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The double materiality of climate physical and transition risks in the euro area

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Abstract

We analyse the double materiality of climate physical and transition risks in the euro area economy and banking sector. By tailoring the EIRIN Stock-Flow Consistent behavioural model, we provide a dynamic balance sheet assessment of the Network for Greening the Financial System scenarios. We find that an orderly transition achieves early co-benefits by reducing carbon emissions (12% less in 2040 than in 2020) while supporting growth in economic output. In contrast, a disorderly transition worsens the economic performance and financial stability of the euro area. Further, in disorderly transition with high physical risks, real GDP decreases by 12,5% in 2050 relative to an orderly transition. Second, by extending the concept of climate sentiments to firms, we analyse how expectations about climate policy credibility affect investment decision in high or low-carbon goods. Firms that trust an orderly policy introduction and anticipate carbon price scenarios switch earlier to low-carbon investments. This, in turn, accelerates economic decarbonization and decreases the risk of carbon stranded assets for investors. Our results highlight the crucial role of early and credible climate policies to signal investment decisions in the low-carbon transition.

JEL: B59, Q50.

Keywords: climate physical risk; climate transition risk; Network for Greening the Financial System scenarios; double materiality; Stock-Flow Consistent model.

Non-technical summary

Financial supervisors and policymakers, including the European Commission, have recognized the importance to disclose and assess climate-related financial risks. To support investors in this process, the Network for Greening the Financial System (NGFS) has developed supervisory climate mitigation scenarios for climate stress test. Recent studies contributed to assess the macro-financial relevance of climate scenarios. However, the opposite feedback loop, i.e. the impact of climate-adjusted financial risk assessment by banks, and of firms' expectations about carbon pricing (or climate sentiments), and the implications of both on investment decisions, have not been analysed yet. This represents a main knowledge gap to assess the double materiality of climate-related financial risks, and it could have a direct impact on the feasibility of climate scenarios themselves. We address this gap by tailoring the EIRIN Stock-Flow Consistent (SFC) model to run a dynamic macro-financial assessment of climate physical and transition risk scenarios of the euro area economy and banking sector. We quantitatively assess the feedback from banks' internalization of climate risk across NGFS scenarios on firms' performance, decarbonization and the low-carbon transition. Furthermore, we analyse the impact of firms' expectations about the impact of carbon pricing, coherently with the NGFS scenarios, on their business, and the anticipation in their investment decisions (i.e. firms' climate sentiments).

We find that, under the model conditions, an orderly transition achieves important co-benefits already in the midterm, with respect to CO_2 emissions' abatement, banks' financial stability and distributive effects. In contrast, a late and disorderly transition fosters banks' financial instability. This, in turn, leads to cascading effects onto the economy, affecting firms' ability to invest in the low-carbon transition, the realization of stranded assets, and households' inequality. The climate sentiments of firms with regard to their investments can further affect climate policy effectiveness in these scenarios. The impact on GDP of orderly and disorderly scenarios is relevant and significant, while the impact on GDP of the hot house world scenario is lower than expected. This result is largely driven by the NGFS scenarios design. Indeed, at their current stage, NGFS scenarios do not include acute physical risk, nor their potential compounding (Ranger et al., 2022). In addition, the long term dimension (after 2060) of chronic physical risk and its impacts are excluded by the time horizon of the analysis (which runs up to 2050).

Our results highlight the importance for financial supervisors to consider the role of the finance-economy-climate feedback, especially in the design of appropriate macro-prudential policies to tackle climate risks. In this regard, our analysis shows the contribution of SFC models for dynamic balance sheet assessment. Our results also point out the urgent need to strengthen climate physical risk scenarios in order to avoid underestimating risks.

1 Introduction

Climate change from unabated greenhouse gas (GHG) emissions is expected to increase acute and chronic physical risks, negatively affecting ecosystems, living conditions, the economy and finance (IPCC, 2014; IPCC, 2018; IPCC, 2021; IPCC, 2022). However, delays in climate policy action concern several central banks and financial supervisors, which recognized climate change as a source of risk for financial stability (Carney, 2015; Gros et al., 2016; Hilaire and Bertram, 2019; UNEP, 2020; Dunz and Power, 2021; BIS, 2021; Clerc et al., 2021; Brunetti et al., 2021) also building on research results (see e.g. Dietz et al., 2016; Battiston, Dafermos, et al., 2021; Battiston, Mandel, et al., 2017; Mercure, Hector Pollitt, et al., 2018).

Most literature focused on the impact of climate change and low-carbon transition in the economy and finance. However, so far the literature neglected the opposite feedback from investors' expectations about climate change and climate policies on their risk assessment, lending and investment decisions, is still missing. Analysing the "double materiality" of climate risk represents a main knowledge gap to analyse the role of finance and policies in achieving low-carbon transition scenarios (Battiston, Monasterolo, et al., 2021).

Our analysis contributed to fill this knowledge gap by providing a dynamic balance-sheet assessment of the double materiality of climate physical and transition risks in the euro area (EA) economy and banking sector. The double materiality concept was introduced in 2019 by the European Commission (European Commission, 2019) and considers both the impact of climate change on firms and on finance, as well as the impact of finance on firms' investments and through that on the climate (Oman, Svartzman, et al., 2021; Boissinot et al., 2022).

To analyse climate-related financial risks, the Network of Central Banks and Supervisors for Greening the Financial System (NGFS), which includes over 120 central banks and financial regulators worldwide,[1] has developed climate scenarios (NGFS, 2020) to support climate-financial risk assessment.[2] The NGFS scenarios provide climate transition pathways coherent with a 1.5 or 2°C carbon budget, considering the introduction of a carbon tax, technological change, and the laws of physics. Numerous investors already use the NGFS scenarios for climate stress-test (UNEP, 2020), including those required to assess climate-related financial risks by their supervisory authorities, and so do central banks and financial regulators.[3]

For instance, in 2021, the European Central Bank (ECB) economy-wide climate stress test used the first vintage of NGFS scenarios to assess the implications of transition and physical risk on a set of approximately 4 million companies and 1,600 consolidated banking groups in the EA (Alogoskoufis et al., 2021). More recently, the ECB Banking Supervision used the second vintage of NGFS scenarios to perform the 2022 climate stress test of 104 participating banks (ECB, 2022). Furthermore, the 2022 ECB/European Systemic Risk Board (ESRB) report analysed the impact of NGFS scenarios on

[1] https://www.ngfs.net/en

[2] For more information about the IAM community: https://www.iamconsortium.org/

[3] This includes stress tests by the Dutch National Bank (Vermeulen et al., 2018), Banque de France (Allen et al., 2020), the French market regulator (Clerc et al., 2021) and the National Bank of Austria (Guth et al., 2021).

corporates and financial institutions (ECB/ESRB, 2022).

While these, and other studies, examined the channel from climate scenarios to the economy and finance, the opposite link, from investors to the economy and decarbonization scenarios has yet to be analysed. This is a main knowledge gap to assess the double materiality of climate risks. Indeed, investors that look at climate scenarios may form expectations about the future profitability of high-carbon and low-carbon activities and adjust their investment decisions accordingly. For instance, if banks deem an early introduction of a carbon tax credible, they could revise their financial risk assessment for high- and low-carbon firms, by respectively increasing and decreasing the cost of capital (Battiston, Monasterolo, et al., 2021). Adjustments in firms' cost of capital, in turn, influence firms' investment decisions for high- and low-carbon goods. Similarly, if firms deem an orderly climate policy introduction likely, they would anticipate the impact of the carbon tax in their Net Present Value (NPV) calculations and switch earlier from high-carbon to low-carbon investments.

Our analysis builds on the EIRIN Stock-Flow Consistent behavioural model (Monasterolo and Raberto, 2018; Monasterolo and Raberto, 2019; Dunz, Essenfelder, et al., 2021) in which we embed the climate scenarios of the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) (NGFS, 2021). EIRIN is a macro-financial model populated by heterogeneous, interacting agents of the economy and finance, which are endowed with adaptive expectations. These features allow us to capture the effects of investors' expectations on the realization of climate mitigation scenarios, and on the costs and co-benefits that emerge in the economy.

Our approach complements the ECB economy-wide climate stress test (Alogoskoufis et al., 2021). Indeed, while we adopt the same NGFS climate scenarios used by the ECB, our analysis differs concerning the modelling solution, the climate-financial risk adjustment of banks, the treatment of expectations and decisions, and spatial resolution. We focus on the credit and equity markets, and we consider private investors, commercial banks and the ECB as financial actors. Then, we extend the concept of climate sentiments (Dunz, Naqvi, et al., 2021) to firms and analyse how firms' expectations about climate policy credibility affect their investment in high or low-carbon goods, and economic decarbonization. The importance of analysing feedback from investors' expectations about climate scenarios and their adjustment in investments in the economy has been recently recognized (Battiston, Monasterolo, et al., 2021; IPCC, 2022). Assessing this feedback loop is important to study the double materiality of climate risks (European Commission, 2019; ESMA, 2020; Oman, Svartzman, et al., 2021; Robins et al., 2021; Boissinot et al., 2022), and the costs and feasibility of the transition.

Our contribution to the state of the art is as follows:

(i) Analysing climate scenarios' entry points in the economy and the transmission channels to agents and sectors.

(ii) Providing a joint assessment of climate transition and physical risk scenarios in the economy and banking sector.

(iii) Modelling adjustment in firms' probability of default (PD) conditioned to the scenarios, and

their impact on credit risk adjustment and lending decisions.

(iv) Assessing how investors' expectations about climate policy credibility affect investment decisions and economic decarbonization.

Our results show that an orderly transition achieves early co-benefits by reducing carbon emissions (12% less in 2040 than in 2020) while supporting growth in economic output. In contrast, a disorderly transition worsens the euro area's economic performance and financial stability, while high physical risks can make real GDP 12,5% lower by 2050 relative to an orderly transition. Moreover, by extending the concept of climate sentiments, we analyse how firms' expectations about climate policy credibility affect their investment decision in high or low-carbon goods and the impact on economic decarbonization. We find that firms that trust an orderly policy introduction and anticipate carbon price scenarios switch earlier to low-carbon investments. This, in turn, contributes to decreasing the risk of stranded assets for the economy and for the banking sector. Our findings highlight the crucial role of early and credible climate policies to steer the economy towards a low-carbon transition while decreasing the risk of stranded assets.

The remainder of the paper is organized as follows. Section 2 provides a review of the state of the art about the macroeconomic and financial impacts of climate physical and transition risks. Section 3 describes the methodology, focusing on the novel characteristics of the EIRIN model introduced for this application. Section 4 presents the NGFS scenarios considered in the paper, and how chronic physical risk and transition risks scenarios are used as input to the EIRIN model. Section 5 presents the transmission channels of physical and transition risks to the agents and sectors of the economy and finance. Section 6 details the calibration of the model to the EA. Section 7 discusses the simulation results of the analysis, and section 8 concludes by discussing the implications of results for policy at central banks and financial supervisors.

2 Review of the state of the art and research challenges

2.1 Climate risks and financial stability

Financial supervisors identified two main channels of climate risks transmission to the economy and finance (Carney, 2015; Batten et al., 2016; Hilaire and Bertram, 2019), i.e.:

- *Climate physical risks*, arising from the impact of natural hazards (e.g. hurricanes, floods, droughts) on physical assets, lead to plants' destruction, lower firms' productive capacity and output, and lower value of firms' financial contracts. This, in turn, negatively affects the value of the portfolio of financial actors (e.g. banks, insurance, pension funds) who hold such contracts. For instance, a firm whose productive capital is destroyed by severe floods, and has borrowed from a bank, may not be able to repay the interests and principals of the loan, affecting the recovery rate and banks' balance sheet.

- *Climate transition risks*, stemming from a disorderly transition to a low-carbon economy, which is defined as a situation in which climate policies (e.g. carbon tax) and regulations are implemented late with regard to the climate targets and cannot be fully anticipated by investors. In this context, high-carbon firms are expected to experience higher costs and lower revenues, giving rise to "carbon stranded assets" (Leaton, 2011; Ploeg and Rezai, 2020; Cahen-Fourot et al., 2021). Carbon stranded assets, in turn, can lead to large adjustments in asset prices, with potential implications on economic and financial stability (Gros et al., 2016; Battiston, Mandel, et al., 2017; Stolbova et al., 2018).

Climate physical and transition risks are interconnected. Indeed, delaying the introduction of climate policies and the decarbonization of the economy leads to higher concentration of emissions in the atmosphere, and thus to a higher probability of earlier and more disruptive climate shocks (Monasterolo, 2020a).

In the last decade, several studies investigated the macroeconomic and financial impacts of climate physical and transition risks, and the introduction of most debated climate policies (i.e. green fiscal, monetary and macro-prudential policies) on the low-carbon transition, focusing on:

- The conditions for and impact of carbon pricing on the transition (Dafermos, Nikolaidi, and Galanis, 2017; Stolbova et al., 2018; Naqvi and Stockhammer, 2018; Bovari, Lecuyer, et al., 2018);
- The trade-offs that governments can face while financing the transition with a carbon tax or by issuing green sovereign bonds (Monasterolo and Raberto, 2018);
- The interplay between the phasing out of fossil fuel subsidies versus the introduction of a carbon tax (Monasterolo and Raberto, 2019);
- The interplay between feed-in tariffs and carbon pricing (Ponta et al., 2018);
- The role of green finance in supporting green innovation (D'Orazio and Valente, 2019) and its potential unintended effects on unequal diffusion of green technologies and assets in the global South (Carnevali et al., 2021);
- The role of green monetary policies implemented via asset purchase programs (Monasterolo and Raberto, 2017; Golosov et al., 2014; Dafermos, Nikolaidi, and Galanis, 2018), as well as environmental and monetary policy mix (Annicchiarico and Di Dio, 2017; Diluiso et al., 2020);
- Potential financial instability implications of private debt increase induced by sudden low-carbon transition policies (Bovari, Giraud, et al., 2018);
- The role of green macro-prudential policies, e.g. implemented via a Green Supporting Factor that affects banks' capital requirements (Carattini et al., 2021; Dunz, Naqvi, et al., 2021; Dafermos and Nikolaidi, 2021; Lamperti, Bosetti, et al., 2021).
- The impact of the transition on the realization of carbon stranded assets in the energy sector (Mercure, Hector Pollitt, et al., 2018; Mercure, Salas, et al., 2021);
- The impact of high-end carbon-intensive scenario consistent with a Representative Concentration Pathway (RCP) 8.5 on economic crises (Lamperti, Dosi, et al., 2018).

These studies contributed to better understand the macro-financial relevance of climate-related financial risk, addressing the climate-economy and/or finance impacts. However, the feedback from the impact of investors' expectations and adjustment in risk assessment onto firms' investment decisions and on the transition, is still missing.

2.2 Contribution to the state of the art

The concept of double materiality of climate risks stands on the recognition of a feedback loop between climate change and the financial system (European Commission, 2019). On the one hand, climate change can affect firms' investment and financial institutions' financing decisions by introducing new sources of risk (e.g. by decreasing the profitability of non-financial institutions to which financial institutions are exposed). On the other hand, financial institutions' investment decisions affect the realization of climate scenarios, through adjustments in risk assessment, potentially increasing the risks they are exposed to. This is a knowledge gap with relevant implications for monetary and macro-prudential policies.

Our paper contributes to fill this gap by addressing the following research questions:

- Through which channels climate physical and transition risks interact in the EA economy and finance?
- What are the drivers of climate shocks' amplification, and their implications in the economy and finance?
- Under which conditions firms' climate sentiments affect the decarbonization of the economy and the trajectories of NGFS scenarios?

Using the EIRIN model (Monasterolo and Raberto, 2018; Dunz, Essenfelder, et al., 2021), we quantitatively assess the double materiality feedback loop represented in figure 1, focusing on the credit and bonds markets, and on commercial banks and the ECB as financial actors. Capturing the finance-economy-climate feedback is fundamental to assess the double materiality of climate risks. In particular, it allows us to translate investors' expectations towards climate change and policy scenarios into a revision of their risk assessment and cost of capital, which in turn affects the feasibility of transition scenarios (Battiston, Monasterolo, et al., 2021).

3 Model description

Here we provide a description of the key structural and behavioural characteristics of the EIRIN model, as well as of the innovations specific to this application.

3.1 Model overview

EIRIN is a Stock-Flow Consistent (SFC) model[4] of an open economy composed of a limited number of heterogeneous and interacting agents of the real economy and financial system. Agents are

[4]See for instance Caverzasi and Godin (2015), Dafermos, Nikolaidi, and Galanis (2017), Dunz, Naqvi, et al. (2021), Naqvi and Stockhammer (2018), Ponta et al. (2018), Caiani et al. (2016), and Carnevali et al. (2021).

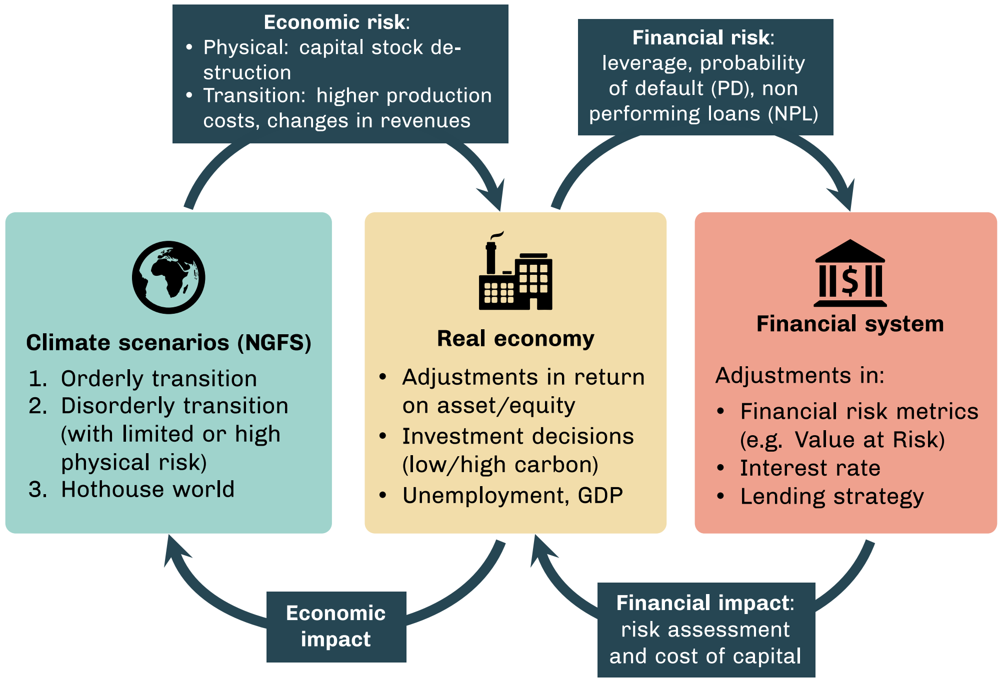


FIGURE 1: Double materiality of climate risks in the economy and finance. The figure shows how the concept of double materiality of climate risks is implemented in the EIRIN model, and the respective macro-financial feedbacks. Top, *first channel*: climate scenarios impact firms' performance via climate physical risk and transition risk, leading to adjustments in firms' profitability, cost of capital and investment decisions (i.e. in high or low-carbon activities), and the economic performance more broadly. Financial actors (e.g. banks), which are exposed to firms via securities and loans, experience adjustments in probability of default (PD), non-performing loans (NPL) and in portfolio risk metrics, e.g. the Value at Risk (VaR). Bottom, *second channel*: banks' climate-financial risk assessment drive adjustments in the cost of capital (interest rate) for firms, based on firms' energy technology and climate risk exposure. This, in turn, affects firms' access to credit, and their investment decisions in the low-carbon transition (i.e. in high or low-carbon activities). The adjustment in the structure of the economy, in turn, affects the realization of climate transition and physical risks scenarios.

heterogeneous in terms of source of income and wealth, and preferences, and include wage and capital-income earning households, energy firms, capital goods producers, consumption goods and service firms, a bank, the government, the central bank (which mimics the ECB), and a foreign sector (Rest of the World). EIRIN's agents are represented as a network of interconnected balance sheets items and calibrated on real data,[5] making it possible to trace a direct correspondence between stocks and flows.

The rigorous accounting framework allows us to display the dynamics of agents' balance sheets, and to analyse: *(i)* the direct impact of the shock on agents of the economy, at the level of balance sheet entry, *(ii)* the indirect impact of the shock on macroeconomic variables (e.g. GDP, unemployment, interest rate) and financial risk variables, e.g. banks' probability of default (PD) and non-performing loans (NPL), and *(iii)* the reinforcing feedback generated in the financial sector that could amplify the original shocks, leading to cascading economic losses. In addition, the SFC model

[5] We use publicly available socioeconomic and financial information, as well as supervisory data when provided.

characteristics make it possible to trace a direct correspondence between stocks and flows, thus increasing the transparency of shocks' transmission channels.

