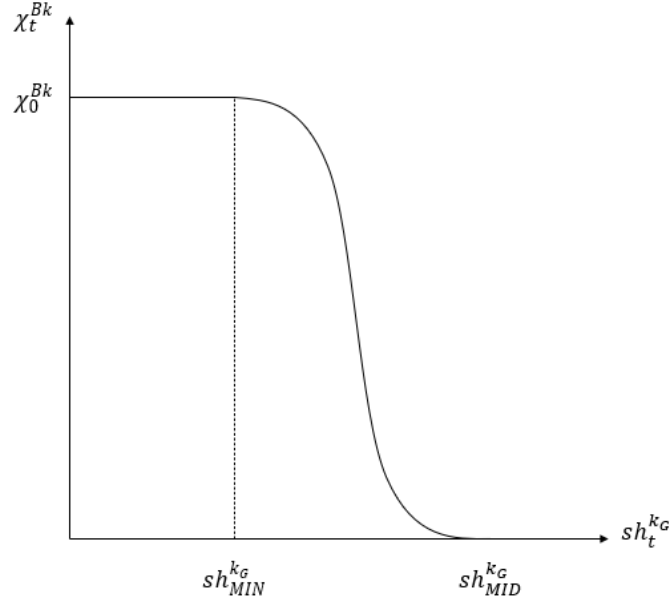


Figure 45: Overestimation of risks by banks

The debt service ratio is the ratio of debt payment commitments (interest plus principal repayments) to gross profits before interest payments (Dafermos & Nikolaidi, 2022):

$$dsr_t^n = \frac{KB_t^n + REP_t^n}{Y_t^n - WB_t^n} \quad (162)$$

The interest rate on households' loans is the same for green and brown loans ($z = B, G$), and it depends on their loan default ratio (Dunz et al., 2021) and the variation of their disposable income:

$$r_t^{H_z} = r_t^L + \kappa_1^H \left(\frac{DL_t^{H_z}}{L_t^{H_z}} - \frac{YD_t^H - YD_{t-1}^H}{YD_{t-1}^H} \right) \quad (163)$$

Appendix 4.1.5 Central bank

Central bank's profits are the sum of interest payments from advances and government bonds, minus the interest payments on government deposits and on government loan guarantee reserves:

$$\Pi_t^{CB} = r^A A_{t-1} + r^{Gov} GB_{t-1}^{CB} - \bar{r} D_{t-1}^{Gov} - \bar{r} RES_{t-1}^{Gov} \quad (164)$$

The central bank ensures the equality between government bond demand and government bond supply by buying the rest of the supply of government bonds that banks did not purchase:

$$\Delta GB_t^{CB} = \Delta GB_t - \Delta GB_t^{Bk} \quad (165)$$

The capital account of the central bank balances, so the variation of advances is logically implied by all the other equations of this system (redundant equation):

$$\Delta A_t = \Delta HPM_t + \Delta D_t^{Gov} + \Delta RES_t^{Gov} - \Delta GB_t^{CB} \quad (166)$$

Appendix 4.1.6 Accounting identities

Net worth of agents

Households' net worth:

$$V_t^H = K_t^H + D_t^H - L_t^{HB} - L_t^{HG} + \sum_m \bar{p}_{b,t}^m b_t^{H_m} \quad (167)$$

Firms' net worth:

$$V_t^n = K_t^n + D_t^n - L_t^{nB} - L_t^{nG} - \sum_z \bar{p}_{b,t}^{n_z} b_t^{n_z} \quad (168)$$

Banks' net worth:

$$V_t^{Bk} = L_t^{Bk} + GB_t^{Bk} + HPM_t - D_t - A_t \quad (169)$$

Government's net worth:

$$V_t^{Gov} = K_t^{Gov} + D_t^{Gov} + RES_t^{Gov} - GB_t \quad (170)$$

Central bank's net worth (the net worth of the central bank should be equal to zero, as it does not do capital gains):

$$V_t^{CB} = GB_t^{CB} + A_t - HPM_t - D_t^{Gov} - RES_t^{Gov} = 0 \quad (171)$$

Net lending positions

Net lending position of households:

$$NLP_t^H = YD_t - C_t^H - I_t^H = \Delta D_t^H - \Delta L_t^{HB} - \Delta L_t^{HG} + \sum_m \bar{p}_b^m \Delta b_t^{H_m} - DL_t^{HB} - DL_t^{HG} \quad (172)$$

Net lending position of firms:

$$\begin{aligned} NLP_t^n &= RP_t^n - I_t^n \\ &= \Delta D_t^n - \Delta L_t^{nB} - \Delta L_t^{nG} - \sum_n \bar{p}_b^{n_B} \Delta b_t^{n_B} - \sum_n \bar{p}_b^{n_G} \Delta b_t^{n_G} - DL_t^{nB} - DL_t^{nG} \end{aligned} \quad (173)$$

Net lending position of banks:

$$NLP_t^{Bk} = RP_t^{Bk} = \Delta L_t^{Bk} - \Delta D_t^{Bk} + \Delta GB_t^{Bk} - \Delta A_t + \Delta HPM_t + DL_t^{Bk} \quad (174)$$

Net lending position of the government:

$$NLP_t^{Gov} = R_t^{Gov} - G_t^{Gov} - I_t^{Gov} = \Delta D_t^{Gov} - \Delta GB_t + \Delta RES_t^{Gov} \quad (175)$$

Net lending position of the central bank:

$$NLP_t^{CB} = 0 = \Delta D_t^{Gov} - \Delta GB_t^{CB} - \Delta A_t + \Delta HPM_t + \Delta RES_t^{Gov} \quad (176)$$

Appendix 4.2 Balance sheet matrix

Table 10: Balance sheet matrix

	Households	Consumption goods firms	Green capital firms	Brown capital firms	Banks	Government	Central bank	Total
Capital stock	$+K_t^H$	$+K_t^F$	$+K_t^G$	$+K_t^B$		$+K_t^{Gov}$		$+K_t$
Deposits	$+D_t^H$	$+D_t^F$	$+D_t^G$	$+D_t^B$	$-D_t$	$+D_t^{Gov}$	$-D_t^{Gov}$	0
Loans	$-L_t^H$	$-L_t^F$	$-L_t^G$	$-L_t^B$	$+L_t$			0
Government bonds					$+GB_t^{Bk}$	$-GB_t$	$+GB_t^{CB}$	0
Corporate bonds	$+\overline{p}_{b,t}b_t^H$	$-\overline{p}_{b,t}b_t^F$	$-\overline{p}_{b,t}b_t^G$	$-\overline{p}_{b,t}b_t^B$				0
Advances					$-A_t$		$+A_t$	0
High-powered money					$+HPM_t$		$-HPM_t$	0
Loan guarantee reserves						$+RES_t^{Gov}$	$-RES_t^{Gov}$	0
Net worth	$+V_t^H$	$+V_t^F$	$+V_t^G$	$+V_t^B$	$+V_t^{Bk}$	$+V_t^{Gov}$	$+V_t^{CB}$	$+K_t$

Appendix 4.3 Transaction flow matrix

Table 11: Transaction flow matrix

	Households		Consumption goods firms		Green capital firms		Brown capital firms		Banks		Government		Central bank		Total
	Current	Capital	Current	Capital	Current	Capital	Current	Capital	Current	Capital	Current	Capital	Current	Capital	
Private consumption	$-C_t^H$		$+C_t^H$												0
Government consumption			$+C_t^{Gov}$								$-C_t^{Gov}$				0
Brown investment		$-I_t^{HB}$		$-I_t^{FB}$		$-I_t^{GB}$	$+I_t^B$	$-I_t^{BB}$				$-I_t^{GovB}$			0
Green investment		$-I_t^{HG}$		$-I_t^{FG}$	$+I_t^G$	$-I_t^{GG}$		$-I_t^{BG}$				$-I_t^{GovG}$			0
Wages	$+WB_t$		$-WB_t^F$		$-WB_t^G$		$-WB_t^B$								0
Taxes	$-T_t^H$		$-T_t^F$ $-CT_t^F$		$-T_t^G$ $-CT_t^G$		$-T_t^B$ $-CT_t^B$		$-T_t^{Bk}$		$+T_t + CT_t$				0
Firms profits	$+DP_t^H$		$-TP_t^F$	$+RP_t^F$	$-TP_t^G$	$+RP_t^G$	$-TP_t^B$	$+RP_t^B$			$+DP_t^{Gov}$				0
Bank profits	$+DP_t^{Bk}$								$-TP_t^{Bk}$	$+RP_t^{Bk}$					0
Central bank profits											$+TP_t^{CB}$		$-TP_t^{CB}$		0
Households' savings	$-(YD_t^H - C_t^H)$	$+(YD_t^H - C_t^H)$													0
Government's net savings											$-(R_t^{Gov} - G_t^{Gov})$	$+(R_t^{Gov} - G_t^{Gov})$			0
Interest on deposits	$+r_{t-1}^D D_{t-1}^H$		$+r_{t-1}^D D_{t-1}^F$		$+r_{t-1}^D D_{t-1}^G$		$+r_{t-1}^D D_{t-1}^B$		$-r_{t-1}^D D_{t-1}$		$+r_{t-1}^D D_{t-1}^{Gov}$		$-r_{t-1}^D D_{t-1}^{Gov}$		0
Interest on loans	$-Int_{t-1}^H$		$-Int_{t-1}^F$		$-Int_{t-1}^G$		$-Int_{t-1}^B$		$+Int_{t-1}$						0
Interest on government bonds									$+r_{t-1}^{GovGB} B_{t-1}^{Bk}$		$-r_{t-1}^{Gov} GB_{t-1}$		$+r_{t-1}^{GovGB} B_{t-1}^{CB}$		0
Interest on corporate bonds	$+Int_{b,t-1}^H$		$-Int_{b,t-1}^F$		$-Int_{b,t-1}^G$		$-Int_{b,t-1}^B$								0
Interest on advances									$-r^A A_{t-1}$				$+r^A A_{t-1}$		0
Interest on loan guarantee reserves											$+r_{t-1}^{Gov} RES_{t-1}^{Gov}$		$-r_{t-1}^{Gov} RES_{t-1}^{Gov}$		0
Δ Deposits		$-\Delta D_t^H$		$-\Delta D_t^F$		$-\Delta D_t^G$		$-\Delta D_t^B$		$+\Delta D_t$		$-\Delta D_t^{Gov}$		$+\Delta D_t^{Gov}$	0
Δ Loans		$+\Delta L_t^H$		$+\Delta L_t^F$		$+\Delta L_t^G$		$+\Delta L_t^B$		$-\Delta L_t$					0
Δ GB										$-\Delta GB_t^{Bk}$		$+\Delta GB_t$		$-\Delta GB_t^{CB}$	0
ΔB		$-\overline{p}_{b,t} \Delta b_t^H$		$+\overline{p}_{b,t} \Delta b_t^F$		$+\overline{p}_{b,t} \Delta b_t^G$		$+\overline{p}_{b,t} \Delta b_t^B$							0

Δ Advances										$+\Delta A_t$				$-\Delta A_t$	0
Δ High powered money										$-\Delta HPM_t$				$+\Delta HPM_t$	0
Δ Loan guarantee reserves												$-\Delta RES_t^{Gov}$		$+\Delta RES_t^{Gov}$	0
Defaulted loans		$+DL_t^H$		$+DL_t^F$		$+DL_t^G$		$+DL_t^B$		$-DL_t$					0
Guarantee payments									$+\rho_G \sum_n DL_t^{nG}$		$-\rho_G \sum_n DL_t^{nG}$				0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 4.4 Parameters