EIRIN is a behavioural model, meaning that agents' decisions are informed by behavioural rules and heuristics. In addition, EIRIN's agents are endowed with adaptive expectations about the future, i.e. making projections from past values and internalizing policy changes. The departure from traditional forward-looking expectations allows us to consider the impact of uncertainty, lack of market coordination, and mispricing on the economic outcome of climate change and the transition. In addition, this contributes to the understanding of the drivers of out-of-equilibrium states in the economy, and of potential amplification effects on economic performance and investors' balance sheets.

The capital and current account flows of the model are represented in figure 2. The model is composed of five macro-sectors, i.e. the non-financial sector, the financial sector, households, the government, and the foreign sector. The non-financial sector is composed by:

a) two energy firms (EnB and EnG, high-carbon and green respectively) that supply energy to households and to firms as an input factor for production (orange lines in figure 2);

b) an oil and mining firm that extracts and supplies EnB with fossil fuels (dark brown line);

c) a capital-intensive consumption goods producer, and a labour-intensive consumption goods producer (service, tourism, agriculture) that supply heterogeneous consumption goods to households and the government (light brown lines);

d) two capital goods producers (KpB and KpG), which supply all the above with respectively high-carbon (i.e. high emissions and resource intensity) and low-carbon (i.e. low-emissions profile and resource intensity) capital (black lines).

The energy firms and the consumption goods producers require capital as an input factor for production. To build up their capital stock, they invest in capital goods (black lines), which are produced either by the green or the high-carbon capital goods producer. To finance investment expenditures, firms can borrow from the commercial bank (teal line), which applies an interest rate to their loans (red line). Households, firms, and the government have deposits in the commercial bank. The commercial bank also holds reserves at the central bank, which could provide refinancing lines.

The government pays public employees (pink line), collects tax revenues from households and firms (light green line), and finances its current spending by issuing sovereign bonds (electric blue line). Sovereign bonds can be bought by capitalist households, by the commercial bank, and by the central bank. The government pays coupons on sovereign bonds.

Households are divided into workers and capitalists, based on their functional source of income: workers receive wage income (pink lines); capitalists own domestic firms for which they receive dividend income (purple line) and coupon payments for their sovereign bond holdings (dark blue lines).

The rest of the world receives remittances (yellow line) and exports consumption goods to households (light brown line). It sells resources to firms as inputs for the production factors while it generates tourism flows and domestic firms buy raw materials from it (grey line).

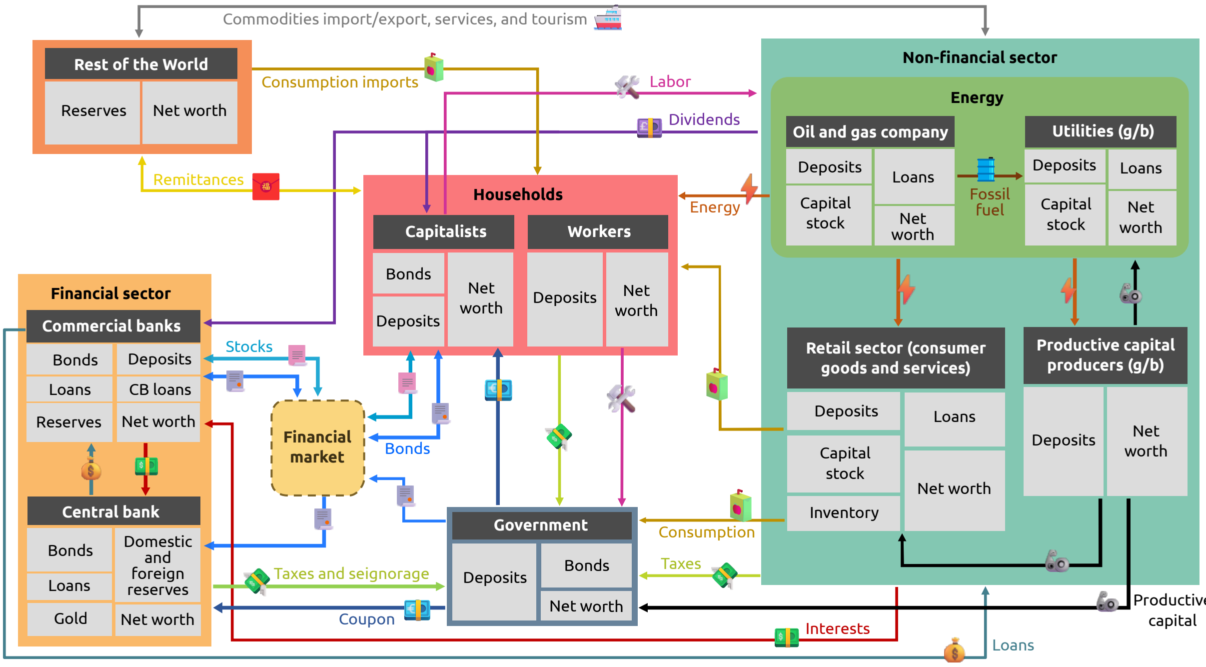


Figure 2: The EIRIN model framework: capital and current account flows of the EIRIN economy. For each sector and agent of the economy and finance, a representation in terms of their balance sheet entries (i.e. assets and liabilities) and their connections, is provided.

3.2 Markets and sequence of events

EIRIN's agents and sectors interact through a set of markets. Their operations are defined by the sequence of events occurring in each simulation step, as follows:

1. Policymakers make their policy decisions. The central bank sets the policy rate according to a Taylor-like rule. The government adjusts the tax rates on labour and capital income, on corporate earnings, and on Value Added to meet its budget deficit target.

2. The *credit market* opens. The bank sets its maximum credit supply according to its equity base. If supply is lower than demand, proportional rationing is applied and prospective borrowers revise negatively their investment and production plans accordingly.

3. *Real markets* open in parallel. They include the market for *consumption goods and services*, the *energy* market, the *labour* market, and the *raw materials* market. Prices of the exchanged goods or services are determined, then the nominal or real demand and supply are provided by the relevant firms in each market. Finally, transactions occur generally at disequilibrium, i.e. at the minimum between demand and supply.

4. The *financial market* opens. The capitalist household and the bank determine their desired portfolio allocation of financial wealth on securities. The government offers newly issued

bonds to finance a budget deficit, which includes green investments. The central bank may perform market operations and enter the bond market as a buyer of sovereign bonds. Then, new asset prices are determined.

5. All transactions and monetary flows are recorded, taxes paid are determined, and the balance sheets of the agents and sectors of the EIRIN economy are updated accordingly.

The formation of demand, supply, and prices in each market (except for the credit market) are independent of each other at any given simulation step. In the credit market, demand depends on the demand for capital goods. Demand rationing affects the effective demand for capital goods by firms. In each market, prices are made by the supply side as a markup on unit costs. In addition, in the financial market, sovereign bond prices are determined based on the existing stock of public debt, and on the performance of the real economy (see Appendix A.6 for the balance sheet matrix, the cash flow matrix and the net worth matrix of the EIRIN economy).

3.3 Agents and sectors' behaviour

We detail here the model's behaviours. First, we introduce the notation used. Let i and j be two agents. Then, p_i is the price of the output produced by i, while $p_i^\dagger$ is the price of the security issued by i. $D_{i,j}$ is the demand by j of what i produces, and $\mathbf{D}_i = \sum_j D_{i,j}$. Moreover, $\mathbf{Q}_i$ is the total production of i, and Q_j^i is the part of it that is given to j. We also denote by M_i the liquidity of i, akin to holdings of cash, and by K_i its stock of productive capital where applicable.

By building on Goodwin (1982), **households** are divided into two classes. Income class heterogeneity is functional to assess the distributive effects of the policies introduced in the low-carbon transition and on the channels of inequality. First, the working class (Hw) lives on wages, with gross revenues

$$Y_{\mathrm{Hw}}^{\mathrm{gross}} = \sum_i N_i \times w_i \tag{1}$$

where w_i is the wage paid by i and N_i the size of the workforce it employs (we omit the time dimension for simplicity as all variables are contemporaneous). The labour market mechanism, whose details are given in appendix A.3, determines the final workforce N_i of each agent based on the total N_{tot} of workers available and the demand for labour of firms. It also determines the salary level $w_i(t)$ paid by i, based on the required skills of employing firms. Second, the capitalist class (Hk) earns its income out of financial markets through government bonds' coupons and firms' dividends:

$$Y_{\mathrm{Hk}}^{\mathrm{gross}} = \mathfrak{c} \times S_{\mathrm{G,Hk}} + \sum_i \mathfrak{d}_i \times S_{i,\mathrm{Hk}}, \tag{2}$$

where $\mathfrak{d}_i$ are the dividends of i and $\mathfrak{c}$ is the coupon's rate. Both households are then taxed, with τ_{Hw} the rate of the income tax, and τ_{Hk} the rate of the tax on profits from capital. Furthermore, both household classes receive net remittances Rem_i from abroad, negative in the case of the EA.

All households pay their energy bill. This leaves them with Y_i^{disp} as net disposable income:

$$\forall i \in \{\text{Hw}, \text{Hk}\}, \quad Y_i^{\text{disp}} = \underbrace{(1-\tau_i) \times Y_i}_{\text{net income}} - p_{\text{En}} D_i^{\text{En}} + \text{Rem}_i \tag{3}$$

Households' consumption plans (eq. (4)) are based on the Buffer-Stock Theory of savings (Deaton, 1991; Carroll, 2001), with consumers adjusting their consumption path around their net income, considering a target level of liquid wealth to income ratio. In particular, consumers spend more (resp. less) than their net income if their actual liquid wealth to income ratio is higher (resp. lower) than the target level. This results in a quasi-target wealth level that households pursue. Then, households split their consumption budget C_i between consumption goods and services, also importing a share β_0 from the rest of the world.

$$C_i = Y_i^{\text{disp}} + \rho_i \left(M_i - \phi_i \times Y_i^{\text{disp}} \right) \tag{4}$$

$$D_i^{\text{Fl}} = (1-\beta_0) \times \beta_1 \times C_i \tag{5}$$

$$D_i^{\text{Fk}} = (1-\beta_0) \times (1-\beta_1) \times C_i \; . \tag{6}$$

The **service firm** Fl (also called labour intensive) and **consumption goods producer** Fk (also referred to as capital intensive) produce their respective outputs by relying on a Leontief technology. This implies no substitution of input factors, meaning that if an input factor is constrained (e.g. limited access to credit to finance investments), the overall production is proportionately reduced:

$$\forall j \in \{\text{Fl}, \text{Fk}\}, \quad \mathbf{Q}_j = \min \left\{ \gamma_j^N N_j, \; \gamma_j^K K_j \right\} \; . \tag{7}$$

In contrast, several macroeconomic models allow for the substitution of input factors (elasticity of substitution equals 1) by using a Cobb-Douglas production technology. In our case, this would imply a substitution of constrained input factors such as capital stock with labour, while still generating the same level of output.

The two firms set their consumption goods price as a mark-up μ_j on their labour costs w_j/γ_j^N, capital costs $\kappa_j L_j$, energy $p_{\text{En}} Q_j^{\text{En}}$ and resource costs $p_R Q_j^R$, such that

$$\forall j \in \{\text{Fl}, \text{Fk}\}, \quad p_j = (1+\mu_j) \times (1+\tau_{\text{VAT}}) \left[\frac{w_j}{\gamma_j^N} + \frac{\kappa_j L_j + p_{\text{En}} Q_j^{\text{En}} + p_R Q_j^R}{\mathbf{Q}_j} \right] . \tag{8}$$

In particular, it can be affected by firms' interest rates κ_j on loans, more expensive imports (p_R), energy, and/or wages. Higher prices of consumption goods and services constrain households' consumption budgets, which in turn lower aggregate demand. This represents a counterbalancing mechanism on aggregate demand.

The minimum between the real demand of the two consumption goods and the real supply (equations (9) and (10)) determines the transaction amount $\tilde{q}_j$ that is traded in the goods market. The supply of capital-intensive consumption goods also takes the firm's inventories (IN_{Fk}) into account. In case that demand exceeds supply, both capitalist and worker households are rationed proportionally to their demand. The share of newly produced but unsold products adds up to the stock of Fk's inventories (IN_{Fk}). Finally, both consumption goods producers make a production plan $\hat{q}_j$ for the next simulation step based on recent sales and inventory levels.

$$\tilde{q}_{\text{Fk}} = \min\left(\text{IN}_{\text{Fk}} + \mathbf{Q}_{\text{Fk}},\ \frac{1}{p_{\text{Fk}}}\left(D^{\text{Fk}}_{\text{Hw}} + D^{\text{Fk}}_{\text{Hk}} + D^{\text{Fk}}_{\text{G}} + D^{\text{Fk}}_{\text{RoW}}\right)\right) \tag{9}$$

$$\tilde{q}_{\text{Fl}} = \min\left(\mathbf{Q}_{\text{Fl}},\ \frac{1}{p_{\text{Fl}}}\left(D^{\text{Fl}}_{\text{Hw}} + D^{\text{Fl}}_{\text{Hk}} + D^{\text{Fl}}_{\text{G}} + D^{\text{Fl}}_{\text{RoW}}\right)\right) \tag{10}$$

The **energy sector (**En**)**, divided into green and high-carbon energy producers (EnG and EnB respectively), produces energy that is demanded by households and firms, respectively for consumption and for production. We assume that all demand is met, even if EnB might have to buy energy from the foreign sector, such that $\mathbf{Q}_{\text{En}} = \mathbf{D}_{\text{En}}$. Households' energy demand is inelastic (i.e. the daily uses for heat and transportation), while firms' energy requirements are proportional to their output. The high-carbon energy company requires capital stock and oil as input factors for production and only productive capital for its green counterpart but in higher quantity. The energy price is endogenously set from the unit cost of both firms, as described in appendix A.4.

Hw and Hk subtract the energy bill from their wage bill as shown by their disposable income, while firms transfer the costs of energy via mark-ups on their unit costs to their customers (equation (8)). To be able to deliver the demanded energy, the energy sector requires capital stock and conducts investments to compensate for capital depreciation and expand its capital stock to be able to satisfy energy demand (further details are provided in appendix A.4). The **oil and mining** company MO supplies EnB in oil and exports to the rest of the world as well. It faces no restriction on extraction but requires a proportional amount of productive capital to operate.

Both Fl and Fk make **endogenous investment decisions** based on the expected production plans $\hat{q}_j$ that determine a target capital stock level $\hat{K}_j$. The target investment amount $I^{\dagger}_j$ is set by the target capital level $\hat{K}_j$, considering the previous capital endowment $K_j(t-1)$ subject to depreciation $\delta_j \cdot K_j(t-1)$, hence

$$I^{\dagger}_j(t) = \max\left\{\hat{K}_j(t) - K_j(t-1) + \delta_j \cdot K_j(t-1), 0\right\} \tag{11}$$

Differently from supply-led models (e.g. Solow, 1956), in EIRIN investment decisions are fully endogenous, and they are based on firms' Net Present Value (NPV). This in turn is influenced by six factors: (i) investment costs, (ii) expected future discounted revenue streams (e.g. endogenously generated demand), (iii) expected future discounted variable costs, (iv) the agent's specific interest rate set by the commercial bank, (v) the government's fiscal policy and (vi) government subsidies.

More precisely, the planned investment is given by $I^{\star}_j(t) = \left(\varphi_j \cdot M_j(t-1) + \Delta^{+} L_j(t)\right) / p_{\text{Kp},j}(t)$, where φ_j is the share of liquidity that j uses to finance investment, $\Delta^{+} L_j$ is the part that comes from new credit, and $p_{\text{Kp},j}$ is the average price of capital, which depends on the ratio of green and high-carbon, at unit prices p_{KpG} and p_{KpB} respectively. The NPV calculations allow us to compare the present cost of real investments in new capital goods to the present value of future expected (positive or negative) cash flows, and it constrains what can be financed through credit. We differentiate in that regard between green and high-carbon capital, that is, for a level ι of investment, the related NPVs are

$$\mathrm{NPV}_j^{\mathrm{G}}(\iota, t) = -p_{\mathrm{KpG}}(t) \cdot \iota + \sum_{s=t+1}^{+\infty} \frac{\mathrm{CF}_j^{\mathrm{G}}(\iota, t, s)}{(1+\kappa_i)^{s-t}} \tag{12}$$

$$\mathrm{NPV}_j^{\mathrm{B}}(\iota, t) = -p_{\mathrm{KpB}}(t) \cdot \iota + \sum_{s=t+1}^{+\infty} \frac{\mathrm{CF}_j^{\mathrm{B}}(\iota, t, s)}{(1+\kappa_i)^{s-t}} \tag{13}$$

where $\mathrm{CF}_j^{\cdot}(\iota, t, s)$ describes total expected cash flows expected at s from the new investment. Details of the cash flow calculations are given in appendix A.2. Cash flows are discounted using the sector's interest rate κ_j set by the commercial bank. The final realized investment $I_i(t)$ is divided into green and high-carbon capital such that $I_i = I_i^{\mathrm{G}} + I_i^{\mathrm{B}}$. Then, it is potentially constrained by the supply capacity of the producers.

The **capital goods producers** (Kp, divided into green and high-carbon capital producers, KpG and KpB respectively) supply productive capital to fulfill the production capacity of Fl, Fk, and En:

$$\mathbf{Q}_{\mathrm{KpB}} = I_{\mathrm{Fl}}^{\mathrm{B}} + I_{\mathrm{Fk}}^{\mathrm{B}} + I_{\mathrm{EnB}} \leq \mathbf{D}_{\mathrm{KpB}}, \quad \mathbf{Q}_{\mathrm{KpG}} = I_{\mathrm{Fl}}^{\mathrm{G}} + I_{\mathrm{Fk}}^{\mathrm{G}} + I_{\mathrm{EnG}} \leq \mathbf{D}_{\mathrm{KpG}} \,. \tag{14}$$

Newly produced capital goods will be delivered to the consumption goods producers and the energy firm at the next simulation step. Capital goods producers rely on energy and high-skilled labour as input factors. There are differences between the green and high-carbon versions of capital goods in both its production and its use. In production, green capital requires more skilled labour than the high carbon one, as well as more material imported from the rest of the world. The latter represents the more complex supply chain and international dependencies that can be involved in green capital, such as rare metals for batteries. Therefore, a unit of green capital is more expensive than a unit of high-carbon capital (for the same productive capacity). On the other hand, in their use, green capital is the most interesting per unit for the service sector and the consumption goods producers (the ones with the choice as to which type of capital to use). This is due to a lesser use of raw material and energy, resulting in a lower bill per unit of capital used, and lower related GHG emissions. Capital good prices p_{KpB} and p_{KpG} are set as a fixed mark-up μ_{Kp} on unit costs:

$$\forall i \in \{\mathrm{KpG}, \mathrm{KpB}\}, \quad p_i = (1 + \mu_{\mathrm{Kp}}) \times \frac{w_{\mathrm{Kp}} N_i + D_i^{\mathrm{En}} p_{\mathrm{En}}}{\mathbf{Q}_i} \tag{15}$$

In the financial sector, the **commercial bank** (BA) provides loans and keeps deposits. The commercial bank endogenously creates money (Jakab and Kumhof, 2015), meaning that it increases its balance sheet at every lending (i.e. the bank creates new deposits as it grants a new credit). This is consistent with recent literature on endogenous money creation by banks (McLeay et al., 2014). The EIRIN economy money supply is displayed by the level of demand deposits, including for all other agents in the European economy (i.e. excluding the foreign sector). Furthermore, BA gives out loans to finance firms' investment plans. The bank sets sector-specific interest rates that affect firms' capital costs and NPV calculations. The commercial bank can grant credit under the condition that it complies with regulatory capital requirements (eq. 16). When this does not happen, credit is rationed and firms have to scale down their investment plan. In this situation, the commercial bank reacts by retaining part of its earnings to increase the equity base and, thus, the Capital Adequacy Ratio (CAR) and the lending capacity. Thus, the lending activity in EIRIN can be endogenously affected by the performance of the borrowers, which pay interest on loans, thus impacting on bank's profits and equity. Within this framework, policies and/or shocks which influence firms' activity and investments may be sources of financial instability.

The credit market is characterized by the level of credit, the cost of credit, and the level of Non-Performing Loans. The *level of credit* designates how much the bank is ready to lend at a time t. The maximum credit supply of the bank is set by its equity level E_{BA} divided by the Capital Adequacy Ratio (CAR) parameter $\widetilde{\mathrm{CAR}}$, in order to comply with banking regulator provisions. Other relevant information is the demand for new credit $\mathbf{D}_{\mathrm{BA}}(t)$ and the previous credit level $\mathbf{L}(t-1)$. The additional credit that the bank can provide at each time step is given by its maximum supply, minus the value of loans already outstanding, so that the total of loans makes it realized capital adequacy ratio remains over $\widetilde{\mathrm{CAR}}$:

$$\Delta^{+}\mathbf{L} = \min\left\{\mathbf{D}_{\mathrm{BA}}(t), E_{\mathrm{BA}}(t-1)/\widetilde{\mathrm{CAR}} - \mathbf{L}(t-1)\right\} \ . \tag{16}$$

The *cost of credit*, i.e., the interest rate applied to the different sectors. The interest rate is sector-specific and based on macroeconomic indicators. In addition, credit can be constrained depending on the profitability of the investment and on the bank's lending capacity.

Let ν be the risk-free interest rate, which is the sum of the policy rate and the bank's net interest margin (NIM). Given the annualized probability of default PD_i of sector i, we seek to determine its objective loan interest rate $\hat{\kappa}_i$ granted by the bank. We verify

$$\underbrace{\hat{\kappa}_i(t) - \nu(t)}_{\text{credit spread}} = \mathrm{PD}_i(t) \times (1 - \mathcal{R}_i), \tag{17}$$

where $\mathcal{R}_i$ is the (constant) expected recovery rate[6] of i. The PDs themselves are computed following Alogoskoufis et al. (2021), that is $\mathrm{PD}_i = \alpha + \beta_1 \Delta^{\%}\mathsf{ROA}_i + \beta_2 \mathsf{Leverage}_i + \mathsf{GICS}_i$, where $\Delta^{\%}$ denotes the growth operator, ROA stands for returns on assets, and GICS_i is a sector-specific constant.

Then, in order to determine the actual rate applied, we allow for bridging only part of the distance between the previous interest rate and the objective interest rate. That means, denoting as $\kappa_i(t)$ the realized interest rate at t we have $\kappa_i(t) = \kappa_i(t-1) + \lambda \times (\hat{\kappa}_i(t) - \kappa_i(t-1))$, where $\lambda \in]0,1]$ is the

[6]See Hamilton and Cantor (2006) on the model itself, and Bruche and González-Aguado (2010) on the macroeconomic determinants of recovery rates.

interest adjustment speed.

With this approach, we analyse financial stability through the lens of banks' CAR and firms' interest rates. The CAR determines the propensity of banks to extend their lending and their capacity to absorb shocks. The interest rate reflects the credit risk born by the real economy.

The *non-performing loans (NPL):* as a final part of the credit market mechanism, we compute the NPL ratio based on the literature[7], such that

$$\Delta^{\%}\mathsf{NPL}(t) = \eta + \sum_{j=1}^{2} \alpha_j \Delta^{\%}\mathsf{NPL}(t-j) + \sum_{j=1}^{p} \beta_j \cdot \mathbf{X}(t-j) + \varepsilon(t) \tag{18}$$

where $\Delta^{\%}$ is the quarter-on-quarter growth operator, while η, α and β represent parameters. The vector $\mathbf{X}$ of predictor variables includes the growth rate of real GDP and the change in the policy rate. Therefore, the computation of the NPL ratio is completely endogenous in the model, as no predictor variable is part of the scenario.

A sector i pays interests with rate $\kappa_i(t)$ at t on its total loans $L_i(t-1)$ of the previous period. Taking into account the NPL ratio, the total interests paid are:[8]

$$\mathsf{ID}_i(t) = \kappa_i(t) \times L_i(t-1) \times (1 - \mathsf{NPL}(t)) \tag{19}$$

The interests paid on debt are subtracted from the operating earnings of i and added to that of the banking sector. Similarly, the repayment of the debt is reduced:

$$\Delta^{-} L_i(t) = \chi_i \times L_i(t-1) \times (1 - \mathsf{NPL}(t)) \tag{20}$$

where χ_i is the (constant) repayment rate of i, inversely proportional to the typical loan length of the sector.

The **central bank** (CB) sets the risk-free interest rate ν according to a Taylor-like rule (Taylor, 1993). The EIRIN's implementation of the Taylor rule differs from the traditional one because we do not define the potential output based on the Non-Accelerating Inflation Rate of Unemployment (NAIRU) (Blanchard, 2017). Indeed, NAIRU's theoretical underpinnings are rooted in general equilibrium theory, while EIRIN is not constrained to equilibrium solutions, focusing on the analysis of out-of-equilibrium dynamics. Thus, it would not be logically consistent to adopt a standard Taylor rule and NAIRU.

The interest rate in EIRIN indirectly affects households' consumption via price increases stemming from firms that adjust their prices, based on the costs of credit. Households have a target level of wealth stemming from the Buffer-Stock Theory of Saving. Lack of full intertemporal optimization prevents potential crowding-out effects of monetary policies on households' consumption.

[7]Following in particular Beck et al. (2015) and Tente et al. (2019) with regard to NPL determinants.

[8]Note that, the unpaid interest should normally start in the previous period, because of the 90 days limit used to define the NPL. This can be neglected provided that variations in the NPL ratio are small.

The policy interest rate depends on the inflation gap $\pi - \bar{\pi}$ and output gap (measured as employment gap $u - \bar{u}$, i.e. the distance to a target level of employment $\bar{u}$):

$$\nu(t) = \omega_\pi(\pi(t) - \bar{\pi}) - \omega_u(u(t) - \bar{u}) \tag{21}$$

where π is the one-period inflation of the weighted basket of consumption goods and services (with a computation smoothed over a year, i.e. m periods):

$$\pi(t) = \frac{\mathbf{Q}_{\mathrm{Fl}}(t)}{\mathbf{Q}_{\mathrm{Fk}}(t) + \mathbf{Q}_{\mathrm{Fl}}(t)} \cdot \left(\frac{p_{\mathrm{Fl}}(t)}{p_{\mathrm{Fl}}(t-m)}\right)^{1/m} + \frac{\mathbf{Q}_{\mathrm{Fk}}(t)}{\mathbf{Q}_{\mathrm{Fk}}(t) + \mathbf{Q}_{\mathrm{Fl}}(t)} \cdot \left(\frac{p_{\mathrm{Fk}}(t)}{p_{\mathrm{Fk}}(t-m)}\right)^{1/m} - 1 \tag{22}$$

The inflation gap is computed as the distance of the actual inflation π to the pre-defined target inflation rate $\bar{\pi}$. Moreover, the central bank can provide liquidity to banks in case of a shortage of liquid assets.

The **foreign sector (**RoW**)** interacts through tourism import, consumption goods imports and exports, raw material supply, fossil fuels imports, and potential energy export to the euro area economy. What it sells is provided in infinite supply and at a given price to meet internal production needs. Tourists' inflows consist of the consumption of labour-intensive consumption goods. Raw material, consumption goods, and intermediate goods exports are a calibrated share of the country's GDP and are sold at world prices.

The **government** (G) is in charge of implementing the fiscal policy, via tax collection and public spending, including welfare expenditures, subsidies (e.g. for households' consumption of basic commodities), public service wages, and consumption.

In order to cover its regular expenses, the government raises taxes and issues sovereign bonds, which are bought by the capitalist households, by the commercial bank, and by the central bank. The government pays a coupon $\mathfrak{c}$ on its outstanding bonds $\mathbf{S}_{\mathrm{G}}$. Taxes are applied to labour income (wage), capital income (dividends and coupons), profits of firms, and GHG emissions. If the government's deposits are lower than a given positive threshold $\bar{M}$, i.e., $M_{\mathrm{G}} < \bar{M}_{\mathrm{G}}$, the government issues a new amount $\Delta\mathbf{S}_{\mathrm{G}} = \frac{\bar{M}_{\mathrm{G}} - M_{\mathrm{G}}}{p^{\dagger}_{\mathrm{G}}}$ of bonds to cover the gap, where $p^{\dagger}_{\mathrm{G}}$ is the endogenously determined government bond price. The government's spending C_{G} is a fixed percentage of revenues from taxes R_{G}. Government spending during crises contributes to avoiding credit crunch and compensates households and firms' liquidity constraints (Brunnermeier et al., 2020).

For a detailed description of all sectors, market interactions, and behavioural equations, refer to Monasterolo and Raberto (2018), Monasterolo and Raberto (2019), and Dunz, Essenfelder, et al. (2021). Further details are also provided in Appendix A.

4 Climate physical and transition risk scenarios

4.1 The NGFS scenarios

The NGFS developed supervisory climate mitigation scenarios for investors and financial authorities to assess and manage climate-related risks (NGFS, 2020). The NGFS scenarios are regularly updated (see e.g. NGFS, 2021; NGFS, 2022).

In our analysis, we use the 2020 NGFS scenarios to ensure consistency and comparability with the ECB economy-wide climate stress test (Alogoskoufis et al., 2021). This study includes eight scenarios that differ with respect to temperature targets (e.g. 1.5°C, 2°C), climate policy ambition, the timing of the climate policy introduction (early in 2020, or delayed to 2030) and assumptions about the availability of Carbon Dioxide Removal (CDR).

The NGFS scenarios are simulated with three large-scale, process-based IAMs, i.e. GCAM (UMD's Calvin et al., 2019), MESSAGEix-GLOBIOM (IIASA's Krey et al., 2020), and REMIND-MAgPIE (PIK's Leimbach et al., 2010). The three process-based IAM combine a rather simple macroeconomic module with detailed land-use, energy, water and climate system modules. However, the process-based IAMs differ in terms of solution concept (partial equilibrium vs. general equilibrium), agent foresight (recursive dynamic vs. perfect foresight), solution method (cost minimization vs. welfare maximization), temporal, and spatial dimension (see Table 2 in Bertram et al. (2020) for details).

The NGFS scenarios follow the underlying socioeconomic assumptions of the Socioeconomic Shared Pathway 2 (SSP2). Kriegler et al. (2012) introduced SSPs as narratives of the challenges to climate mitigation and adaptation efforts, conditioned to alternative socioeconomic developments. SSP2 is a middle-of-the-road scenario, where historical trends with respect to technology, economic, and social developments remain mostly unaltered (O'Neill et al., 2014; Oliver Fricko et al., 2017).

4.1.1 Climate mitigation scenarios of the low-carbon transition

The NGFS scenarios distinguish between an orderly and a disorderly transition. In an orderly transition, climate policies are assumed to be implemented early and become gradually more stringent over time. A disorderly transition assumes no additional climate policies to be introduced before 2030. Delayed climate policy action, combined with limited available low-carbon technologies, results in sharper emission reductions required to still achieve the Paris Agreement temperature goals. Thus, more stringent and costly climate policies (including a carbon tax) are assumed to be implemented.

The orderly and disorderly trajectories are developed using process-based IAMs generate transition pathways, conditioned to temperature targets, technology and innovation, and climate policy assumptions.

In order to meet the temperature targets at certain points in time (e.g. 2050 or 2100), a carbon price that affects energy choice, land use and the real economy is set. Energy is used as an input factor in output production. This implies that a higher price of fossil fuel-based energy (e.g. from coal, oil, and gas) results in higher input costs and lower demand. The IAMs report the outcomes of the transition pathways in terms of GDP, investments and GHG emission reduction.

Nevertheless, at the current stage of development, NGFS scenarios do not account for the role of finance, nor for investors' expectations and their interplay with policy credibility (Battiston, Monasterolo, et al., 2021). Accounting for investors' climate sentiments is crucial to address the double materiality of climate change, and to avoid the underestimation of the cost of inaction and of the macro-financial impacts.

4.1.2 Climate damage scenarios

The IAMs used in the NGFS 1.0 scenarios compute physical risk damages to GDP based on emission trajectories that stem from climate transition pathways. A quadratic damage function is calibrated, with specifications given by 3 different studies:

- a statistical analysis of damages assumptions from the literature;
- a meta-analysis by Howard and Sterner (2017);
- a panel regression on regional GDP data (Kalkuhl and Wenz, 2020).

However, the physical risk does not feed back into the economy in the current IAMs pathways, meaning that the economic trajectories do not capture emission and temperature feedback into infrastructure systems (Bertram et al., 2020). Therefore, climate transition trajectories provide only a lower bound for the related climate transition and climate physical risks.

4.2 Implementation of the NGFS scenarios in the EIRIN model

We closely follow the scenario design of the NGFS database.[9] In particular, we apply the trajectories of the REMIND-MagPie model, developed by the Potsdam Institute for Climate Impact Research (PIK) (Hilaire and Bertram, 2020). REMIND-MagPie assesses economic and energy technology trajectories via an iterative process between a macroeconomic Ramsey model and a cost-minimising energy technology choice model. The macroeconomic model determines the energy demand, while the energy model computes energy supply and respective input costs, given a target emission level and a corresponding carbon price.

Following Alogoskoufis et al. (2021), we select the three groups of scenarios representing an orderly transition, a disorderly transition and the hothouse world (NGFS, 2020). Orderly transition scenario refers to the REMIND-MagPie "Immediate 1.5°C with CDR (Orderly, Alt)" scenario[10], disorderly transition to the "Delayed 2°C with limited CDR (Disorderly, Rep)" scenario[11] and a hothouse world to the "Current policies (Hot house world, Rep)."[12]

[9]Transition pathways and respective outcomes for core variables are publicly available via the NGFS scenarios explorer 1.0: https://data.ene.iiasa.ac.at/ngfs/.

[10]Global climate action after 2020 to limit cumulative emissions between 2011-2100 to 400 GtCO2 (67% chance of limiting warming to 1.5°C).

[11]Global climate action after 2030 to limit cumulative emissions between 2011- 2100 to 1000 GtCO2 (67% chance of limiting warming to 2°C), assuming limited availability of carbon dioxide removal options.

[12]Extrapolation of current national policies implemented.

The NGFS scenarios differ in terms of their carbon price, which is influenced by the level of ambition and timing of climate policy (the more stringent the policy, the higher the carbon price), and by the assumptions about the availability and cost-effectiveness of green technologies (the cheaper the green technology, the lower the carbon price). The resulting transition trajectories are reported on a five-year basis before 2050, and on a ten-year basis after 2060. EIRIN's scenario simulations are calibrated to a semester time step, until 2050. Thus, the introduction of the NGFS scenarios in the EIRIN model required an interpolation of NGFS REMIND-MagPie scenario inputs and outcomes.

We implement four scenarios that are characterized by different climate policy targets and climate physical impacts (see Figure 3). Orderly and disorderly transition scenarios reduce physical risk impacts due to ambitious mitigation policies. The hothouse world scenario, which captures the current situation with no further strengthening of climate policies, leads to a high climate physical risk and to a failed mitigation. All scenarios run until 2050. Physical impacts are only assumed to differ after 2025 across scenarios, given the inertia and delayed response to emission reductions in the climate system.

First, the scenario "Orderly transition scenario with limited physical risk" follows an emission path that would allow staying within an average temperature change of 1.5°C in 2100. Climate policies are assumed to be implemented in a coordinated manner and early, with a relatively low carbon entry price, a smooth trajectory and supplementary government measures such as green subsidies. Physical damages until 2050 are assumed to occur due to inertia in the climate system by current emissions but are limited, taking the lowest 10^{th} percentile of the reported damage distribution in the NGFS scenario database, adjusted for the EA.[13]

Second, we design a "Disorderly transition scenario with limited physical risk", following an emission path conducting to an average temperature change of 2°C by 2100, but with limited carbon dioxide removal technologies. Climate policies are assumed to be implemented unexpectedly and late (after 2030), characterized by a fast carbon price growth trajectory and strong government measures such as green subsidies. Physical climate damages until 2050 are also assumed to be limited, taking the lowest 10^{th} percentile of the Kalkuhl and Wenz (2020) reported damage distribution in the NGFS scenario database, adjusted for the EA. After 2030, physical damages across the orderly and disorderly transition scenario start to differ, given the 2°C temperature target of the disorderly transition scenario, resulting in higher physical impacts.

Third, we consider a scenario where physical shocks lead to high damages, i.e. a "Disorderly transition scenario with average physical risk". This scenario shows the same climate policy trajectory as the previous but differs from it by considering physical climate damages until 2050 at the median of the Kalkuhl and Wenz (2020) reported damage distribution in the NGFS scenario database, adjusted for the EA. We use several quantiles of the damage distribution to cover a broader spectrum of cases within our set of scenarios.

Finally, we employ a "Hot House World scenario with high physical risk", where no additional

[13]The representation of damages and their level is coherent to the path of the EIRIN scenario, as it is for the following ones.

climate policies are implemented, and physical damages are very high. This scenario shows physical damages from the median percentile until 2030 and subsequently very high damages until 2050, taking the 90th percentile of the Kalkuhl and Wenz (2020) reported damage distribution in the NGFS scenario database, adjusted for the EA.

To the difference of NGFS models, physical damages in EIRIN are fully integrated and cause long-lasting effects to the economy. The damage trajectories are taken from the NGFS global scenarios (see Section 5.3 for details) but are adjusted to the EA, using climate physical-risk scores provided by Four Twenty Seven. The climate damages are exogenous, meaning that climate policies do not affect the degree of climate damages over the model run. This reflects first the inertia in the climate system and then the fact that the EA is only responsible for about 6% of global GHG emissions, meaning that climate actions of the EA alone might not be sufficient to substantially alter the climate damage trajectories. However, in EIRIN, the economic and financial impacts of climate damages, such as lower production capacity or higher credit levels, feed back into the next time periods, showing a dynamic climate damage impact. For instance, firms need to finance post-disaster reconstruction, affecting their debt levels and their financial soundness indicators.

Furthermore, we leverage the characteristics of the EIRIN model to include a wider range of climate policy options, beyond the carbon tax (described in subsection 5.2.1). Indeed, we consider other debated climate policies, i.e. green subsidies and green incentives for firms. This choice is motivated on the one hand by the fact that current climate policy packages in the EU, such as the European Green Deal (EC, 2021), include a wide range of climate policies beyond carbon pricing. On the other hand, our solution brings us closer to the logic of the NGFS scenarios, whereby the "shadow emission prices are a proxy of government policy intensity" (Bertram et al., 2020).

5 Climate risk transmission channels

This section identifies the risk transmission channels to the agents and sectors of the EIRIN economy, considering the direct and indirect impacts of climate physical and transition risks. Then, it discusses how they are quantitatively assessed by the EIRIN model.

5.1 Climate transition risk transmission to the euro area economy and banking sector

The analysis of climate risk transmission channels is crucial to identify the shocks' entry points, the direct and the indirect impacts to the agents and sectors of the economy, and of public and private finance, given the type of shock and country's characteristics (Monasterolo, 2020b). Our analysis of the climate risk transmission channels builds on recent literature (Battiston, Mandel, et al., 2017; Volz et al., 2020; Gregor Semieniuk et al., 2021; Ramos et al., 2021; Battiston and Monasterolo, 2020).

Figure 4 shows how climate transition risks are implemented in the EIRIN model. Climate transition risks originate as a demand shock to the EA economy. The introduction of carbon pricing (consistent with the NGFS scenarios) and other climate policies such as green subsidies, directly af-

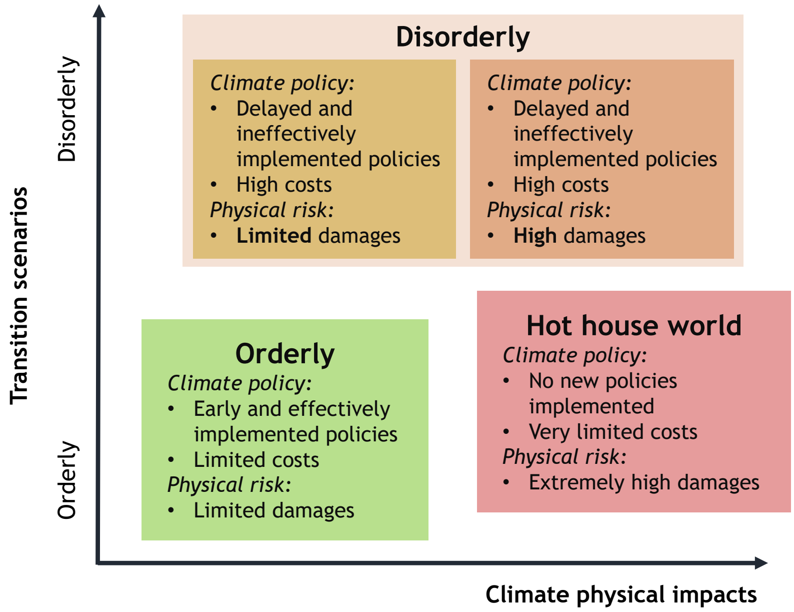


FIGURE 3: EIRIN-NGFS scenarios, adapted from Hilaire and Bertram (2019).
The *x*-axis indicates the strength of physical risk, and the *y*-axis gives the steepness of climate policy.

fect the demand for fossil fuels-based energy and for high-carbon goods, and the cost of production of high-carbon firms. On the contrary, positive adjustments in demand and value of green assets occur. Due to lower demand and higher costs, high-carbon firms start to lay-off workers, leading to indirect effects in the economy in terms of investments, unemployment, households' consumption and GDP growth. Adjustments in firms and economic performance, in turn, also affect banks' financial indicators, i.e. NPL, PD, leverage, and banks' financial stability. Economic and financial shocks affect government's fiscal revenues, budget balance, and contribute to the building up of sovereign risk.

5.2 EIRIN modelling of climate transition risk

EIRIN differs from the IAM used to produce the NGFS pathways in terms of model's structure, agents' behaviours and sector disaggregation. The carbon tax trajectories applied are taken from the 2020 NGFS scenarios – from the REMIND-MagPie model more specifically – and integrated exogenously to the model.