Table 12: Parameters

Parameter	Description	Value	Source
Firms			
λ_1^B	Elasticity of the investment in brown capital relative to the price of brown capital	-0.02	Selected in a range of reasonable values
λ_2^B	Elasticity of the investment in brown capital relative to the price of green capital	0.02	Selected in a range of reasonable values
λ_3^B	Elasticity of the investment in brown capital relative to the financing cost of brown capital	-7	Selected in a range of reasonable values
λ_4^B	Elasticity of the investment in brown capital relative to the financing cost of green capital	7	Selected in a range of reasonable values
λ_5^B	Elasticity of the investment in brown capital relative to the depreciation rate of brown capital	0	Assumption that the depreciation rates on green and brown capital are the same
λ_6^B	Elasticity of the investment in brown capital relative to the depreciation rate of green capital	0	Assumption that the depreciation rates on green and brown capital are the same
λ_7^B	Elasticity of the investment in brown capital relative to the risk on brown capital investment	-0.2	Selected in a range of reasonable values
λ_8^B	Elasticity of the investment in brown capital relative to the risk on green capital investment	0.2	Selected in a range of reasonable values
λ_9^B	Elasticity of the investment in brown capital relative to brown capital productivity	200	Selected in a range of reasonable values
λ_{10}^B	Elasticity of the investment in brown capital relative to green capital productivity	-200	Selected in a range of reasonable values

λ_{11}^B	Elasticity of the investment in brown capital relative to the unit production cost when using brown capital	-30	Selected in a range of reasonable values
λ_{12}^B	Elasticity of the investment in brown capital relative to the unit production cost when using green capital	30	Selected in a range of reasonable values
ω^B	Perceived risk of investing in brown capital	0.5	Selected in a range of reasonable values
γ_i	Adjustment factor of investment to the capacity utilization rate	0.7	Calibrated such that the model generates the baseline scenario
κ_{CT}	Sensitivity of the price markup rate to carbon tax costs	0.2	Deduced from Känzig (2023)
π^H	Share of firms' profits going to households as distributed profits	0.7	Computed such as the share of firms distributed profits is equal to 0.75 (Dunz et al., 2021)
π^{Gov}	Share of firms' profits going to the government as distributed profits	0.05	Computed such as the share of firms distributed profits is equal to 0.75 (Dunz et al., 2021)
η	Share of firms' profits going to investment	0.25	Following Dunz et al. (2021)
$\bar{u}$	Capacity utilization rate target	0.75	Botte (2020)
δ	Depreciation rate on green/brown capital	0.1	Following Dunz et al. (2021)
$\bar{\theta}$	Constant markup rate	1.04	Calibrated such that the model generates the baseline scenario
μ_{pb}	Sensitivity of the par value of bonds relative to bond prices	0.1	Selected in a range of reasonable values

$\mu_{b,0}$	Constant term in the share of corporate bonds in the external financial needs	0.1	Calibrated to generate baseline
$\mu_{b,1}$	Sensitivity of the share of bonds relative to the bonds' interest rate	0.8	Selected in a range of reasonable values
$\mu_{b,2}$	Sensitivity of the share of bonds relative to the loan's interest rate	0.8	Selected in a range of reasonable values
κ_I	Sensitivity of the autonomous demand for green/brown capital relative to the share of green/brown investment in the economy in the previous period	0.9	Selected in a range of reasonable values
ν_ϵ	Sensitivity of labor productivity growth to real output growth	0.825	From Dafermos & Nikolaidi (2021)
ν_{w1}	Sensitivity of nominal wage growth to past inflation	0.7	Calibrated to generate baseline
ν_{w2}	Sensitivity of nominal wage growth to past growth	1.1	Calibrated to generate baseline
$sh_{MIN}^{k_G}$	Minimal value of the share of green capital in the economy used to compute the evolution of risks for firms and banks, of the probability of defaults on green loans, and of capital productivity	0.2	Calibrated to generate baseline
$sh_{MAX}^{k_G}$	Maximum value of the share of green capital in the economy used to compute the evolution of capital productivity	0.8	Calibrated to generate baseline
$sh_{MID}^{k_G}$	Middle value of the share of green capital in the economy used to compute the evolution of risk for firms and banks, and the probability of defaults on green loans	0.5	Selected in a range of reasonable values

par_a	Steepness of the approximated logistic function of capital productivities	20	Selected in a range of reasonable values
par_b	Midpoint of the approximated logistic function of capital productivities	0.5	Selected in a range of reasonable values
par_e	Steepness of the approximated logistic function of the probability of defaults on green loans related to the share of green capital in the economy	30	Selected in a range of reasonable values
par_d	Midpoint of the approximated logistic function of the probability of defaults on green loans related to the share of green capital in the economy	0.35	Selected in a range of reasonable values
par_f	Steepness of the approximated logistic function of the risk for firms	30	Selected in a range of reasonable values
par_g	Midpoint of the approximated logistic function of the risk for firms	0.35	Selected in a range of reasonable values
par_h	Steepness of the approximated logistic function of the perception of risk by banks	30	Selected in a range of reasonable values
par_i	Midpoint of the approximated logistic function of the perception of risk by banks	0.35	Selected in a range of reasonable values
par_j	Steepness of the approximated logistic function of the share of green capital to follow the regulation	10	Selected in a range of reasonable values
par_k	Midpoint of the approximated logistic function of the share of green capital to follow the regulation	0.5	Selected in a range of reasonable values
par_l	Steepness of the approximated logistic function of the share of brown investment by the	0.5	Selected in a range of reasonable values