However, we introduce additional climate policies in order to study climate policy complementarity. Indeed, in the NGFS scenarios, the carbon tax revenues are recycled via the general government budget. In EIRIN-NGFS, part of those revenues are used to create climate incentives for firms, coherently with the EU Green Deal proposal. In order to add these dimensions of low-carbon transition policies, we further distinguish the use of carbon tax revenues by the government (i.e. green subsidies) and responsiveness of firms' investment decision between the orderly and disorderly transition scenarios.

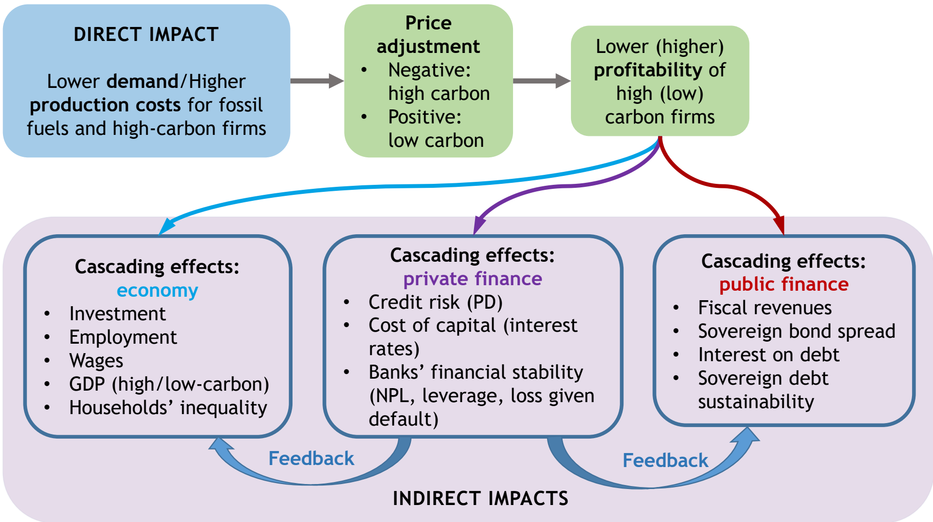


FIGURE 4: Channels of transmission of climate transition risks to the economy and finance. The figure shows the entry point, the direct, and indirect impacts of the introduction of carbon pricing in the economy and finance.

5.2.1 Carbon tax

First, as described in section 4, and represented in figure 5, a carbon tax on emissions is applied by the government. It affects the cost of production and revenues of fossil fuels and of high carbon firms. In a disorderly transition, being climate policy delayed (after 2030), and in absence of CDR technology, a higher carbon price is needed to achieve the 2°C target. The carbon price is introduced at time t by a rate $\tau^{\mathrm{GHG}}(t)$ such that the revenues paid to the government by a sector i are given by $\mathrm{Em}_i(t) \times \tau^{\mathrm{GHG}}(t)$ where Em_i denotes the total carbon emissions of i and covers scope 1 and 2 emissions. In our framework, emissions are calibrated to represent the proportions of emissions among sectors.[14]

While in EIRIN the carbon price is an exogenous policy variable, in REMIND-MagPie the carbon price is the shadow price of the cost-minimisation procedure to reach the target emission level. To ensure comparability of the two modelling approaches, we select the same timing of the carbon price implementation and target emission level at the end of the scenario run in 2050. Similarly to REMIND-MagPie, the EIRIN carbon price trajectory is introduced early (2020) and smoothly grows over time in case of the orderly transition. In contrast, in the disorderly transition scenario, the carbon price is introduced late (2030) and at a higher level, growing fast over time to allow reaching the emission target corresponding to the 1.5 or 2°C carbon budget.

[14] We do not directly represent emissions in tons of CO_2, but we consider the importance of the tax relative to GDP, as represented in figure 6.

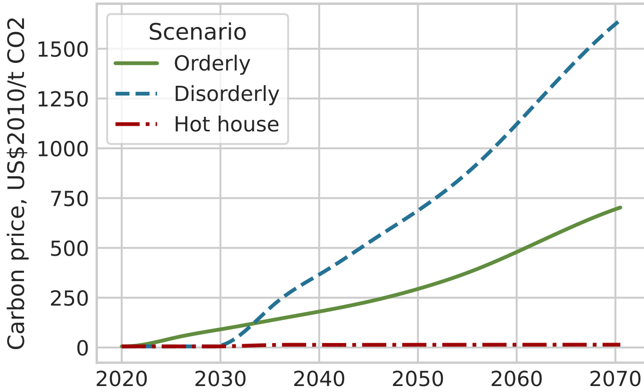


FIGURE 5: Carbon price trajectories from NGFS scenarios.
The scenarios chosen are generated by the model REMIND-MAgPIE 1.7-3.0, where orderly corresponds to "Immediate 1.5°C with CDR", disorderly to "Delayed 2°C with limited CDR" and hot house to "Current policies". Values are interpolated from five years to six months periods. We modify the original paths in the disorderly and hot house world scenarios, while the price is kept constant on the period 2020-2029, and the value for 2030 is not taken into account, so that the 2035 point guides the initial increase.

5.2.2 The transition to renewable energy

An important characteristic for an orderly low-carbon transition is the speed at which renewable energy replaces fossil fuel supply. For instance, the approval of wind parks in Germany currently takes 4-5 years on average[15], substantially slowing down needed renewable energy investments.[16] This is another aspect that differs between the orderly and disorderly transition scenario in EIRIN.

The energy supply not covered by renewable sources is given by $\mathbf{D}_{\text{En}} - \mathbf{q}_{\text{EnG}}$. Moreover, we assume that there is a share of the energy supply for which the transition to renewable sources is not possible in the near term, which caps the green energy to a share ξ_{EnG} of the total.

The capital efficiency of the green utility firm is denoted by γ_{EnG}, and the green utility firm aims to replace a share λ_{EnG} of the non-renewable market. Thus, the capital quantity to acquire is given by

$$\widehat{\Delta K}_{\text{EnG}}(t) = \frac{\lambda_{\text{EnG}}}{\gamma_{\text{EnG}}} \times (\xi_{\text{EnG}} \cdot \mathbf{D}_{\text{En}}(t-1) - \mathbf{q}_{\text{EnG}}(t-1)) \ . \quad (23)$$

Note that this component is only one aspect of the investment by the green energy sector, which also needs to invest in order to compensate for capital depletion and climate damages.

Moreover, investments depend on the conditions of access to capital. Parameter λ_{EnG} represents the time necessary to achieve a climate-aligned energy mix. Suppose for example that the starting point is a ratio of renewable energy of 18%, and we want to achieve 75%, given a maximum of $\xi_{\text{EnG}} = 80\%$, and we have $\lambda_{\text{EnG}} = 0.05$ (supposed, in line with our exercise, to apply to a semester). Then, a numerical application[17] tells us that reaching the target will take 25 years. This is a lower

[15] https://www.wind-energie.de/themen/mensch-und-umwelt/planung/

[16] The coalition contract of the new German government puts a specific emphasis on speeding up renewable energy approval procedures.

[17] Let $\forall t, u_t = \mathbf{q}_{\text{EnB}}(t)/\mathbf{D}_{\text{En}}(t) - 1 + \xi_{\text{EnG}}$, the ratio at t of non-renewable energy over the production that could be ensured

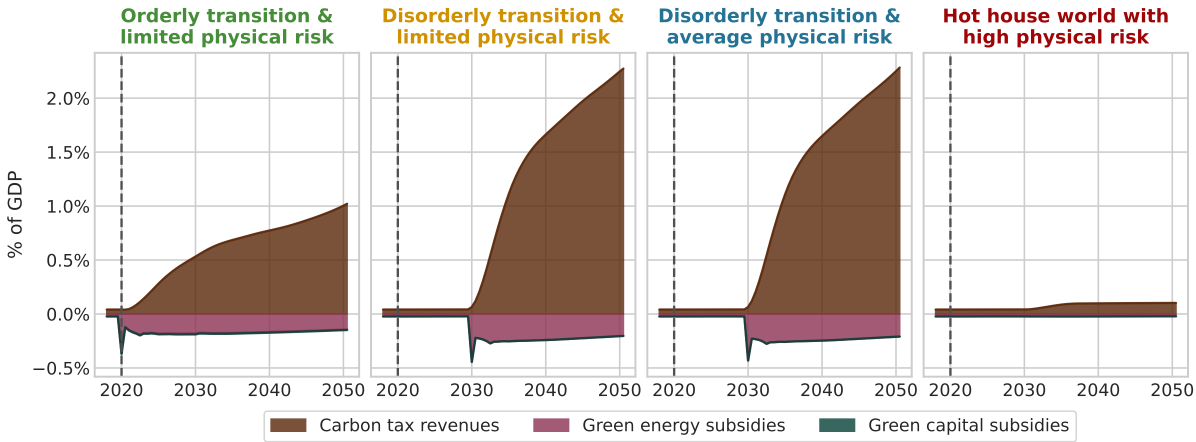


FIGURE 6: Nominal revenues and expenditures from climate policies, as a share to GDP.
The x-axis displays the simulation timeline and the y-axis displays the climate policies budgets as ratios to GDP. Policies include the carbon tax, introduced in 5.2.1; the subsidies to renewable energy, introduced in 5.2.3; and the subsidies to green capital, introduced in 5.2.4. Note that the GDP differs across scenarios.

bound to the time needed when factoring in the additional limitations embedded in the model.

5.2.3 Renewable energy rebate

Another scenario-dependent parameter that differs between the orderly and disorderly transition scenarios is the government's tax rebate for renewable energy producers. Indeed, already today, several tax incentives are used to support the low-carbon transition (European Commission, 2021). We assume EA governments to implement a green energy subsidy that influences the speed of new renewable energy investments. This subsidy to the green energy producer is implemented as a price discount to buy green capital, which will help to boost its production capacity. The respective parameter in the EIRIN model affects the discount rate for investment planning and differs between the orderly and disorderly transition scenario. The subsidy stimulates renewable energy investment by increasing the NPV of the sector, making it more attractive for firms.

5.2.4 Incentives for green capital use

High-carbon production facilities, such as steel production, could be replaced with low-carbon alternatives, such as steel produced with green hydrogen. However, this implies different production costs and input factors. As such, in EIRIN, the sectors that produce consumption goods (Fk) and provide services (Fl) can choose between green and high-carbon productive capital. Especially in the beginning of the transition, green capital alternatives, such as green hydrogen steel, are still more expensive, giving a role to the government to create incentives for green capital use. Thereby the government can support technology improvements, efficiency gains, and scale effects over time. For

by both producers. Then we have $\forall t, u_{t+1} = (1-\lambda_{\text{EnG}})u_t$ under the assumptions given. Thus, $u_n = u_0 \times (1-\lambda_{\text{EnG}})^n$ and $n = \ln(u_n/u_0)/\ln(1-\lambda_{\text{UG}})$. Taking $u_0 = 0.82 - 0.2 = 0.62$ and $u_n = 0.05$ gives 49.1 semesters.

firms, the key step when making investment decisions is the computation of the NPV associated with the purchases of green and high-carbon capital, respectively. The NPV calculation is influenced by several parameters, including the carbon tax that makes high-carbon production more expensive.

Nonetheless, the carbon tax alone might not be sufficient to make the green NPV more favourable than the traditional one, in particular early stage green capital alternatives. Therefore, the government introduces a minimum share in green capital investments, as long as the NPV is positive (see figure 7). This weight parameter differs between the orderly and disorderly transition scenarios. By increasing it between the initial period and the transition, it allows for the greening to occur in the production of the two sectors affected. Note that the green capital is not necessarily greener at the point of its production, and it may require more energy[18] or more raw materials.

The advantage of green capital stands in the fact that it produces lower emissions when in use is lower than for high-carbon capital alternatives.

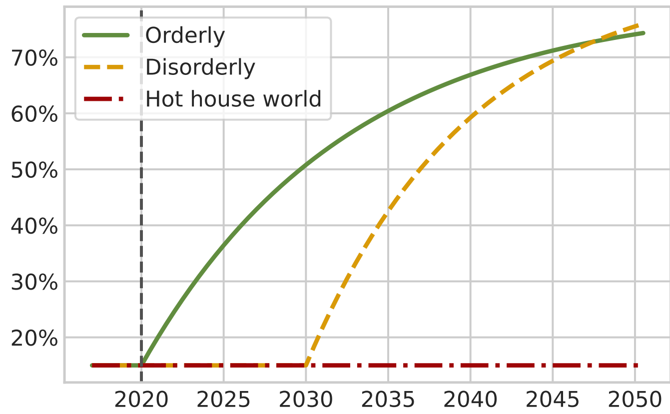


FIGURE 7: Green weight ration across scenarios.
The x-axis displays the simulation time and the y-axis displays the green weight ratio, which is indicative of the minimum share of green capital that the labour intensive and capital intensive sectors have to buy, provided that the green capital is profitable at some level. For both sectors, using green capital leads to lower energy consumption, and to fiscal advantages when compared to the high-carbon one.

5.3 Climate physical risk transmission to the EA economy and banking sector

In EIRIN, GDP is a fully endogenous outcome variable. Hence, exogenous GDP impacts cannot be used as an input in the EIRIN model. Thus, we use the impacts on agents or sectors' balance sheets (demand and supply) as an input, analysing GDP damages to productive capital[19] in EIRIN (see figure 8).

Figure 9 shows how climate physical risk is included in the EIRIN model, including the direct and indirect impacts of natural hazards on the economy and finance. Consider the example of floods, which represent a common physical risk for the EA member states. Floods enter the EA member

[18]Note that the accompanying emissions depend on the share of renewable energy at the time of the investment.
[19]The application of disaster risk modelling (e.g. those in (Dunz, Monasterolo, et al., 2020) can provide a more accurate estimation of disaster impacts on productive capital stock at the disaggregated sector and geographical level.

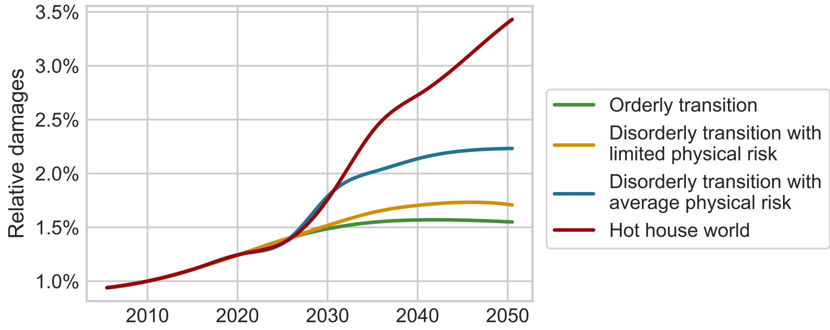


FIGURE 8: Physical risk trajectories across scenarios.
The x-axis displays the simulation time, while the y-axis shows the share of capital affected by physical damages at each period and that is used as an input in the model.

states' economies by destroying productive capital and infrastructures, impacting firms' production (direct impact) via shocks on production factors (e.g. capital, labour, energy). Thus, floods represent a supply shock that limits firms' ability to serve demand. In the short run, firms cannot easily substitute input factors, and they start to lay-off workers. Unemployment increases and affects households' income, and indirectly weakens workers' wage bargaining power, lowering households' consumption and real GDP. Shocks on firms' performance translate into the financial performance of banks and affect their financial risk metrics and financial stability. Overall, the shock affects sovereign risk via changes in tax revenues and sovereign debt.

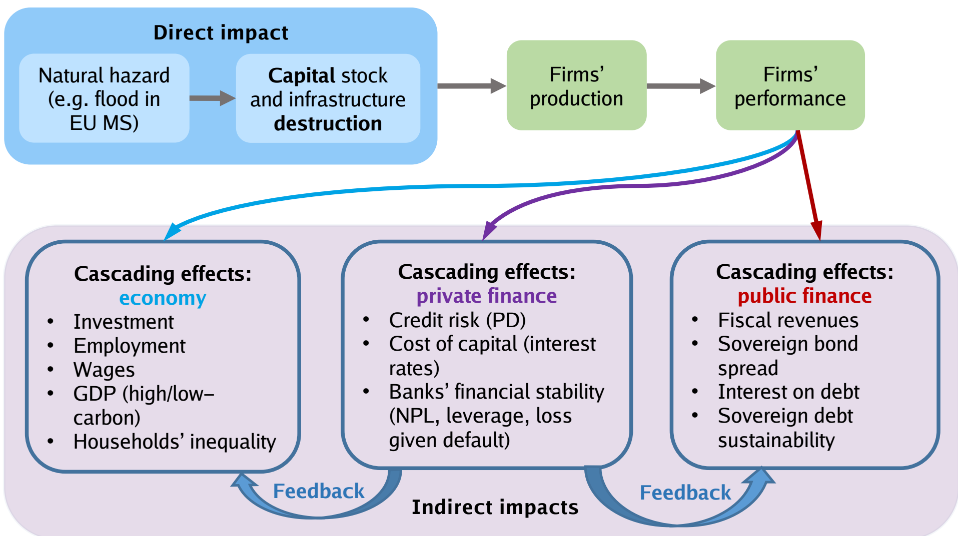


FIGURE 9: Channels of transmission of climate physical risks to the economy and finance. The figure shows the entry point, the direct, and indirect impacts of a natural hazard (e.g. flood) in the economy and finance.

6 Model dimensioning and calibration

We initialize, calibrate and empirically validate the EIRIN model to selected characteristics and real data from the EA to ensure that the shocks' dimensions are quantitatively meaningful. We rely on official data provided by Eurostat, by the ECB data warehouse and by the OECD.[20]

The model depends on more than 100 parameters, and the calibration is split in two sets of parameters and benchmark values. The first part considers parameters that appear explicitly in the model dynamics and are also observable from data (for example tax rates on labour income, corporate or dividends). A list of key parameters is provided in the appendix, see table 2. Some additional values relate to the initialization of the model. For instance the unemployment level at the beginning will be set to match the data.

The second part consists of ex-post calibration of the stable level of the economy, which is crucial to adjust the endogenous behaviour of the model to mimic realistic dynamics. It relies on a set of free parameters that cannot be observed directly. These parameters are set to allow for endogenously produced time series that match observed data, such as GDP, policy rate, etc. In this second part of the calibration, we initialize the model to a state where key dynamics are stable. This represents a baseline scenario in which mild climate impacts occur, and the economy keeps on evolving similarly to past years with no additional climate risk. This is common practice in complex systems models (Fagiolo et al., 2019).

In particular, the GDP growth rate depends on a number of factors, both in reality and in the model. Thus, it cannot be set exogenously. However, other variables, such as the ones that inform the evolution of workers' productivity and their salaries, can be set to reach a sensible value. The calibration process also considers the value added by sector, the energy consumption of the sectors and their contribution to carbon emissions, and the relation with the rest of the world through imports and exports. In table 1, we present the outcomes of this second-step calibration by comparing model's indicator means with observed data means during a time span of six years, which serve as benchmark values to calibrate the model.

This first multi-regional application of the EIRIN model represents an advancement on previous applications and required a model's tailoring. Indeed, the calibration of multi-regions models is complex and requires going beyond standard national statistics, for both parts of the calibration. In some cases, overall EA values are available. When national-level statistics are available, we use the mean across EA countries. Consider for example the case of the replacement rate, i.e. what determines the revenues given by the government to unemployed labour force. Since this value is set at the country level by state policies, an EA aggregate would not be meaningful and is not available. Therefore, we compute an aggregate based on national statistics.

Our double calibration strategy allows us to ensure that the modelled economy presents the same behaviour as what is observed in reality, when subjected to the same policy variables. This is

[20] See https://ec.europa.eu/eurostat, https://sdw.ecb.europa.eu/ and https://data.oecd.org/ respectively.

complemented by an extensive sensitivity analysis embedded in our framework. For all parameters, it is possible to test the impact of deviations with regard to key outputs, including GDP growth, unemployment, the value added and emissions of every sector.

		Simulation values		Real values	
		Mean	Standard deviation	Mean	Standard deviation
Energy	Energy bill of households (% of GDP)	4.00	0.00	2.10	0.13
	Share of households' expenses in energy (% of disposable income)	5.12	0.01	3.97	0.15
	Share of renewable (% of total energy consumption)	19.48	0.01	17.14	0.93
Energy consumption share (% of total energy demand)	Capital producers	0.11	0.00	0.16	0.00
	Consumption goods sector	0.05	0.00	0.10	0.00
	Households	0.45	0.01	0.26	0.00
	Service sector	0.37	0.01	0.48	0.00
Financial indicators	Lending rate from the commercial bank (%)	2.14	0.01	2.32	0.43
	Main refinancing operations rate (%)	-0.26	0.01	0.02	0.03
Investment and credit	Firms' total credit (% of GDP)	49.17	1.56	82.18	1.84
	Total investments (% of GDP)	16.15	0.23	21.08	0.88
Key indicators	Inflation (%)	1.41	0.01	0.88	0.71
	Real GDP growth (%)	1.57	0.01	1.88	0.41
	Share of labour in the total income of labour and capital (%)	73.90	0.29	88.88	0.24
	Share of unemployment (% of total workforce)	3.42	0.15	9.58	1.56
National accounts (% of GDP)	Disposable incomes of households	78.02	0.23	56.89	0.58
	Exports of goods and commodities	33.11	0.01	33.80	0.66
	Exports of services	11.94	0.00	12.75	0.86
	Level of the public debt	53.78	2.15	88.35	3.44
	Net remittances received	-0.04	0.00	-0.03	0.00
	Revenues from tourism	2.56	0.00	2.38	0.20
	Revenues generated from the carbon tax	0.08	0.00	0.08	0.00
	Social benefits (transferred to households)	13.76	0.05	18.89	0.31
	Total government expenditures	50.44	0.18	47.72	0.97
	Total government revenues	50.53	0.10	46.40	0.21
	Total imports	44.86	0.04	42.50	1.63
Share of GHG emissions (% of total emissions)	Capital producers	0.13	0.00	0.18	0.00
	Consumption goods sector	0.04	0.00	0.05	0.00
	Energy sector	0.24	0.00	0.22	0.01
	Households	0.21	0.00	0.22	0.00
	Mining sector	0.01	0.00	0.01	0.00
	Service sector	0.37	0.00	0.32	0.01
Share of employees (% of total employees)	Consumption goods sector	12.76	0.02	13.98	0.13
	Intermediary goods production sector	6.47	0.15	5.39	0.05
	Oil and mining	0.67	0.01	0.10	0.00
	Service sector	64.57	0.19	55.67	0.20
Value added (% of GDP)	Consumption goods sector	34.88	0.04	17.24	0.11
	Energy sector	8.10	0.13	2.36	0.03
	Intermediary goods producers	7.37	0.11	9.53	0.10
	Oil and mining sector	0.92	0.01	0.29	0.00
	Service sector	61.44	0.23	70.58	0.18

TABLE 1: Values of the variables used in the model compared to the target values.

7 Simulation results

In this section, we present the results of the climate physical and transition risk analyses. In 7.1, we compare the macroeconomic, environmental, distributional and financial results of the scenarios, and we discuss the underlying dynamics that drive the outcomes. In 7.2, we assess the role of firms' climate sentiments, i.e. their expectations about carbon pricing that lead to a revision of the NPV investments.

7.1 Macroeconomic indicators

In figure 10a we observe different real GDP dynamics between orderly and disorderly transition scenarios concerning the timing and magnitude of impact. Figure 10b shows that the orderly transition scenario implies short-term, yet limited, costs to economic growth (0.3% less than the other scenarios in 2025). After this first phase, GDP in the orderly transition outperforms the disorderly and hot house world scenarios already in 2030. In particular, better financing conditions for low-carbon firms in the orderly transition scenario, based on revised risk assessment, foster the economic recovery after the initial shock. Overall, the orderly transition achieves important, and early, co-benefits in terms of lower carbon emissions (12% less in 2040 relative to 2020) and strengthened financial stability.

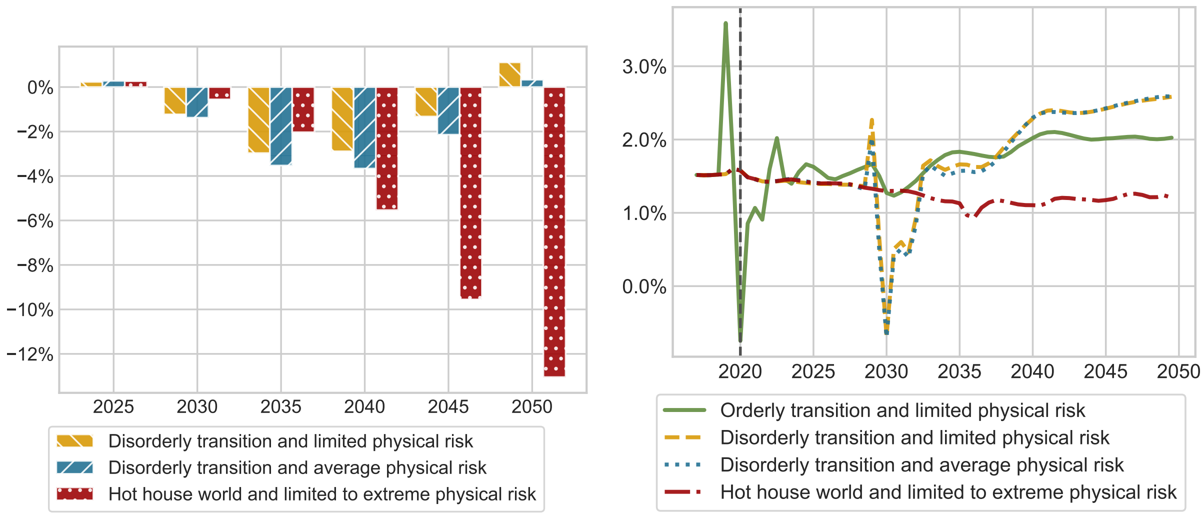
In contrast, a disorderly transition scenario generated real GDP contraction (-2.8% by 2035 compared to the orderly scenario). The negative shock is amplified by severe physical risks (up to -3.3% in 2035). A catching-up only occurs at the end of the simulation period. Thus, a disorderly transition implies larger trade-offs for economic growth in the EA. Finally, the scenario with current policies, i.e. the hothouse world, results in a more significant negative impact on real GDP, which is 12.5% less than in the orderly transition scenario by 2050, due to no climate policies and thus high physical risk.

Note that our shock results are large in magnitude and larger than the ones obtained in previous supervisory exercises (see e.g. Alogoskoufis et al., 2021; Allen et al., 2020). However, the shocks should be considered as a lower bound and thus conservative, since the NGFS scenarios do not model sufficiently the acute physical risks, nor their potential compounding with other risks, and could therefore underestimate the economic and financial impacts of climate risks (Ranger et al., 2022).

A relevant element that explains the economic outcomes is the facility with which capital can be replaced.[21] Importantly, the impact of physical risks increases over time, as shown in figure 8, representing the average expected damages. Thus, capital has to be replaced more frequently, driving up investment and financing needs in the affected scenarios (figure 19 in the appendix shows the costs of reconstruction).

In the hothouse world scenario, physical risk gradually shifts the economy to a more capital-

[21] Our results are in line with the literature, which finds that economies in developed countries with more advanced financial systems suffer less from climate disasters (Toya and Skidmore, 2007; Loayza et al., 2012). Our scenarios simulations end in 2050, while the largest physical risk impacts are expected to occur after 2050 (IPCC, 2018).



(A) Real GDP comparison to the orderly transition scenario (B) Yearly growth of GDP

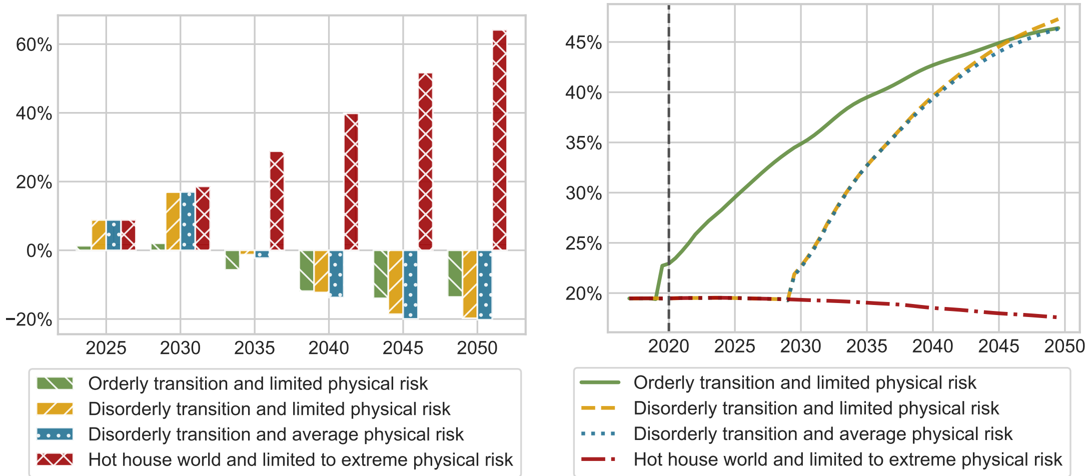
FIGURE 10: Real GDP comparison and growth across the NGFS scenarios.
Left panel: the *x*-axis displays the simulation time and the *y*-axis displays the real GDP difference of the last three scenarios relative to the orderly scenario, in percentage points of the orderly scenario. Right panel: the *x*-axis displays the simulation time and the *y*-axis displays the yearly growth of real GDP in percentage points.

replacement economy, i.e. the market of productive capital increases its share over value added. As a consequence, the capital available is close to the levels that are required to achieve the replacement of the destroyed capital. If capital can be replaced immediately, production is only affected to a low extent.[22] Nevertheless, firms' leverage ratios strongly increase, indicating potential financial stability risks that could arise (see credit levels in the appendix, figure 15c).

Large differences in GHG emission trajectories emerge across scenarios (see figure 11a). GHG emissions increase considerably in the hothouse world scenario compared to 2020 levels. In contrast, the orderly transition scenario shows the earliest decrease in GHG emissions, due to the decoupling of GHG emissions from GDP growth. Thus, our results show that an orderly transition leads to the most effective GHG emissions reduction, while in the disorderly transition scenarios policies are implemented later, leading to emission reduction only after 2030. While GHG emission levels converge between the orderly and disorderly transition scenarios, by design in NGFS scenarios, their cumulative difference over the entire simulation remains sizeable. It is worth noting that the assumption of constant energy efficiency of technology over time mitigates the decoupling, and economic growth tends to increase emissions (differently from IEA (2021), with energy efficiency improvements equal

[22] A more realistic type of shock would be considering a stochastic impact of climate physical risk. Capital producers plan their production based on the demand of the previous periods, which is influenced by the strength of past physical shocks. Then, the production level would not be enough to fully replenish the capital stock in case of a large physical shock. The situation would be suboptimal in case of a small shock, as only part of the production is sold and the profitability of the capital producers falls. The existence of inventory for capital producers would partially mitigate this effect. Nevertheless, it is still likely that any series of clustered shocks of similar magnitude would have an impact We leave that assessment to further research at this point.

to 4% per year to reach Net-Zero targets).



(A) Additional GHG emissions compared to the initial value

(B) Ratio of renewables in the energy mix

FIGURE 11: Transition results for GHG emissions and energy mix across NGFS scenarios.
Left panel: the x-axis displays the simulation time and the y-axis displays total GHG emissions at each semester, indexed at 100 in 2020. Right panel: the x-axis displays the simulation time and the y-axis displays the ratio of renewable energies, as a percentage of supply from renewable energy over the total energy mix at each period.

A large share of GHG emission reduction is due to the change in energy production technology (from fossil fuels to renewable energy), which is triggered by the mechanism described in section 5.2.2, in figure 11b. In the orderly scenario, the increase in renewable energy is gradual, leading to smaller asset price adjustments, and thus smaller financial stability impacts. In contrast, in the disorderly scenario, the increase is sudden and materializes later, leading to abrupt adjustments in costs and thus in asset prices, in the other economic sectors.[23]

We also explore the impact of climate scenarios on the cost of credit. In figure 12 we plot the interest rates for the different sectors that access the credit market. The interest rate is an important indicator that reflects the health of the sectors and is also at the core of the interaction between the firms and the banking sector. As detailed in 3.3, the main determinants of interest rates, which are the PDs, depend on two sector-level variables, i.e. the return on assets and the leverage. Thus, the dynamics observed are influenced by these two variables, which are affected by the feedback loop from interest rates. In particular, higher interest rates reduce firms' profitability via capital constraints, which lower the NPVs, which in turn influence investments in productive capital.

We observe that climate policies contribute to increasing the interest rates of loans to consumption goods producer, service, and oil and mining sectors. In disorderly scenarios, the changes are more abrupt, with implications for financial instability. In contrast, in the orderly scenario, interest

[23] Our conservative choice of base parameters leads to an almost constant share of renewable energy under the hothouse world scenario.

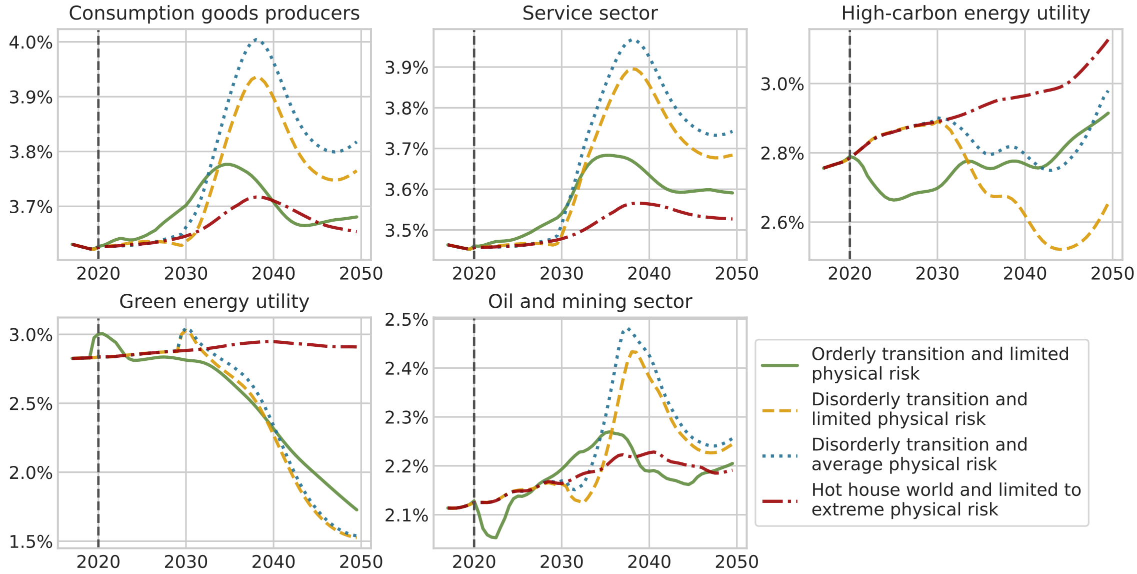


FIGURE 12: Interest rates for real economy firms.
In each panel, the *x*-axis displays the simulation time, and the *y*-axis displays the interest rates (in percentages) that firms pay on their loans in each period.

rates do not differ considerably from those plotted for the hothouse world scenarios, and tend to increase for all firms as a result of extra financing needs due to physical damages. A notable exception is green energy producers, for which interest rates drop significantly a few years after the introduction of the climate policies. This follows a small initial uptake that is driven by an increase in the leverage, as the increase in the share of the energy market requires more capital, which is financed also through credit.

Relatively low interest rates for the oil and mining sector and the high-carbon energy producer in the orderly scenario can be explained by a large deleveraging, which counteracts reduced profitability. Indeed, physical damages are low in the orderly scenario, and the mining firm's capital depreciates slowly due to its limited use. In addition, the demand for fossil fuels decreases in low-carbon transition scenarios. Thus, the investments needed to replace lost capital are smaller than in the other scenarios, putting less strain on the sector and allowing it to deleverage. Therefore, the need for credit in the high-carbon sectors is limited, while the repayment of past loans is not impaired.

Consumption goods and service sectors' financing through credit is constrained because only profitable investments can be financed, after the computation of their NPV. In turn, the final NPV influences the credit allocation by the bank. Being short of their original targets, these sectors cannot satisfy part of the demand, as the total demand defines the original investment target. Figure 13 shows the ratio of investment targets that these two sectors can finance. For both, transition scenarios reduce the realized investment, as carbon prices tend to reduce expected profitability, even when compensatory measures by the government are implemented to help transition to green capital.

Nonetheless, the orderly scenario leads to a higher realized investment, due to a lower carbon price than in the disorderly scenarios. Meanwhile, physical risk reduces the ratio of realized investment, as shown by a drop in this variable for the hothouse world scenario.

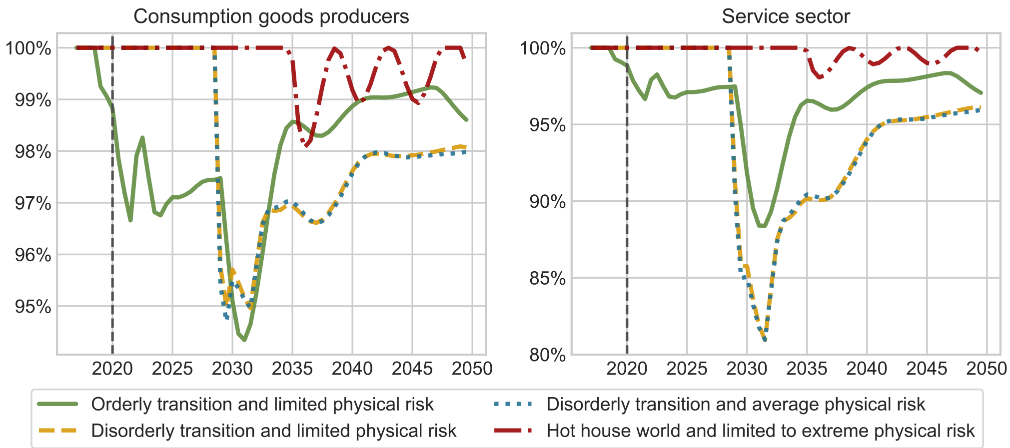


FIGURE 13: Ratio of investment achieved by the consumption goods producers and the service sector.
For each sector, the x-axis displays the simulation time, and the y-axis displays the realized investment as a ratio to the target. The realized investments are totals in units of capital that each sector acquires, while the target is the number of units that it was initially aiming to acquire to fully satisfy the demand. The target computation, as from equation (11), uses sector-level expectations for both the demand and the deterioration of capital, including from climate damages.

7.2 Firms' climate sentiments

In this section, we analyse the impact of firms' expectations about policy credibility (orderly scenarios) and their reaction through anticipation of carbon price across the NGFS scenarios. Firms' investment decisions, while playing a main role in achieving the low-carbon transition, are affected by the financing conditions of banks, and by regulatory policies (when applicable).

We analyse how firms' anticipation of the carbon price in the orderly scenario affects their investment decisions in high- or low-carbon activities. We study four variations of the orderly scenario where the consumption goods producer and service sector have different levels of foresight: none (i.e. using current carbon prices), 10 years, 20 years, and 30 years. More specifically, investments by consumer goods producers in green and high-carbon capital depend on expected returns. Therefore, when firms internalize future carbon prices earlier in their NPV, they transition earlier to green capital.

Two important results emerge. First, if firms believe in the early introduction of an ambitious carbon tax and start to internalize the scenarios of carbon prices in their NPV assessment, they promote an earlier low-carbon energy transition, as shown in figure 14a. The effect on GHG emissions reduction is particularly pronounced when firms extend their policy anticipation up to 20 years for their NPV assessment, resulting in 20% fewer emissions in 2035, compared to a case with no anticipation. Changes are instead more limited beyond that horizon because the carbon price path then stabilizes in the scenarios. The impacts of firms' climate sentiments on growth (see figure 14b) and unemployment (figure 14c) are contained, meaning that firms' anticipation of the switching to renewable energy and capital has no visible economic trade-off.

Second, the longer the investment horizon of firms, the higher the credit in the initial phase of the simulation. This result emerges from the fact that the price of green capital is still comparatively high, and from the fact that in the short term, investment decisions would be less profitable. Thus, the benefits from lowering its carbon tax payments appear when the carbon price does reach the levels anticipated.

8 Conclusion

In this paper, we quantitatively assessed the double materiality of climate physical and transition risks in the EA economy and banking sector. To this aim, we further tailored the EIRIN macroeconomic model and embedded the NGFS climate scenarios in order to implement a dynamic, macro-financial assessment of climate risks. In addition, we considered the impact of climate sentiments in the low-carbon transition, focusing on firms' foresight of carbon pricing across the NGFS scenarios.

Orderly, disorderly or hot house world scenarios have different implications on firms' performance, which in turn affect banks' financial performance and investment decisions. Importantly, in our analysis, the orderly and disorderly characteristics of NGFS scenarios emerge endogenously from the EIRIN model simulations.

An orderly transition has co-benefits (in terms of GDP, GHG emissions, firms and banks' financing conditions) already in the midterm. Indeed, in the absence of early and credible transition policies, the GDP level projected for 2050 is around 12% lower than in transition scenarios. Importantly, trade-offs between GDP growth and GHG emissions decrease are smoothed in an orderly transition scenario.