	government when the green public expenditure policy modifies this share		
par_n	Number of years needed to reach the target share of government brown investment when the green public expenditure policy modifies this share	20	Selected in a range of reasonable values
par_s	Steepness of the approximated logistic function of the probability of defaults on green loans related to the age of the loan	0.5	Selected in a range of reasonable values
par_m	Midpoint of the approximated logistic function of the probability of defaults on green loans related to the age of the loan	10	Selected in a range of reasonable values
ϕ_{MIN}^B	Minimum share of brown capital investment	0.1	Selected in a range of reasonable values
ϕ_{MIN}^G	Minimum share of green capital investment	0.2	Calibrated to generate baseline
ϕ_{MAX}^B	Maximum share of brown capital investment	0.8	Calibrated to generate baseline
ϕ_{MAX}^G	Maximum share of green capital investment	0.9	Selected in a range of reasonable values
def_0	Parameter of the default rate function	0.55	Calibrated to generate baseline
def_1	Parameter of the default rate function	6.12	From Dafermos & Nikolaidi (2021)
def_2	Parameter of the default rate function	3	Calibrated to generate baseline
Households			
$\lambda_1^{H_B}$	Elasticity of the investment in brown capital relative to the price of brown capital in the	-0.02	Selected in a range of reasonable values

	portfolio allocation model of households' investment		
λ_2^{HB}	Elasticity of the investment in brown capital relative to the price of green capital in the portfolio allocation model of households' investment	0.02	Selected in a range of reasonable values
λ_3^{HB}	Elasticity of the investment in brown capital relative to the productivity of brown capital in the portfolio allocation model of households' investment	200	Selected in a range of reasonable values
λ_4^{HB}	Elasticity of the investment in brown capital relative to the productivity of green capital in the portfolio allocation model of households' investment	-200	Selected in a range of reasonable values
α_1	Propensity to consume out of disposable income	0.83	Calibrated such that the propensity to consume and investment out of disposable income is equal to the EU average in 2015 (Dunz et al., 2021)
α_2	Propensity to consume out of wealth	0.01	Calibrated to generate baseline
α_3	Propensity to invest out of disposable income	0.02	Calibrated such that the propensity to consume and investment out of disposable income is equal to the EU average in 2015 (Dunz et al., 2021)
α_4	Propensity to invest out of wealth	0.01	Calibrated to generate baseline
κ_H	Sensitivity of the ratio of the investment constraint of households relative to the gap between their past investment and their investment target	0.1	Selected in a range of reasonable values

ζ^H	Share of households' investment target financed through loans	0.6	Equal to the initial share of loans in households' capital
κ_1^H	Adjustment rate on households' loan interest rates related to defaults and disposable income	0.1	Selected in a range of reasonable values
$\lambda_0^{D^H}$	Autonomous demand of deposits in the portfolio allocation model of the financial wealth of households	0.6822	Computed as the ratio of initial households' deposits and initial households' financial wealth
λ_1^{AH}	Elasticity of the demand of AH relative to the interest rate on deposits in the portfolio allocation model of financial wealth of households ($AH = D^H, B^{H_{FG}}, B^{H_{FB}}, B^{H_{BG}}, B^{H_{BB}}, B^{H_{GG}}$).	0.12 for deposits and -0.02 for other assets	Selected in a range of reasonable values
λ_2^{AH}	Elasticity of the demand of AH relative to the interest rate on brown bonds of consumption goods producers in the portfolio allocation model of financial wealth of households ($AH = D^H, B^{H_{FG}}, B^{H_{FB}}, B^{H_{BG}}, B^{H_{BB}}, B^{H_{GG}}$).	0.12 for brown bonds of consumption goods producers and -0.02 for other assets	Selected in a range of reasonable values
λ_3^{AH}	Elasticity of the demand of AH relative to the interest rate on green bonds of consumption goods producers in the portfolio allocation model of financial wealth of households ($AH = D^H, B^{H_{FG}}, B^{H_{FB}}, B^{H_{BG}}, B^{H_{BB}}, B^{H_{GG}}$).	0.12 for green bonds of consumption goods producers and -0.02 for other assets	Selected in a range of reasonable values
λ_4^{AH}	Elasticity of the demand of AH relative to the interest rate on brown bonds of brown capital producers in the portfolio allocation model of financial wealth of households ($AH =$	0.12 for brown bonds of brown capital producers and -0.02 for other assets	Selected in a range of reasonable values

λ_5^{AH}	$D^H, B^{H_{FG}}, B^{H_{FB}}, B^{H_{BG}}, B^{H_{BB}}, B^{H_{GG}}$). Elasticity of the demand of AH relative to the interest rate on green bonds of brown capital producers in the portfolio allocation model of financial wealth of households ($AH = D^H, B^{H_{FG}}, B^{H_{FB}}, B^{H_{BG}}, B^{H_{BB}}, B^{H_{GG}}$).	0.12 for green bonds of brown capital producers and -0.02 for other assets	Selected in a range of reasonable values
λ_6^{AH}	$D^H, B^{H_{FG}}, B^{H_{FB}}, B^{H_{BG}}, B^{H_{BB}}, B^{H_{GG}}$). Elasticity of the demand of AH relative to the interest rate on brown bonds of green capital producers in the portfolio allocation model of financial wealth of households ($AH = D^H, B^{H_{FG}}, B^{H_{FB}}, B^{H_{BG}}, B^{H_{BB}}, B^{H_{GG}}$).	0.12 for brown bonds of green capital producers and -0.02 for other assets	Selected in a range of reasonable values
λ_7^{AH}	$D^H, B^{H_{FG}}, B^{H_{FB}}, B^{H_{BG}}, B^{H_{BB}}, B^{H_{GG}}$). Elasticity of the demand of AH relative to the interest rate on green bonds of green capital producers in the portfolio allocation model of financial wealth of households ($AH = D^H, B^{H_{FG}}, B^{H_{FB}}, B^{H_{BG}}, B^{H_{BB}}, B^{H_{GG}}$).	0.12 for green bonds of green capital producers and -0.02 for other assets	Selected in a range of reasonable values
Government			
g_{τ}^{CT}	Growth rate of the carbon tax rate	0.07	Calibrated such that the share of green capital in the economy reaches 80% in $t = 80$ when a carbon tax is implemented in Scenario 1
τ_{RED}	Rate of carbon tax revenue redistribution	0	
g_{ϕ^G}	Growth rate of the share of green capital investment to follow the regulation	0.008	Calibrated such that the share of green capital in the economy reaches 80% in $t = 80$ when a regulation is

			implemented in Scenario 1
$\overline{sh}^{k_G}$	Targeted share of green capital in the economy	0.8	
τ^n	Firms' profits tax rate	0.15	Selected in a range of reasonable values following Dafermos & Nikolaidi (2021)
τ^H	Households' tax rate	0.23	Calibrated to generate baseline following Dafermos & Nikolaidi (2021)
τ^{Bk}	Banks' profits tax rate	0.15	Same as firms
r^{Gov}	Interest rate on government bonds	0.025	Dafermos & Nikolaidi (2021)
$\bar{G}$	Government running costs	10 000	Calibrated to generate baseline
g_1^{Gov}	Propensity to consume out of government revenue	0.73	Calibrated to have the share of government consumption in GDP at 20% in the baseline (World Bank, 2025b)
g_2^{Gov}	Propensity to invest out of government revenue	0.11	Calibrated to generate baseline
d^T	Target ratio of government deposits to government bonds	0.1	Selected in a range of reasonable values
g_{ρ_G}	Growth rate of guarantees	0.0004	Calibrated such that the share of green capital in the economy reaches 80% in $t = 80$ when a green guarantee policy is implemented in Scenario 1
ρ_{RES}	Rate of reserves on guaranteed loans	0.1	Selected in a range of reasonable values

g_{sl_G}	Growth rate of the share of the supplementary amount of public green investment in output	0.22	Calibrated such that the share of green capital in the economy reaches 80% in $t = 80$ when a green public investment policy is implemented in Scenario 1
λ_1^{GOVB}	Elasticity of the investment in brown capital relative to the price of brown capital in the portfolio allocation model of government investment	-0.02	Selected in a range of reasonable values
λ_2^{GOVB}	Elasticity of the investment in brown capital relative to the price of green capital in the portfolio allocation model of government investment	0.02	Selected in a range of reasonable values
λ_3^{GOVB}	Elasticity of the investment in brown capital relative to the productivity of brown capital in the portfolio allocation model of government investment	200	Selected in a range of reasonable values
λ_4^{GOVB}	Elasticity of the investment in brown capital relative to the productivity of green capital in the portfolio allocation model of government investment	-200	Selected in a range of reasonable values
Banks			
π^{HBk}	Share of banks' profits going to households as distributed profits	0.2	Calibrated to generate baseline
ω_L^1	Risk-weight on loans	1	Following Dafermos & Nikolaidi (2021)
CAR^T	Targeted capital adequacy ratio	0.18	ECB (2020)
κ_0	Capital adequacy ratio adjustment rate	5	Selected from a range of reasonable values
κ_1	Sectoral interest rate adjustment rate related to green/brown defaults	0.8	Selected from a range of reasonable values

κ_2	Sectoral interest rate adjustment rate related to firms' debt service ratio	0.02	Following Dafermos & Nikolaidi (2021)
spr^L	Minimum banks' profit markup on top of the risk-free interest rate	0.029	Computed such as the lending spread on brown loans ($spr^L - \kappa_0 \frac{CAR_t - CAR^T}{CAR^T} + \kappa_1 \frac{DL_t^{nB}}{L_{t-1}^{nB}} + \kappa_2 dsr_t^n$) is equal to 5.9% (World Bank, 2025b), Interest rate spread (lending rate minus deposit rate, %))
h_1	Share of deposits required for banks to have as high-powered money	0.18	Based on World Bank, following Dafermos & Nikolaidi (2021)
h_2	Share of deposits invested by banks in government bonds	0.2	Calibrated to generate baseline
M	Loans maturity	30	Selected from a range of reasonable values
Central bank			
$\bar{r}$	Central Bank base interest rate	0.03	Following Dafermos & Nikolaidi (2021)
r^A	Central Bank interest rate on advances	0.03	Following Dafermos & Nikolaidi (2021)

Appendix 4.5 Variables

Table 13: Variables

Variables	Description	Initial value
Production, investment, and capital in the economy		
Y_t	Output in the economy	Sum of the product $\sum_n y_t^n p_t^n$
y_t	Real output in the economy	Sum of production $\sum_n y_t^n$