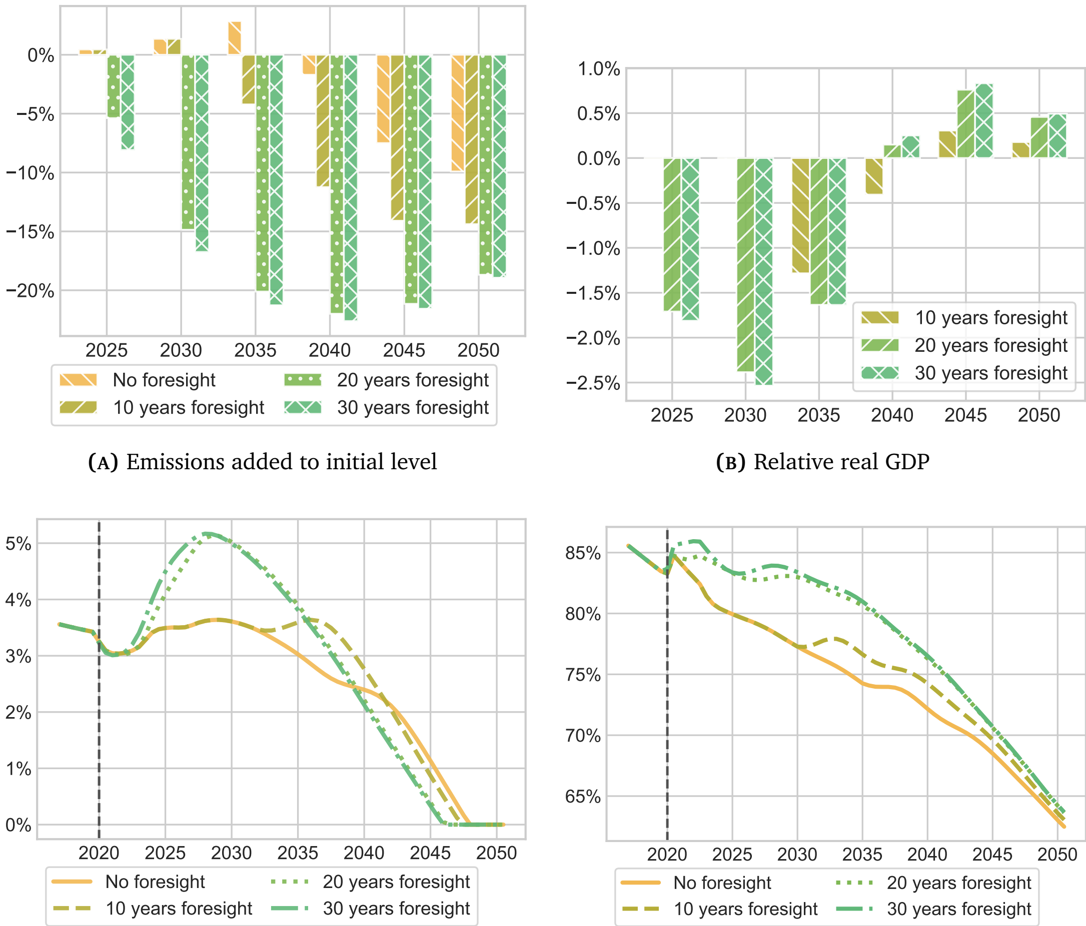
In contrast, in the disorderly transition scenarios, constraints on firms' investments can lead to potential implications on firms and banks' financial stability. Firms' challenges to access credit and to invest in low-carbon energy technologies could lead to the realization of carbon stranded assets, with negative implications on economic and financial stability.

Our results highlight the importance to consider the interplay between the economy and the financial sector in the assessment of climate transition and physical risks. We find that banks' climate risk assessment and firms' climate sentiments are tightly connected to the patterns of the low-carbon transition trajectories that we obtain, and to the conditions for trade-offs to emerge. Under the model conditions, an orderly transition has important co-benefits in terms of GHG emissions abatement in the midterm. In this regard, firms' anticipation of carbon pricing trajectories coherently with NGFS scenarios play a main role in the achievement of a smooth low-carbon transition.

Our results have relevant implications for financial policy. In particular, they make the case for financial supervisors, central banks and financial regulators to embed endogenous macro-financial feedback loops, and firms' expectations, in their climate stress tests exercises. In this regard, macro-prudential policies could be considered in order to mitigate climate-related financial risks for banks. However, the specific forward-looking nature of climate risks requires an appropriate policy calibration, that should consider its future costs and benefits not only depending on possible future climate scenarios, but also based on how these scenarios could be impacted by institutions' behaviours, ultimately affecting the likelihood of the scenarios themselves to materialize.

In conclusion, our study provides a methodological framework to assess the double materiality of climate risks, in line with current discussions in the European Union about the revision of the Corporate Sustainability Reporting Standards.[24] Therefore, our paper not only confirms, via modelling tools, the importance of the double materiality principle to enhance disclosures, but could also support the calibration of prudential instruments to account for and internalize such principle. Finally, our analysis highlights the importance of strengthening climate scenarios, and in particular physical risk scenarios (Ranger et al., 2022) for climate financial risk assessment. There is an urgent need to include acute shocks on assets (Bressan et al., 2022) and the potential compounding of shocks (Dunz, Essenfelder, et al., 2021), and combination with chronic shocks. This would allow for estimating larger shocks on GDP before 2050, with potential for economic recession, making the scenarios more relevant for banks' climate stress test exercises.

[24] See https://ec.europa.eu/info/business-economy-euro/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en.



(A) Emissions added to initial level

(B) Relative real GDP

(C) Unemployment

(D) Credit to GDP

FIGURE 14: Simulation results of the orderly transition scenarios conditioned to firms' climate sentiments. The *x*-axis displays the simulation time. In the top left panel, the *y*-axis displays GHG emissions for selected years, as a percentage deviation from the 2020 level. In the top right panel, the *y*-axis represents the real GDP deviation from the case with no foresight, in percentage. In the bottom left panel, the *y*-axis displays unemployment as a percentage of the total active workforce. In the bottom right panel, values on the *y*-axis are given as ratios in percentages of the overall credit granted to GDP.

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A Model methodology

A.1 Financial market pricing

We model the secondary security market using a mechanism that builds on that of Dunz, Monasterolo, et al. (2020). It proceeds as follows:

1) Every agent i starts with liquidity $M_i(t-1)$ and a vector $(S_{j,i}(t-1))_j$ of holdings, at initial prices $(p^\dagger_j(t-1))_j$.

2) Each agent determines its participation in the market, i.e. how much it can invest in total, how much to acquire or how much to issue. In the case of i being either banks or capitalist households, it computes its perceived fundamental prices $(p^\star_{j,i}(t))_j$ and the total amount $X_i(t)$ that it should be able to invest, which is the sum of its liquidity and wealth from holdings at (previous) market values:

$$X_i(t) = M_i(t-1) + \sum_j S_{j,i}(t-1) p^\dagger_j(t-1)\,. \tag{24}$$

3) Each agent seeks to acquire what it sees as a representative slice of the market in value, i.e. it wants to achieve

$$\frac{S_{j,i}(t) \times p^\star_{j,i}(t)}{X_i(t)} = \frac{\mathbf{S}_j(t) \times p^\star_{j,i}(t)}{\sum_k \mathbf{S}_k p^\star_{k,i}(t)}\,.$$

4) New prices $p^\dagger(t)$ are formed for all securities based on the demand, i.e. the joint allocation of all sectors.

5) Holdings of securities change, assuming that they are traded between agents at new prices to achieve desired allocations. Importantly, the mechanism is liquidity preserving because of this last step. The new liquidity of agents after trading is given by

$$\forall i, \quad M_i(t) = M_i(t-1) + \sum_j \underbrace{\left(S_{i,j}(t-1) - S_{i,j}(t)\right)}_{\Delta S_{i,j}(t)} p^\dagger_j(t), \tag{25}$$

which verifies $\sum_i M_i(t) = \sum_i M_i(t-1)$ from the fact that $\forall j, \sum_i \Delta S_{i,j}(t) = 0$, where we count newly issued securities as if they were held at time $t-1$ by the issuing entity.

A.2 Net present value and investment for service and goods production

We start by detailing the calculation of the net present value for new investment by the consumption goods producers or the service firms, i.e. $j \in \{\mathrm{Fk}, \mathrm{Fl}\}$. First, we calculate the NPV for high-carbon investments, which we defined as

$$\mathrm{NPV}^{\mathrm{B}}_j(\iota, t) = -p_{\mathrm{KpB}}(t) \cdot \iota + \sum_{s=t+1}^{+\infty} \frac{\mathrm{CF}^{\mathrm{B}}_j(\iota, t, s)}{(1+\kappa_j)^{s-t}}\,.$$

Given a level ι of investment at t, the anticipated total cash flow from high-carbon investment at time $s > t$ is

$$\mathrm{CF}_j^{\mathrm{B}}(\iota, t, s) = \frac{\hat{p}_j(s)}{1+\tau_{\mathrm{VAT}}(t)} \cdot \Delta\hat{\mathbf{q}}_j(\iota) - \hat{w}_j(s) \cdot \Delta N_j(\iota, t, s) - p_R(s) \cdot \Delta^{\mathrm{B}} \hat{q}_{R,j}(\iota, t, s)$$
$$- \hat{p}_{\mathrm{En}}(s) \cdot \Delta^{\mathrm{B}} \hat{D}_{\mathrm{En},j}(\iota, t, s) - \Delta^{\mathrm{B}} \widehat{\mathrm{Em}}_j(\iota, t, s) \times \tau_{\mathrm{Em}}(t)$$

where we distinguish four cash flows. In doing so, we take into account the depreciation with rate δ_j of the capital bought when computing the future expected cash flows.

First, a positive cash flow is given by the additional sales due to investment, with $\Delta\hat{q}_j(\iota)$ the additional expected production (and sale) due to investments, and $\hat{p}_j$ is the expected sale price. The latter is adjusted for VAT, which is assumed constant. They are given respectively by

$$\Delta\hat{\mathbf{q}}_j(\iota, t, s) = \iota(1-\delta_j)^{s-t} \times \gamma_j^K \quad \text{and} \quad \hat{p}_j(s) = p_j(t) \times (1+\pi_j)^{s-t}$$

with γ_j^K the productivity of capital and π_j the expected growth rate of the price.

Second, three negative cash flows include:

- The additional labour costs required to match the need for increased production capacity. This is made of the expected wages $w_j(s)$ to be paid, assuming a salary growth rate $\pi_{w,j}$, and of the additional number ΔN_j of workers to match the additional production capacity due to investments. We get

$$\hat{w}_j(s) = w_j(t) \times (1+\pi_{w,i})^{s-t} \quad \text{and} \quad \Delta N_j(\iota, t, s) = \frac{\Delta\hat{\mathbf{q}}_j(\iota, t, s)}{\gamma_j^N(t) \times (1+\dot{\gamma}^N)^{s-t}}$$

  with , γ_j^N the productivity of labour and $\dot{\gamma}^N$ the growth rate of the latter.

- The additional raw materials costs incurred to produce the additional output. It is described by the expected price $p_R(s)$ and the additional amount $\Delta q_j^R(\iota, s)$ of raw materials required to match the increase in production capacity due to investments. We get

$$p_R(s) = p_R(t) \times (1+\pi_R)^{s-t} \quad \text{and} \quad \Delta^{\mathrm{B}} \hat{q}_{R,j}(\iota, t, s) = \Delta\hat{\mathbf{q}}_j(\iota, t, s) \times \phi_j^R$$

  where π_R is the raw material price growth rate, assumed constant and known to the agent, and ϕ_j^R is the coefficient of raw material necessary per unit of output.

- The extra energy requirements for producing additional output. It is composed of the expected energy price $\hat{p}_{\mathrm{En}}$, and the additional quantity ΔD_j^{En} of energy required to match the additional production capacity due to investments. We get

$$\hat{p}_{\mathrm{En}}(s) = p_{\mathrm{En}}(t) \times (1+\pi_{\mathrm{En}})^{s-t} \quad \text{and} \quad \Delta^{\mathrm{B}} \hat{D}_{\mathrm{En},j}(\iota, t, s) = \Delta\hat{\mathbf{q}}_j(\iota, t, s) \times \phi_j^{\mathrm{En}}$$

  where $\pi_E N$ is the estimated energy price growth rate, and ϕ_j^{En} is the coefficient of energy necessary per unit of output.

- The extra tax on GHG emissions that follow from the use of high-carbon capital bought and the consumption of energy that accompany the surplus of production. For the tax rate, the default setting is that the contemporaneous value $\tau_{\mathrm{Em}}(t)$ is used, i.e. agents do not have expectation for it to change. However, this assumption is relaxed in 7.2, where we can use a foresight of u periods, which translates in the use of $\tau_{\mathrm{Em}}(t+u)$ instead. As for the quantity of emissions, it depends on the added production from high-carbon capital and the consumption of energy from non-renewable sources, such that

$$\Delta^{\mathrm{B}}\widehat{\mathrm{Em}}_j(\iota,t,s) = \Delta\hat{\mathbf{q}}_j(\iota,t,s)\cdot\theta_j^{\mathrm{Em}} + \Delta^{\mathrm{B}}\hat{D}_{\mathrm{En},j}(\iota,t,s)\cdot\hat{z}_{\mathrm{EnB}}(s)\theta_{\mathrm{En}}^{\mathrm{Em}}$$

where θ_j^{Em} and $\theta_{\mathrm{En}}^{\mathrm{Em}}$ are the carbon intensity of the sector production and of energy use respectively, and $\hat{z}_{\mathrm{EnB}}(s)$ is the expected share of high-carbon energy in the total energy mix at time s. The realized increase of the renewable energy share will be in general less than what the green energy producers intend to, based on the mechanism in 5.2.2, as it assumes a constant energy demand and stable damages. Moreover, λ_{EnG} is not necessarily known to other agents, while ξ_{EnG} would be in general. Therefore, the theoretical value λ_{EnG} is replaced by an estimation $\tilde{\lambda}_{\mathrm{EnG}}$ in the above, such that

$$\hat{z}_{\mathrm{EnB}}(s) = 1-\xi_{\mathrm{EnG}} + (1-\tilde{\lambda}_{\mathrm{EnG}})^{s-t}\cdot(\xi_{\mathrm{EnG}} - \mathbf{q}_{\mathrm{EnG}}(t)/\mathbf{q}_{\mathrm{En}}(t))\,.$$

Note that in practice endogeneity arises in how some of these variables will be actually defined. In particular, as detailed in equation (8), the price p_j is a variable of p_R, w_j, p_{En}, and the carbon tax. Moreover, most of the inflation/growth rates are endogenous to the model. Therefore, they have to be estimated from recent values of the corresponding time series.

Let $\Upsilon_j = (1-\delta_j)/(1+\kappa_j)$. Then, the set of conditions for the NPV to be properly defined are

$$\Upsilon_j(1+\pi_j)<1,\quad \Upsilon_j\frac{1+\pi_{w,i}}{1+\dot{\gamma}^N}<1,\quad \Upsilon_j(1+\pi_R)<1,\quad \text{and}\quad \Upsilon_j(1+\pi_{\mathrm{En}})<1\,. \tag{26}$$

When conditions (26) are verified, from the formula for sums of geometric series we get

$$\frac{\mathrm{NPV}_j^{\mathrm{B}}(\iota,t)}{\iota} = -p_{\mathrm{KpB}}(t) + \gamma_j^K\left(\frac{p_j(t)/(1+\tau_{\mathrm{VAT}}(t))}{1-\Upsilon_j(1+\pi_j)} - \frac{w_j(t)/\gamma_j^N(t)}{1-\Upsilon_j\frac{1+\pi_{w,i}}{1+\dot{\gamma}^N}} - \frac{p_R(t)\phi_j^R}{1-\Upsilon_j(1+\pi_R)} - \frac{p_{\mathrm{En}}(t)\phi_j^{\mathrm{En}}}{1-\Upsilon_j(1+\pi_{\mathrm{En}})}\right.$$
$$\left. -\frac{\tau^{\mathrm{GHG}}(t)}{1-\Upsilon_j}\left[\theta_j^{\mathrm{Em}} + \theta_{\mathrm{En}}^{\mathrm{Em}}\phi_j^{\mathrm{En}}(1-\xi_{\mathrm{EnG}})\right] - \frac{\tau^{\mathrm{GHG}}(t)\theta_{\mathrm{En}}^{\mathrm{Em}}\phi_j^{\mathrm{En}}}{1-\Upsilon_j(1-\tilde{\lambda}_{\mathrm{EnG}})}\left[\xi_{\mathrm{EnG}} - \frac{\mathbf{q}_{\mathrm{EnG}}(t)}{\mathbf{q}_{\mathrm{En}}(t)}\right]\right)\,.$$

Thanks to the linearity of the NPV we compute only the above ratio, which eases intertemporal comparisons as this value reflects profitability independently of the amount actually invested. The calculation for the green NPV is similar, with the following equations:

$$\mathsf{NPV}_j^{\mathsf{G}}(\iota,t) = -p_{\mathrm{KpG}}(t)\cdot\iota + \sum_{s=t+1}^{+\infty}\frac{\mathrm{CF}_i^{\mathsf{G}}(\iota,t,s)}{(1+\kappa_j)^{s-t}}$$

$$\mathrm{CF}_j^{\mathsf{G}}(\iota,t,s) = \frac{\hat{p}_j(s)}{1+\tau_{\mathrm{VAT}}(t)}\cdot\Delta\hat{\mathbf{q}}_j(\iota) - \hat{w}_j(s)\cdot\Delta N_j(\iota,t,s) - p_R(s)\cdot\Delta^{\mathsf{G}}\hat{q}_{R,j}(\iota,t,s)$$
$$-\hat{p}_{\mathrm{En}}(s)\cdot\Delta^{\mathsf{G}}\hat{D}_{\mathrm{En},j}(\iota,t,s) - \Delta^{\mathsf{G}}\widehat{\mathrm{Em}}_j(\iota,t,s)\times\tau_{\mathrm{Em}}(t)$$

where the differences in the terms of the cash flows are due to a lower consumption of energy and raw materials when using green capital (with constant discount rates given by $\eta_{\mathrm{En}}^{\mathsf{G}}$ and η_R^{G} respectively), as well as an absence of GHG emissions from the use of capital. This gives us the following:

$$\Delta^{\mathsf{G}}\hat{q}_{R,j}(\iota,t,s) = \Delta\hat{\mathbf{q}}_j(\iota,t,s)\times\phi_j^R(1-\eta_R^{\mathsf{G}})$$
$$\Delta^{\mathsf{G}}\hat{D}_{\mathrm{En},j}(\iota,t,s) = \Delta\hat{\mathbf{q}}_j(\iota,t,s)\times\phi_j^{\mathrm{En}}(1-\eta_{\mathrm{En}}^{\mathsf{G}})$$
$$\Delta^{\mathsf{G}}\widehat{\mathrm{Em}}_j(\iota,t,s) = \Delta^{\mathsf{G}}\hat{D}_{\mathrm{En},j}(\iota,t,s)\cdot\theta_{\mathrm{En}}^{\mathrm{Em}}\cdot\mathbf{q}_{\mathrm{EnB}}(t)/\mathbf{q}_{\mathrm{En}}(t)\,.$$

Note that the condition for the green NPV to be well-defined are then the same as for the high-carbon one, given that only constant factors are added. Thus, the final formula for the green NPV is

$$\frac{\mathsf{NPV}_j^{\mathsf{G}}(\iota,t)}{\iota} = -p_{\mathrm{KpB}}(t) + \gamma_j^K\left(\frac{p_j(t)/(1+\tau_{\mathrm{VAT}}(t))}{1-\Upsilon_j(1+\pi_j)} - \frac{w_j(t)/\gamma_j^N(t)}{1-\Upsilon_j\frac{1+\pi_{w,i}}{1+\dot{\gamma}^N}} - \frac{p_R(t)\phi_j^R(1-\eta_R^{\mathsf{G}})}{1-\Upsilon_j(1+\pi_R)}\right.$$
$$-\phi_j^{\mathrm{En}}(1-\eta_{\mathrm{En}}^{\mathsf{G}})\left[\frac{p_{\mathrm{En}}(t)}{1-\Upsilon_j(1+\pi_{\mathrm{En}})} + \frac{\tau^{\mathrm{GHG}}(t)\theta_{\mathrm{En}}^{\mathrm{Em}}}{1-\Upsilon_j}(1-\xi_{\mathrm{EnG}})\right.$$
$$\left.\left.+\frac{\tau^{\mathrm{GHG}}(t)\theta_{\mathrm{En}}^{\mathrm{Em}}}{1-\Upsilon_j(1-\tilde{\lambda}_{\mathrm{EnG}})}\left(\xi_{\mathrm{EnG}} - \frac{\mathbf{q}_{\mathrm{EnG}}(t)}{\mathbf{q}_{\mathrm{En}}(t)}\right)\right]\right)\,.$$

We then move on to calculate the NPV for the energy producers. Starting with the green energy producer we get

$$\mathsf{NPV}_{\mathrm{EnG}}(\iota,t) = \sum_{s=t+1}^{+\infty}\frac{\hat{p}_{\mathrm{En}}(s)\cdot\Delta\hat{\mathbf{q}}_{\mathrm{EnG}}(\iota,t,s)}{(1+\tau_{\mathrm{En}})(1+\kappa_{\mathrm{EnG}})^{s-t}} - (1-\eta_K)p_{\mathrm{KpG}}(t)\cdot\iota$$

where $\Delta\hat{\mathbf{q}}_{\mathrm{EnG}}(\iota,t,s) = \iota(1-\delta_{\mathrm{EnG}})^{s-t}\cdot\gamma_{\mathrm{EnG}}^K$ is the expected future production added, τ_{En} is the VAT rate on energy, and η_K is the government-financed rebate on capital for EnG. Let $\Upsilon_{\mathrm{EnG}} = (1-\delta_{\mathrm{EnG}})/(1+\kappa_{\mathrm{EnG}})$. If $\Upsilon_{\mathrm{EnG}}(1+\pi_{\mathrm{En}}) < 1$ then the series in the above sum converges, and we get

$$\frac{\mathsf{NPV}_{\mathrm{EnG}}(\iota,t)}{\iota} = \frac{\gamma_{\mathrm{EnG}}^K\hat{p}_{\mathrm{En}}(t)/(1+\tau_{\mathrm{En}})}{1-\Upsilon_{\mathrm{EnG}}(1+\pi_{\mathrm{En}})} - (1-\eta_K)p_{\mathrm{KpG}}(t)\,.$$

For the high-carbon energy sector, which buys high-carbon productive capital, we get

$$\mathsf{NPV}_{\mathrm{EnB}}(\iota, t) = -p_{\mathrm{KpB}}(t) \cdot \iota + \sum_{s=t+1}^{+\infty} \frac{\mathrm{CF}_{\mathrm{EnB}}(\iota, t, s)}{(1+\kappa_{\mathrm{EnB}})^{s-t}},$$

where we have the expected cash flows that is made up of revenues from energy production (except for what is consumed in the process itself, see A.4), the expenses from oil consumption and the tax on added carbon emissions:

$$\frac{\mathrm{CF}_{\mathrm{EnB}}(\iota, t, s)}{(1-\delta_j)^{s-t} \cdot \iota} = \frac{\hat{p}_{\mathrm{En}}}{1+\tau_{\mathrm{En}}} \cdot \frac{\gamma^K_{\mathrm{EnB}}}{1+\rho_{\mathrm{EnB}}} - \hat{p}_{\mathrm{MO}} \cdot \frac{\gamma^K_{\mathrm{EnB}}}{\gamma^o_{\mathrm{EnB}}} - \tau_{\mathrm{Em}}(t)\gamma^K_{\mathrm{EnB}}\left(\theta_{\mathrm{EnB}} + \rho_{\mathrm{EnB}}\hat{z}_{\mathrm{EnB}}(s)\theta^{\mathrm{Em}}_{\mathrm{En}}\right) .$$

so that, if we set $\Upsilon_{\mathrm{EnB}} = (1-\delta_{\mathrm{EnG}})/(1+\kappa_{\mathrm{EnG}})$, then the NPV is correctly defined when we verify $\Upsilon_{\mathrm{EnB}} < 1$,

$$\begin{aligned}\frac{\mathsf{NPV}_{\mathrm{EnB}}(\iota, t)}{\iota} = &- p_{\mathrm{KpB}}(t) + \gamma^K_{\mathrm{EnB}}\left(\frac{p_{\mathrm{En}}(t)/(1+\tau_{\mathrm{En}})}{1-\Upsilon_{\mathrm{EnB}}(1+\pi_{\mathrm{En}})} - \frac{p_{\mathrm{MO}}(t)/\gamma^o_{\mathrm{EnB}}}{1-\Upsilon_{\mathrm{EnB}}(1+\pi_{\mathrm{MO}})}\right.\\ &\left. - \frac{\tau^{\mathrm{GHG}}(t)}{1-\Upsilon_{\mathrm{EnB}}}\left[\theta^{\mathrm{Em}}_{\mathrm{EnB}} + \theta^{\mathrm{Em}}_{\mathrm{En}}\rho_{\mathrm{EnB}}(1-\xi_{\mathrm{EnG}})\right] - \frac{\tau^{\mathrm{GHG}}(t)\theta^{\mathrm{Em}}_{\mathrm{En}}\rho_{\mathrm{EnB}}}{1-\Upsilon_{\mathrm{EnB}}(1-\tilde{\lambda}_{\mathrm{EnG}})}\left[\xi_{\mathrm{EnG}} - \frac{\mathbf{q}_{\mathrm{EnG}}(t)}{\mathbf{q}_{\mathrm{En}}(t)}\right]\right) .\end{aligned}$$

A.3 Workers allocation and wages

Skills of working households are heterogeneous, divided between low and high. The consumption goods producer and capital producers employ workers with the highest skills, in exchange for higher salaries, while workers in the labour intensive sector require lower skills, thus receiving lower wages (Blanchard, 2017). The shares of low and high-skilled workers are not fixed, but we limit the inter-period movement of workers relative to what the demand of firms would normally require. This is to account for the frictions of moving between sectors or from a skill category to another.

In EIRIN, wages are computed based on the employment numbers of the previous period. The average wage $\hat{w}$ grows at a rate $1-\theta_1+\theta_2\mathbf{N}/N_{\mathrm{tot}}$, with $\theta_2 > \theta_1$, where $\mathbf{N}/N_{\mathrm{tot}}$ represents the employment rate and drives up the wages. Thus, wages decline with rate $-\theta_1$ in case the labour force is entirely unemployed, they grow at a maximum of $-\theta_1+\theta_2$ in case of full employment, and θ_1/θ_2 is the rate of employment that maintains wages constant. Wage setting for high and low-skilled workers (denoted as w_{high} and w_{low} respectively) is endogenous and set according to the average workers' skills in each sector, following a Phillips curve-like rule (Keen, 2013). We suppose the existence of a legal minimum wage $w_{\min}$ which is dependent on inflation. Denoting as z the share of workers with high wages over the total of the private sector we set

$$w_{\mathrm{high}} = (2-z)\hat{w} - (1-z)w_{\min} \quad \text{and} \quad w_{\mathrm{low}} = (1-z)\hat{w} + zw_{\min},$$

a solution consistent with the total private wage bill equation $N_{\mathrm{high}}w_{\mathrm{high}} + N_{\mathrm{low}}w_{\mathrm{low}} = (N_{\mathrm{high}} + N_{\mathrm{low}})\hat{w}$

and chosen to verify the property that low wages remain at least at the minimum for all values of $z \in [0,1]$.

Furthermore, employment is endogenously determined by labour demand, which itself stems from firms forming adaptive expectations about future demand based on their sales in previous time periods. Those demand expectations then determine firms' production plan $\hat{\mathbf{q}}_j$. For consumption goods producers and service firms, their labour demand $\hat{N}_j$ (with $j \in \{\text{Fl}, \text{Fk}\}$) is determined by their production plan $\hat{\mathbf{q}}_j$, their capital endowment K_j and by the Leontief technology, such that

$$\hat{N}_j = \min\left(\hat{\mathbf{q}}_j, \gamma_j^K K_j\right) / \gamma_j^N$$

where γ_j^K and γ_j^N are the sector-dependent capital and labour productivity respectively. This setup prevents firms from hiring more labour than necessary. Fl is more labour intensive, meaning that $\gamma_{\text{Fl}}^N < \gamma_{\text{Fk}}^N$ but employs low-skilled workers only, receiving low wages w_{low}. Fk is more capital intensive, meaning that $\gamma_{\text{Fk}}^K < \gamma_{\text{Fl}}^K$ and employs high-skilled workers only, receiving high wages w_{high}.

The capital good producer only relies on labour as input factors, and hires workers based on its labour productivity to satisfy the firms' expected demand for capital goods

$$\forall i \in \{\text{KpB}, \text{KpG}\}, \quad \hat{N}_i(t) = \hat{\mathbf{D}}_i(t) / \gamma_i^N$$

where $\hat{\mathbf{D}}_i(t)$ is taken as an average of the demand over a given number of periods, and γ_i^N is the labour productivity.

The model changes from the version in Dunz, Monasterolo, et al. (2020) to have a more intuitive distribution of workers across the different industries. The number of public servants in the model is fixed equal to N_{G}, so that the active population on the labour market to be employed in firms is $N_{\text{priv}} = N_{\text{tot}} - N_{\text{G}}$. Let $\hat{\mathbf{N}} = \sum_i \hat{N}_i$ the total private demand for workers (we omit the time index). If $\hat{\mathbf{N}} \leq N_{\text{priv}}$: each sector i gets as many workers as it wants, i.e. $\forall i, N_i = \hat{N}_i$, and the unemployment rate is given by $(N_{\text{priv}} - \hat{\mathbf{N}})/N_{\text{tot}}$. Then, a replacement rate is defined, so that unemployed workers get unemployment benefits from the government, calculated as a ratio of the previous period mean wage.

However, if $\hat{\mathbf{N}} > N_{\text{priv}}$, the priority between sectors is determined under the assumption that those with higher wages can recruit more easily, and unemployment is zero. We set

$$\forall i, \quad N_i = \hat{N}_i \cdot \frac{N_{\text{priv}}}{\hat{\mathbf{N}}} \left(1 + \alpha_N \frac{w_i - \tilde{w}}{w_{\text{high}} - w_{\text{low}}}\right) \tag{27}$$

where (w_i) is the vector of wages across sectors, and $\tilde{w} = \left(\sum_i \hat{N}_i w_i\right) / \left(\sum_i \hat{N}_i\right)$ is the demand-weighted average salary, to verify $\sum_{i \neq \text{G}} N_i = N_{\text{priv}}$. Moreover, we want to verify $N_i \in [0, \hat{N}_i]$, hence, for every sector i,

$$0 \leq N_i \leq \hat{N}_i \implies -1 \leq \alpha_N \frac{w_i - \tilde{w}}{w_{\text{high}} - w_{\text{low}}} \leq \frac{\hat{\mathbf{N}}}{N_{\text{priv}}} - 1 \,.$$

Then, notice that $\forall i, -1 \leq \frac{w_i - \tilde{w}}{w_{\text{high}} - w_{\text{low}}} \leq 1$. Therefore, a sufficient condition is $\alpha \leq \min\left(1, \hat{\mathbf{N}}/N_{\text{priv}} - 1\right)$. Thus, we set $\alpha_N = \min\left(\hat{\alpha}_N, \hat{\mathbf{N}}/N_{\text{priv}} - 1\right)$, where $\hat{\alpha}_N \in [0,1]$ is a constant parameter, the sensitivity of workers to wage differences.

A.4 Energy utility sector

Compared to previous versions of the model, this exercise also features a more realistic high-carbon energy sector and a flexible way to price energy that can reflect a broad range of policies.

First, the productive capacity of the high-carbon, fossil-fuel dependent utility is now linearly dependent on its capital[25], which is provided by the high-carbon capital producer and subject to depletion. In the new setting, the high-carbon energy producer is similar to its green counterpart in the way is uses capital. Moreover, the sector sets an investment target to maintain production capacity above expected demand (based on a pre-defined parameter). In case demand exceeds generation capacity, no energy shortage happens but the high-carbon energy sector buys the remainder needed from the rest of the world.[26]

Second, the total power that the sector produces is computed to take into account its own contemporaneous consumption[27]. Let $\tilde{\mathbf{D}}_{\text{En}}$ the energy demand from sectors other than EnB. We have:

$$\begin{cases} \mathbf{q}_{\text{En}} = \tilde{\mathbf{D}}_{\text{En}} + D_{\text{En,EnB}} \\ D_{\text{En,EnB}} = \rho_{\text{EnB}} \times \mathbf{q}_{\text{EnB}} \\ \mathbf{q}_{\text{EnB}} = \mathbf{q}_{\text{En}} - \mathbf{q}_{\text{EnG}} \end{cases},$$

where $\rho_{\text{EnB}} \in [0,1)$ is the parameter indicating how many input units of energy are necessary for EnB to produce one unit output of energy. As $\tilde{\mathbf{D}}_{\text{En}}$ and $\mathbf{q}_{\text{EnG}}$ are already determined, we obtain $\mathbf{q}_{\text{EnB}}$, $D_{\text{En,EnB}}$ and $\mathbf{q}_{\text{En}}$, starting from $\mathbf{q}_{\text{EnB}} = (\tilde{\mathbf{D}}_{\text{En}} - \mathbf{q}_{\text{EnG}})/(1 - \rho_{\text{EnB}})$.

The price is then set taking into account the unit cost of both sectors, denoted as UC_{EnB} and UC_{EnG}. These values take into account the basic production needs and the costs linked to debt and capital acquisition. Thus, for EnB we get

$$\text{UC}_{\text{EnB}} = \frac{p_{\text{MO}}}{\gamma^0_{\text{EnB}}} + p_{\text{En}} \times \rho_{\text{EnB}} + \frac{(\kappa_{\text{EnB}} + \chi_{\text{EnB}})L_{\text{EnB}} + \tau_{\text{Em}}\text{Em}_{\text{EnB}} + p_{\text{KpB}}K_{\text{EnB}}(\delta_{\text{EnB}} + \hat{\xi})}{\mathbf{q}_{\text{EnB}}},$$

where κ_i is the interest rate on loans L_{EnB}, with χ_{EnB} the repayment rate, and γ^o_{EnB} is the oil efficiency. For EnG we get

$$\text{UC}_{\text{EnG}} = \frac{(\kappa_{\text{EnG}} + \chi_{\text{EnG}})L_{\text{EnG}} + p_{\text{KpG}}K_{\text{EnG}}(\delta_{\text{EnG}} + \hat{\xi})}{\mathbf{q}_{\text{EnG}}}.$$

Finally, the price is computed as a generalized mean of the unit costs. It is controlled by a unique

[25]This is opposed to a model where the production could be scaled up by simply using more oil, but without requiring additional capital, so that the latter could be kept at its original level.

[26]The energy is bought from abroad at final energy price, hence the energy sector is worse-off from the transfer because of the VAT.

[27]A one-period lag was previously used between the production and the use of that energy.

parameter α_{En} that can be interpreted in terms of the degree of competition imposed by the regulator. More precisely, we set

$$p_{\text{En}} = (1 + \tau_{\text{En}}) \times (1 + \mu_{\text{En}}) \times \left(\frac{q_{\text{EnB}}}{q_{\text{En}}} \cdot \text{UC}_{\text{EnB}}^{\alpha_{\text{En}}} + \frac{q_{\text{EnG}}}{q_{\text{En}}} \cdot \text{UC}_{\text{EnG}}^{\alpha_{\text{En}}} \right)^{1/\alpha_{\text{En}}},$$

where τ_{En} is the VAT rate on energy, and μ^{En} is the energy mark-up.

Then, the approach that consists of choosing the price as a simple weighted average of the energy cost corresponds to $\alpha = 1$ (although profits would not be redistributed as a function of the producers' cost, so this is advantageous for the cheapest producer). A value $\alpha_{\text{En}} > 1$ would be more protective, as the final price is skewed toward the most expensive production, to make sure that both sectors are still profitable. With higher values, e.g. $\alpha_{\text{En}} > 20$, this would get close to taking simply the maximum of the two. On the other hand, a value $\alpha_{\text{En}} < 1$ would reflect a more competitive environment (or better bargaining position for the state or other intermediary electricity provider that buys from utilities and distributes) as the final price is now closer to the lowest of the two.

A.5 Calibration of the model

Relating to the calibration principles defined in 6, we provide in table 2 the set of parameters used explicitly in the model taken from the data.

Variable	Source	Value
Energy consumption of households as part of total budget	Eurostat	10%
Share of goods in households consumption	Eurostat	37%
Ratio of savings to revenue for households	ECB	7
Markup of consumption goods producers	Bundesbank and European Commission	1.25
Markup of service firms	Bundesbank and European Commission	1.35
Depletion rate for the capital of consumption goods producers (by semester)	ECB	2.7%
Depletion rate for the capital of service firms (by semester)	ECB	2.7%
Replacement rate for unemployed households (using previous period income as a base)	OECD	51%
Labour tax	European Commission	20.9%
Corporate tax	taxfoundation.org	24.61%
Tax on dividends	taxfoundation.org	23.5%
Share of public employees over total active population	Eurostat	15%
VAT on consumption goods and services	Eurostat	21.3%

TABLE 2: Parameters of the model that are taken directly from available data on the euro area. Most parameters are estimated by taking average or median values from recent years.

A.6 Matrices for stocks and flows

To complement the mechanisms described in section 3, we provide in table 4 the matrix summary of all flows occurring during one period in the model. Moreover, table 3 gives the related balance-sheet information, i.e. the stock view.

B Additional results

We present in this appendix complementary results to those of section 7.1, i.e. pertaining to the main set of simulations.

First, we investigate the redistributive effects of the scenarios between working households and capitalists. We represent in figure 15a the share of each over their total revenue. We observe that the level of income to labour presents relatively small variations, and that the HHW scenario is the one that reaches the highest values at the end of the period. This can be explained at the light of two mechanisms. First, capital replacement due to physical damages reduces the profitability of companies and hence the amount reversed as dividends. Second, a counteracting effect on income distribution emerges from the higher public debt in the long run, as government bonds are issued to finance the transition. Capitalist households earn coupons from public debt (and are the owners of the banks that also benefit from higher coupon payments). Therefore, if the government action is parametrized so that transition policies weigh more on public finances than physical damage repair, this tends to make capitalist households better off in transition scenarios as it supports financial market participants.

However, findings from the share of labour are mitigated by different employment dynamics. Indeed, the hot house world scenario is where we observe the highest growth in unemployment, especially in the second half of the simulation horizon. This is in line with the mechanism described previously, whereby firms have to lay off workers given the decrease in production capacity caused by physical damages. On the contrary, the orderly transition scenario exhibits a path first constant and then to full employment. This is mostly due to the carbon tax revenues being reinvested by the government in domestic purchases and investment, thus creating a strong demand for labour. This logic eventually dominates in the case of disorderly scenarios as well, but the more abrupt implementation first causes an increase in unemployment. It is in line with a generally higher volatility of these scenarios.

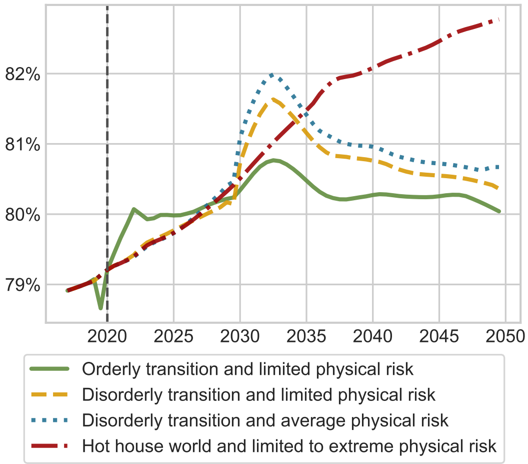
Now, on the financial aspect, we represent in figure 15c the credit level as percentage points of GDP for all scenarios. We observe that the implementation of transition policies is accompanied by a bump in credit, and more so in the disorderly case. This is explained by the surge of investments in green technologies. However, this effect reverses after a few years, such that transition scenarios show strong trends of decreasing credit level in the medium term. One explanation already mentioned in section 7.1 is that there is a deleveraging of high-carbon sector, which have to wind down their investments. On the other hand, for the HHW scenarios, the repair costs induced by physical damages would lead the credit level to remain higher than they would normally do.

	Hw	Hk	Fk	Fl	KpB	KpG	EnB	EnG	BA	CB	G	MO	RoW	Total
Tangible capital														
- high-carbon			$p_{\mathrm{KpB}}K^{\mathrm{B}}_{\mathrm{Fk}}$	$p_{\mathrm{KpB}}K^{\mathrm{B}}_{\mathrm{Fl}}$	$p_{\mathrm{KpB}}\mathrm{IN}_{\mathrm{KpB}}$		$p_{\mathrm{KpB}}K^{\mathrm{B}}_{\mathrm{EnB}}$							$p_{\mathrm{KpB}}\mathbf{K}^{\mathrm{B}}$
- green			$p_{\mathrm{KpG}}K^{\mathrm{G}}_{\mathrm{Fk}}$	$p_{\mathrm{KpG}}K^{\mathrm{G}}_{\mathrm{Fl}}$		$p_{\mathrm{KpG}}\mathrm{IN}_{\mathrm{KpG}}$		$p_{\mathrm{KpG}}K^{\mathrm{G}}_{\mathrm{EnG}}$						$p_{\mathrm{KpG}}\mathbf{K}^{\mathrm{B}}$
Gold in the vault										M_{CB}				M_{CB}
Gov bonds		$p^{\dagger}_{\mathrm{G}}S_{\mathrm{G,Hk}}$							$p^{\dagger}_{\mathrm{G}}S_{\mathrm{G,BA}}$	$p^{\dagger}_{\mathrm{G}}S_{\mathrm{G,CB}}$				$p_{\mathrm{G}}\mathbf{n}_{\mathrm{G}}$
Equity securities		$\sum_{i\neq \mathrm{G}} p^{\dagger}_{i}S_{i,\mathrm{Hk}}$							$\sum_{i\neq \mathrm{G}} p^{\dagger}_{i}S_{i,\mathrm{BA}}$				$p^{\dagger}_{\mathrm{MO}}S_{\mathrm{MO,BA}}$	
Bank's loans			$-L_{\mathrm{Fk}}$	$-L_{\mathrm{Fl}}$			$-L_{\mathrm{EnB}}$	$-L_{\mathrm{EnG}}$	$\mathbf{L}$			$-L_{\mathrm{MO}}$		0
CB's loan									$-L_{\mathrm{CB}}$	L_{CB}				0
Bank's deposits	M_{Hw}	M_{Hk}	M_{Fk}	M_{Fl}	M_{KpB}	M_{KpG}	M_{EnB}	M_{EnG}	$-\mathcal{D}$		M_{G}	M_{MO}		0
CB's reserves									M_{BA}	$-\mathcal{M}_{\mathrm{fiat}}$		M_{RoW}		0
Equity (net worth)			$-E_{\mathrm{Fk}}$	$-E_{\mathrm{Fl}}$	$-E_{\mathrm{KpB}}$	$-E_{\mathrm{KpG}}$	$-E_{\mathrm{EnB}}$	$-E_{\mathrm{EnG}}$	$-E_{\mathrm{BA}}$	$-E_{\mathrm{CB}}$	$-E_{\mathrm{G}}$	$-E_{\mathrm{MO}}$	$-E_{\mathrm{RoW}}$	$-E_{\mathrm{EIRIN}}$
Total			0	0	0	0	0	0	0	0	0			

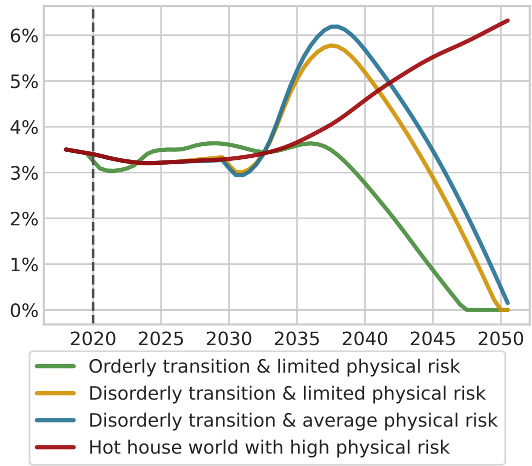
TABLE 3: Balance sheet matrix of the EIRIN economy. Each column represents the balance sheet of an agent or sector. Assets are reported with positive sign and liabilities with a negative sign. Each column always sums to zero to highlight the definition of equity (or net worth).