$g_{y,t}$	Real output growth rate	
$g_{p_Y,t}$	Inflation growth rate	
$p_{y,t}$	Average price of output	Calculated from Eq.(54) using the initial values of Y_t^n and p_t^n
y_t^n	Real output of firms n	Calculated as $\frac{Y_t^n}{p_t^n}$
Y_t^F	Output of the consumption good firms	Calculated from Eq.(35) using the initial values of C_t^H and C_t^{Gov}
Y_t^G	Output of the green capital producers	Calculated from Eq.(36) using the initial values of i_t^{jG} (j = B, G, F, H, Gov)
Y_t^B	Output of the brown capital producers	Calculated from Eq.(37) using the initial values of i_t^{jB} (j = B, G, F, H, Gov)
I_t^j	Investment of agent j with j = B, G, F, H, Gov	Calculated as $I_t^{jB} + I_t^{jG}$
I_t^{jB}	Brown investment of agent j (j = B, G, F, H, Gov)	Calculated as $p_t^{jB} i_t^{jB}$
I_t^{jG}	Green investment of agent j (j = B, G, F, H, Gov)	Calculated as $p_t^{jG} i_t^{jG}$
i_t^j	Investment of agent j (j = B, G, F, H, Gov)	Calculated as $i_t^{jG} + i_t^{jB}$
i_t^{jG}	Green investment of agent j (j = B, G, F, H, Gov)	Calculated as $i_t^{jG} = \delta k_t^{jG}$
i_t^{jB}	Brown investment of agent j (j = B, G, F, H, Gov)	Calculated as $i_t^{jB} = \delta k_t^{jB}$
Φ_t^{jG}	Share of green investment of agent j (j = B, G, F, H, Gov)	Calculated from Eq.(2), Eq.(115), and Eq.(138) using the initial values of the variables of the portfolio allocation model.
Φ_t^{jB}	Share of brown investment of agent j (j = B, G, F, H, Gov)	Calculated from Eq.(1), Eq.(6), and Eq.(136) using the initial values of the variables of the portfolio allocation model.

K_t	Total amount of capital in the economy	Calibrated to reach the target value of capital stock
sh_t^{kz}	Share of green/brown capital in the economy ($z = B, G$)	20%
Firms		
$\lambda_{0,t}^B$	Autonomous brown capital demand by firms	80%
p_t^n	Price of production n ($n = B, G, F$)	Calculated from Eq.(22) using the initial values of w_t and ϵ_t^N
θ_t^n	Price markup rate	Calibrated to allow a 49% wage share in GDP (Timmer et al., 2015)
ϵ_t^B	Productivity of brown capital	1.00015
ϵ_t^G	Productivity of green capital	1.00005
N_t^n	Labor in working hours in production n ($n = B, G, F$)	Calculated as $N_t^n = \frac{y_t^n}{\epsilon_t^N}$
K_t^n	Capital services in production n ($n = B, G, F$)	Calculated as $p_t^n k_t^n$
w_t	Wage rate	100
ϵ_t^N	Labor productivity	1
WB_t^n	Wage bill in production n	Calculated from Eq.(60) with the initial values w_t , ϵ_t^N and y_t^n
UC_t^n	Unit cost in production n	Calculated from Eq.(56) using the initial values of w_t and ϵ_t^N
KB_t^{nG}	Cost of green capital in firm n	Calculated from Eq.(59) using the initial values of Int_t^{nG} , $c_{b,t}^{nG}$, b_t^{HnG} , $c_{b,t}^{nG}$, b_t^{CBnG}
KB_t^{nB}	Cost of brown capital in firm n	Calculated from Eq.(60) using the initial values of Int_t^{nB} , $c_{b,t}^{nB}$, b_t^{HnB} , $c_{b,t}^{nB}$, b_t^{CBnB}
KB_t^n	Capital cost in firm n	Calculated from Eq.(62) with the initial values of KB_t^{nG} and KB_t^{nB}
CT_t^n	Carbon tax on production n	0

ω_t^G	Perceived risk of investing in green capital for firms	Scenario variable
K_t^{nG}	Green capital in production n	Calculated as $p_t^G k_t^{nG}$
K_t^{nB}	Brown capital in production n	Calculated as $p_t^B k_t^{nB}$
k_t^n	Real capital stock in production n	Calculated as the product between average firms' capital share (OECD, 2019) and total capital K_t divided by the price of capital
k_t^{nG}	Real green capital stock in production n	Calculated as $\phi_t^{nG} k_t^n \frac{y_t^n}{\sum_n y_t^n}$, so that the green capital stock of firm n depends on the share of green capital and the share of the firm's value-added in total value-added
k_t^{nB}	Real brown capital stock in production n	Calculated as $\phi_t^{nB} k_t^n \frac{y_t^n}{\sum_n y_t^n}$, so that the brown capital stock of firm n depends on the share of brown capital and the share of the firm's value-added in total value-added
u_t^n	Capacity utilization rate in production n	Calculated from Eq.(74) with the initial values of $y_t^n, \epsilon_t^B, k_t^{nB}, \epsilon_t^G, k_t^{nG}$
Π_t^n	Profits of firm n	Calculated from Eq.(20) with the initial values of $Y_t^n, WB_t^n, KB_t^n, r_t^D D_t^n, T_t^n$
T_t^n	Tax on profits of firm n	Calculated from Eq.(66) with the initial values of $Y_t^n, WB_t^n, KB_t^n, r_t^D D_t^n$
DP_t^{Hn}	Distributed profits of firm n to households	Calculated as $\pi^H \Pi_t^n$
DP_t^{Govn}	Distributed profits of firm n to the government	Calculated as $\pi^{Gov} \Pi_t^n$
RP_t^n	Retained profits of firm n	Calculated from Eq.(68) with the initial values of Π_t^n
$\sigma_{L,t}^{nG}$	Share of green loans in firms n external financial needs	Calculated as $(1 - \sum_n \sigma_{b,t}^{nG})$

$\sigma_{L,t}^{nB}$	Share of brown loans in firms n external financial needs	Calculated as $(1 - \sum_n \sigma_{b,t}^{nB})$
D_t^n	Deposits of firm n	Calculated as $\sum_n D_t^n \frac{y_t^m}{\sum_m y_t^m}$
$illiq_t^n$	Illiquidity ratio of firms n	Calculated from Eq.(10)
dsr_t^n	Debt service ratio of firms n	Calculated from Eq.(162)
Firms' loans		
$L_{v,t}^m$	Stock of loan vintage m contracted at time v ($m = B_G, B_B, G_G, G_B, F_G, F_B$)	Calculated as $\phi_t^m (L_t^F + L_t^B + L_t^G) \frac{y_t^m}{\sum_m y_t^m}$ so that the green/brown loans stock of firm n depends on the share of green/brown capital and the share of the firm's value-added in total value-added. The total amount of firms loans is computed as $L_t^F + L_t^B + L_t^G = \left(credit - \frac{\sum_n B_t^n}{Y_t}\right) Y_t$ where credit represents the share of total credit to the non-financial corporations in percent of GDP taken from BIS (2019) (it is assumed that credit includes both loans and bonds)
r_v^m	Interest rate on loan m contracted at time v	Equal to r_t^L in base year
$REP_{v,t}^m$	Repayments on loan m contracted at time v	Calculated from Eq.(89)
REP_t^m	Total repayments on loans m	Calculated from Eq.(90)
REP_t^n	Total repayments of firm n	Calculated from Eq.(69)
$Int_{v,t}^m$	Interest payments on vintage v of loan m	Calculated from Eq.(88)
$\varphi_{v,t}^{nB}$	Probability of default on brown loans of n contracted at time v	Calculated from Eq.(11)
$\varphi_{v,t}^{nG}$	Probability of default on green loans of n contracted at time v	Calculated from Eq.(17) with the initial values of φ_t^{illiqn} , φ_{t-v}^V and φ_v^ϵ
φ_t^{illiqn}	Probability of default on loans related to the illiquidity ratio of firms n	3% (European Banking Authority, 2019)

$\varphi_{v,t}^V$	Probability of default on green loans related to the age of the loan	Calculated from Eq.(100)
φ_v^ϵ	Probability of default on green loans related to the share of green capital in the economy	Scenario variable
DL_t^m	Defaults on loans m	Calculated from Eq.(9) with the initial values of $\varphi_{v,t}^m$ and $L_{v,t}^m$
$AL_{v,t}^m$	Annual capital cost on loan m contracted at time v	Calculated from Eq.(87)
L_t^m	Total loan stock of loans m	Equal to $L_{v,t}^m$
$L_{t,t}^m$	New loans m contracted at time t	Calculated from Eq.(92)
Corporate bonds		
$\sigma_{b,t}^m$	Share of external financial needs covered by corporate bonds m	Computed from Eq.(79)
$c_{b,t}^m$	Coupon of bond m	Computed from Eq.(106) such that the share of an asset in the portfolio of households is equal to the initial share of the asset
$r_{b,t}^m$	Interest rate on bonds m	Calculated from Eq.(82) with the initial values of $c_{b,t}^m$ and $p_{b,t}^m$
$p_{b,t}^m$	Price of bonds m	100
$\overline{p_{b,t}^{nG}}$	Par value of green corporate bonds of firm n	100
$\overline{p_{b,t}^{nB}}$	Par value of brown corporate bonds of firm n	100
b_t	Total quantity of bonds	Calibrated to generate baseline
b_t^m	Quantity of bonds m	Calculated as $\phi_t^m b_t \frac{y_t^m}{\sum_m y_t^m}$, so that the green/brown bonds quantity of firm n depends on the share of green/brown capital and the share of the firm's value-added in total value-added
b_t^{Hm}	Quantity of bond m held by households	Equals to b_t^m

B_t^m	Value of bonds m	Calculated as $p_{b,t}^m b_t^m$
B_t^{Hm}	Quantity of bond m held by households	Equals to B_t^m
Households		
YD_t	Disposable income	Calculated from Eq.(101)
Int_t^H	Interest payments on households' loans	Calculated from Eq.(104)
Int_t^{Hz}	Interest payments on households' loans on loans z (z = G, B)	Calculated from Eq.(103)
T_t^H	Income tax	Calculated from Eq.(102)
D_t^H	Deposits of households	Calculated as $D_t^{Bk} - \sum_n D_t^n$
r_v^{Hz}	Interest rate on household loans z contracted at time v	Equals to r_t^L in base year
$L_{v,t}^{Hz}$	Loan stock of loan z contracted at time v	Calculated as $\phi_t^{Hz} L_t^H$ so that the green/brown loans stock of firm n depends on the share of green/brown capital and the share of the firm's value-added in total value-added. The total amount of firms' loans is computed as $L_t^H = \text{credit } Y_t$ where credit represents the share of total credit to the households and non-profit institutions serving households in percent of GDP, taken from BIS (2019)
$REP_{v,t}^{Hz}$	Repayments on loan z contracted at time v	Calculated from Eq.(124)(125)
$\varphi_{v,t}^{Hz}$	Probability of default on households' loan z contracted at time v	3% (European Banking Authority, 2019)
$AL_{v,t}^{Hz}$	Annual capital cost corresponding to the vintage taken at time v	Calculated from Eq.(122)
REP_t^{Hz}	Total repayments on loans z of households	Calculated from Eq.(125)
DL_t^{Hz}	Households' defaults on loan z	Calculated from Eq.(128) with the initial values $\varphi_{v,t}^{Hz}$ and $L_{v,t}^{Hz}$
$L_{t,t}^{Hz}$	New loans contracted at time t	Calculated from Eq.(117)

$L_t^{H_z}$	Total stock of loan z of households	Equals to $L_{v,t}^{H_z}$
C_t^H	Consumption of households	Calculated from Eq.(105) with the initial values of YD_t and V_t^H
RED_t	Amount of carbon tax revenues that are redistributed	0
$\lambda_{0,t}^{HB}$	Autonomous brown capital demand in the portfolio allocation of households' investment	0.8
K_t^H	Households' capital	Calculated as the product of the share of capital held by households from (OECD, 2019) (average share of net fixed assets of households, non-profit institutions serving households, and financial corporations in total net fixed assets for 31 OECD countries in 2019) and the total amount of capital K_t from Timmer et al. (2015)
$K_t^{H_z}$	Households' capital z	Calculated as $K_t^{H_z} = \phi_t^{H_z} K_t^H$
V_t^H	Households' wealth	Calculated from Eq.(167)
$V_{F,t}^H$	Households' financial wealth	Calculated from Eq.(109)
μ_t^H	Sensitivity of the investment constraint of households to their past investment	1
$\lambda_{0,t}^{nB}$	Autonomous demand of brown corporate bonds in the portfolio allocation model of financial wealth of households	Calculated as $\frac{\sum_n B_t^{HnB}}{V_{F,t}^H}$
$\lambda_{0,t}^{nG}$	Autonomous demand of green corporate bonds in the portfolio allocation model of financial wealth of households	Calculated as $\frac{\sum_n B_t^{HnG}}{V_{F,t}^H}$
Government		
R_t^{Gov}	Government revenue	Calculated from Eq.(23)
C_t^{Gov}	Consumption of government	Calculated from Eq.(132)
G_t^{Gov}	Total government spending	Calculated from Eq.(27)

GB_t	Government bonds	Calculated as $GB_t = GB_t^{Bk} + GB_t^{CB}$
D_t^{Gov}	Deposits of the government in the central bank	Calculated such as $D_t^{Gov} = d^T GB_t$
K_t^{Gov}	Total government capital	Calculated as the product of the share of capital held by government computed from OECD (2019) (average share of net fixed assets of general government in total net fixed assets for 31 OECD countries in 2019) and the total amount of capital K_t from Timmer et al. (2015)
K_t^{Govz}	Government capital z	Calculated as $K_t^{Govz} = \phi_t^{Govz} K_t^{Gov}$
RES_t^{Gov}	Loan guarantee reserves	Calculated from Eq.(28)
$\lambda_{0,t}^{GovB}$	Autonomous brown capital demand in the portfolio allocation of government investment	0.8
τ_t^{CT}	Carbon tax rate	0.004
$s_{I_{G,t}}$	Share of the supplementary amount of public green investment in output	0.01
$\rho_{G,t}$	Rate of government guarantee on green loans	0.9 or 0.8
$\overline{\phi}_t^G$	Share of green capital investment allowing to follow the regulation	Calculated from Eq.(25)
$\overline{\phi}_t^{LG}$	Logistic function of the forced share of green capital investment to follow the regulation	Calculated from Eq.(48)
Banks		
Π_t^{Bk}	Banks' profits	Calculated from Eq.(148)
GB_t^{Bk}	Government bonds held by banks	Calculated from Eq.(153)
T_t^{Bk}	Tax on banks' profits	Calculated from Eq.(149)
DP_t^{Bk}	Distributed profits of banks to households	Calculated from Eq.(150)

RP_t^{Bk}	Retained profits of banks	Calculated from Eq.(151)
HPM_t^{Bk}	High-powered money in the central bank	Calculated from Eq.(152)
CAR_t	Capital adequacy ratio of banks	18% (ECB, 2020)
V_t^{Bk}	Capital of banks	Calculated from Eq.(169)
r_t^L	Interest rate on loans determined by banks	Calculated from Eq.(7)
r_t^D	Interest rate on deposits	Calculated from Eq.(7) with the initial CAR_t
D_t^{Bk}	Deposits in banks	Calculated as $D_t^{Bk} = GB_t - D_t^{Gov} + L_t^{Bk} - CAR_t L_t^{Bk}$ to allow that GB_t is equal to its base year value
χ_t^{Bk}	Perception of risk on green loans by banks	Scenario variable
Central bank		
Π_t^{CB}	Central bank profits	Calculated from Eq.(164)
A_t	Advances of the central bank to banks	Calculated as $A_t = L_t^{Bk} + HPM_t + GB_t^{Bk} - D_t^{Bk} - CAR_t L_t^{Bk}$, to allow the CAR of banks to be equal to its initial value
GB_t^{CB}	Government bonds held by the central bank	Calculated from Eq.(139), such as the net worth of the central bank equals zero

Appendix 4.6 Reproduction of stylized facts

The model is calibrated using global data for the year 2019. A set of stylized facts, drawn from empirical data, was selected as calibration targets for the baseline scenarios. The model is first solved at an artificial year zero, ensuring consistency with stock-flow norms and key macro-financial ratios such as the wage share and the capital adequacy ratio. Calibration parameters are then adjusted to guide the model toward a stable steady state that replicates the targeted stylized facts. All targets listed in Table 13 are met within a tolerance margin of less than 10% across simulations (less than 0.5 percentage points for government deficit in GDP, inflation, and output growth rates).

Table 14: Target values for endogenous variables

Variable	Description	Target value	Source
Y_t	Nominal GDP	88.15 trillion USD (World, 2019)	(World Bank, 2025b)
CAR_t	Banks' capital adequacy ratio	18% (EU, 2019)	(ECB, 2020)
$\frac{\sum_n WB_t^n}{Y_t}$	Wage share in GDP	49% (World, 2016)	(Timmer et al., 2015)
$g_{y,t}$	Real output growth rate	2.9% (World, 2019)	(IMF, 2020b)
$g_{p,y,t}$	Inflation growth rate	2.21% (World, 2019)	(World Bank, 2025b)
K_t	Total value of capital	226.32 trillion USD (World, 2016)	(Timmer et al., 2015)
$\frac{\Delta GB_t}{Y_t}$	Government deficit in GDP	-2% (between -0.1% and -3% in Advanced economies excluding the US, 2019)	(IMF, 2020a)
$\varphi_{v,t}^{n_B}, \varphi_{v,t}^{H_z}$	Average rate of defaults	2.7% (EU, 2019)	(European Banking Authority, 2019)