Cash flows from:	Hw	Hk	Fk	Fl	KpB	KpG	EnB	EnG	MO	BA	CB	G	RoW
Consumption of:													
- goods	$-p_{\text{Fk}}Q^{\text{Fk}}_{\text{Hw}}$	$-p_{\text{Fk}}Q^{\text{Fk}}_{\text{Hk}}$	$p_{\text{Fk}}\mathbf{Q}_{\text{Fk}}$								$-p_{\text{Fk}}Q^{\text{Fk}}_{\text{G}}$	$-p_{\text{Fk}}Q^{\text{Fk}}_{\text{RoW}}$	
- tourism and services	$-p_{\text{Fl}}Q^{\text{Fl}}_{\text{Hw}}$	$-p_{\text{Fl}}Q^{\text{Fl}}_{\text{Hk}}$		$p_{\text{Fl}}\mathbf{Q}_{\text{Fl}}$								$-p_{\text{Fl}}Q^{\text{Fl}}_{\text{G}}$	$-p_{\text{Fl}}Q^{\text{Fl}}_{\text{RoW}}$
- energy	$-p_{\text{En}}Q^{\text{En}}_{\text{Hw}}$	$-p_{\text{En}}Q^{\text{En}}_{\text{Hk}}$	$-p_{\text{En}}q^{\text{En}}_{\text{Fk}}$	$-p_{\text{En}}Q^{\text{En}}_{\text{Fl}}$	$-p_{\text{En}}Q^{\text{En}}_{\text{KpB}}$	$-p_{\text{En}}Q^{\text{En}}_{\text{KpG}}$	$p_{\text{En}}(\mathbf{Q}_{\text{EnB}} - Q^{\text{RoW}}_{\text{EnB}})$	$p_{\text{En}}\mathbf{Q}_{\text{EnG}}$					$p_{\text{En}}Q^{\text{RoW}}_{\text{EnB}}$
Remittances	Rem_{Hw}	Rem_{Hk}											$-\text{Rem}_{\text{Hw}} - \text{Rem}_{\text{Hk}}$
Wages	Y_{Hw}		$-N_{\text{Fk}}w_{high}$	$-N_{\text{Fl}}w_{low}$	$-N_{\text{KpB}}w_{high}$	$-N_{\text{KpG}}w_{high}$			$-N_{\text{G}}\hat{w}$		0		
Bonds' coupons		$\mathfrak{c}S_{\text{G,Hk}}$					$\mathfrak{c}S_{\text{G,BA}}$	$\mathfrak{c}S_{\text{G,CB}}$	$-\mathfrak{c}\mathbf{S}_{\text{G}}$		0		
Loan interests			$-r_D L_{\text{Hk}}$	$-r_D L_{\text{Fl}}$		$-r_D L_{\text{En}}$	Y_{BA}						
CB's loan							$-r_{\text{CB}}L_{\text{CB}}$	$r_{\text{CB}}L_{\text{CB}}$					
Income tax	$-T_{\text{Hw}}$	$-T_{\text{Hk}}$	$-T_{C_k}$	$-T_{C_l}$	$-T_K$	$-T_{EN}$			T_{G}		0		
Dividend payout		$\sum_i \mathfrak{d}_{ß}S_{i,\text{Hk}}$	$-\mathfrak{d}_{\text{Fk}}\mathbf{S}_{\text{Fk}}$	$-\mathfrak{d}_{\text{Fl}}\mathbf{S}_{\text{Fl}}$	$-\mathfrak{d}_{\text{KpB}}\mathbf{S}_{\text{KpB}}$	$-\mathfrak{d}_{\text{KpG}}\mathbf{S}_{\text{KpG}}$	$-\mathfrak{d}_{\text{EnB}}\mathbf{S}_{\text{EnB}}$	$-\mathfrak{d}_{\text{EnG}}\mathbf{S}_{\text{EnG}}$	$\sum_i \mathfrak{d}_{ß}S_{i,\text{BA}} - \mathfrak{d}_{\text{BA}}\mathbf{S}_{\text{BA}}$				
Seignorage										$-\text{Sgn}$	Sgn		
Investment in capital			$-p_{\text{KpB}}Q^{\text{KpB}}_{\text{Fk}} - p_{\text{KpG}}Q^{\text{KpG}}_{\text{Fk}}$	$-p_{\text{KpB}}Q^{\text{KpB}}_{\text{Fl}} - p_{\text{KpG}}Q^{\text{KpG}}_{\text{Fl}}$	$p_{\text{KpB}}\mathbf{Q}_{\text{KpB}}$	$p_{\text{KpG}}\mathbf{Q}_{\text{KpG}}$	$-p_{\text{KpB}}Q^{\text{KpB}}_{\text{EnB}}$	$-p_{\text{KpG}}Q^{\text{KpG}}_{\text{EnG}}$	$-p_{\text{KpB}}Q^{\text{KpB}}_{\text{MO}}$				
Δ Loans			ΔL_{C_k}	ΔL_{C_l}		ΔL_{EN}	$-\Delta L_{BA} + \Delta L_{CB}$	$-\Delta L_{CB}$			0		
bond issuance		$-p_B\Delta S_{\text{G,Hk}}$					$-p_B\Delta S_{\text{G,BA}}$	$-p_B\Delta S_{\text{G,CB}}$	$p_B\Delta\mathbf{S}_{\text{G}}$		0		
Change in bank deposits													
Change in CB's reserves							$-\Delta M_{BA}$	ΔM_{fiat}		$-\Delta M_{ROW}$	0		

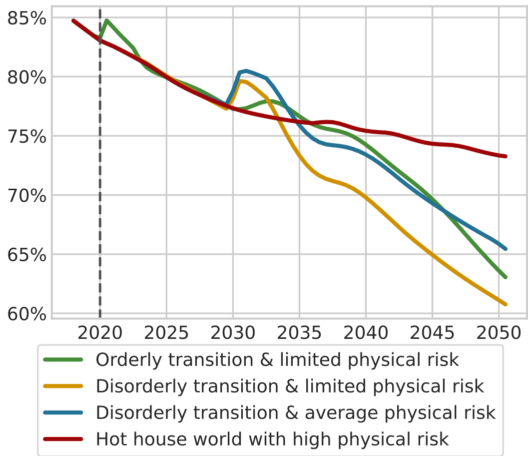
TABLE 4: Financial flow matrix of agents and sectors in the EIRIN economy. The matrix is divided into two sections. The first section refers to cash receipts or outlays of operating activities with an impact on net worth. The second section refers to cash flows generated by variations in real, financial and monetary assets or liabilities.



(A) Share of income to labour



(B) Unemployment rate



(C) Credit level to GDP

FIGURE 15: Additional simulation results.
The *x*-axis displays the simulation time. For the top-left figure, the *y*-axis shows the income share of working households that is derived from labour (i.e. excluding social transfers), taken as its ratio in total households' labour and capital income per period. For the unemployment, the *y*-axis displays the percentage of unemployed working households in the total active workforce. For the credit level, the *y*-axis gives the total value of credit to real economy firms, relative to the GDP of the past year.

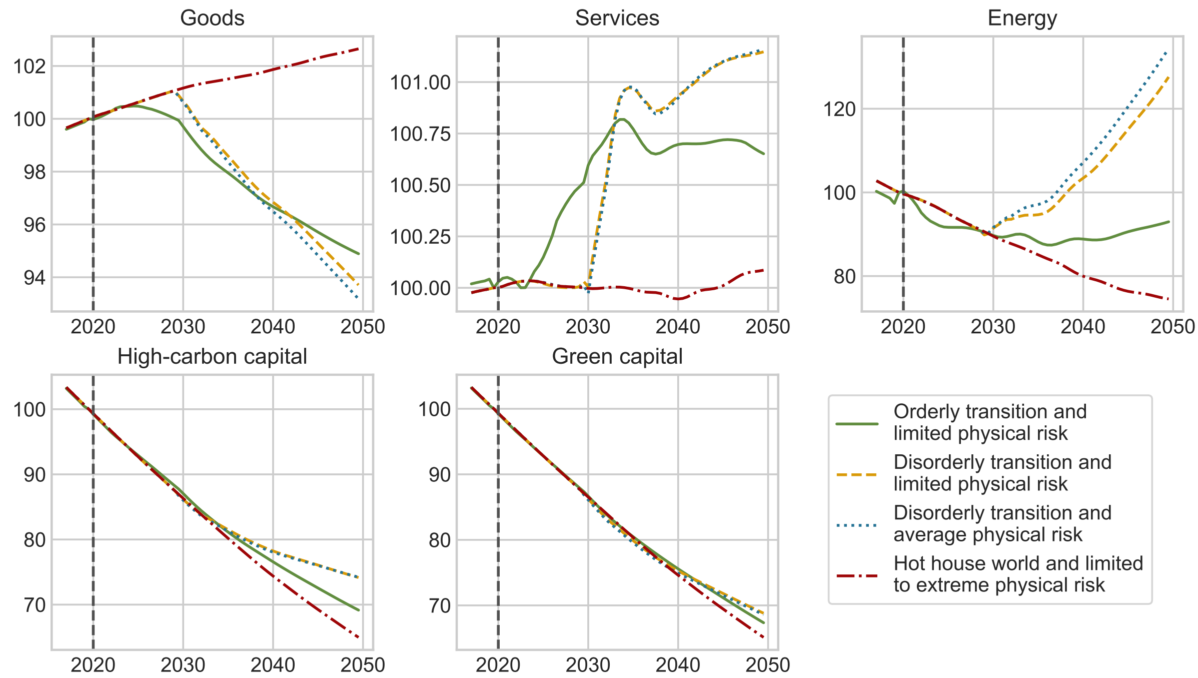


FIGURE 16: Real prices across scenarios.
The *x*-axis displays the simulation time, and the *y*-axis displays the prices of the different real economy goods, reindexed at 100 at the start of 2020. The benchmark inflation rate used to compute real prices is taken from a basket of goods and services with time-varying allocation.

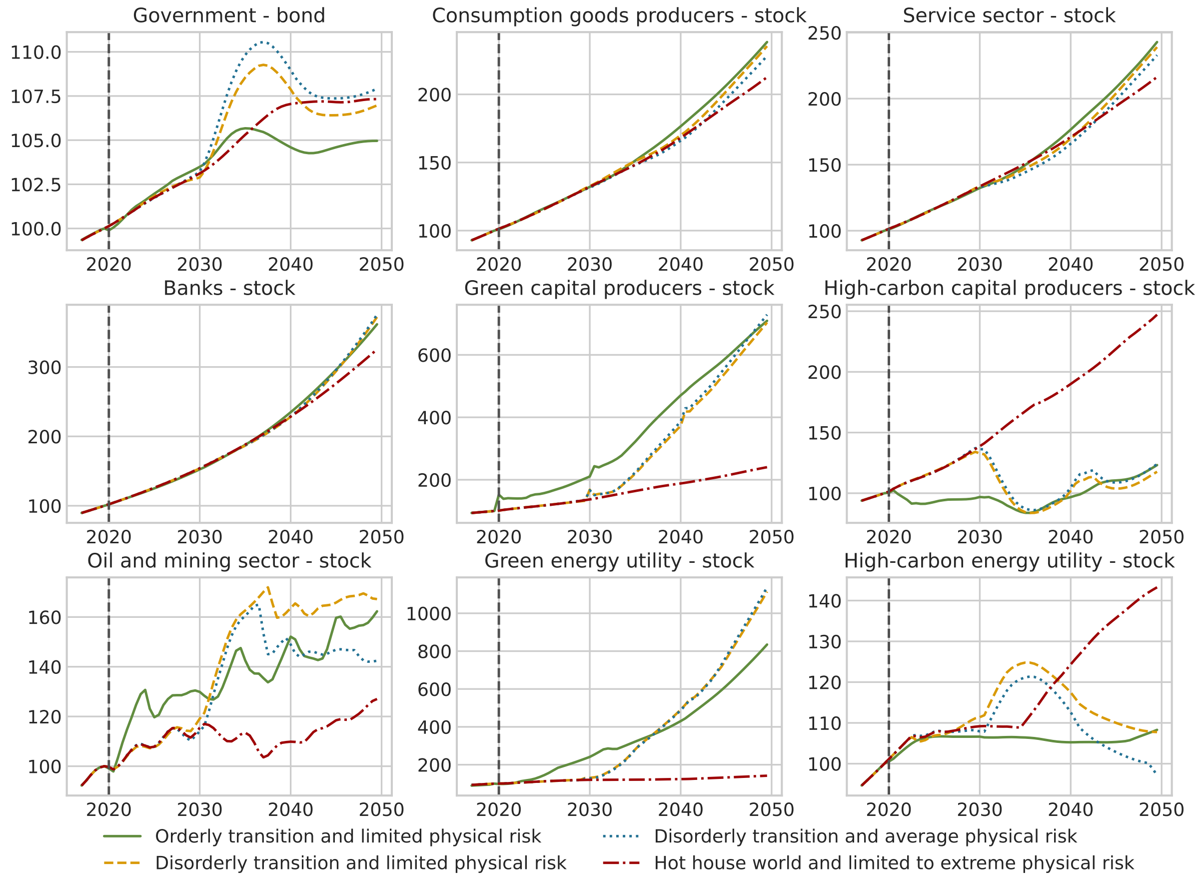


FIGURE 17: Evolution of asset prices on the secondary market.
For each plot, the x-axis displays the simulation time, and the y-axis displays the prices of the plot's financial security, reindexed at 100 at the start of 2020. Asset prices are mostly the result of how banks and capitalist households values the securities, as they are the only two who buy and sell. Bond emission by the government also has an impact.

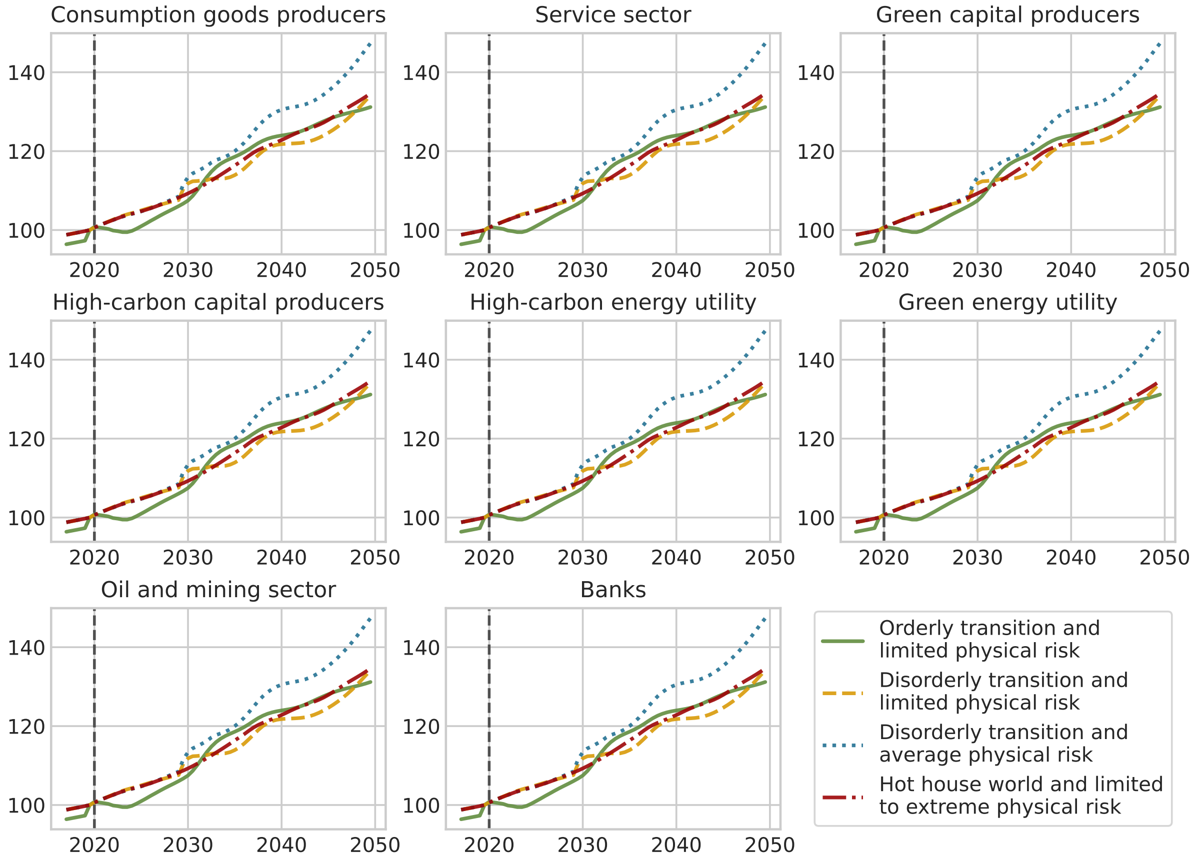


FIGURE 18: GDP components in real terms.
For each firm, the *x*-axis displays the simulation time, and the *y*-axis displays the output using the model's internal monetary units.

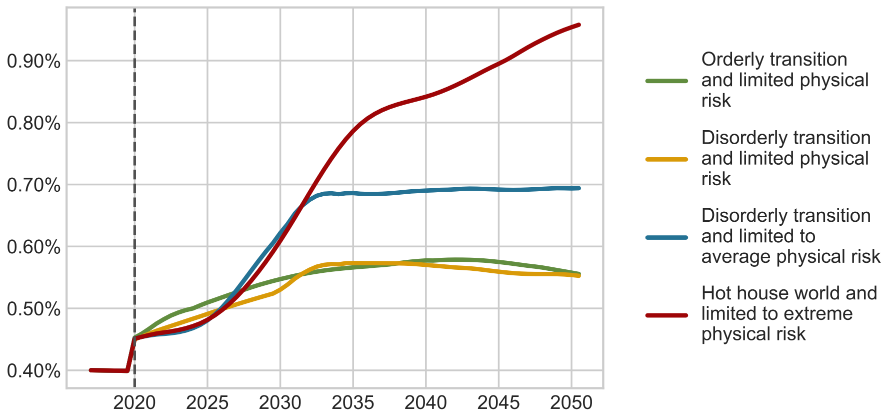
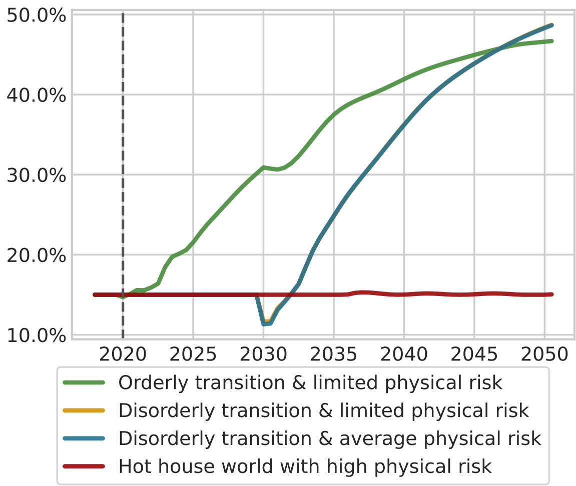
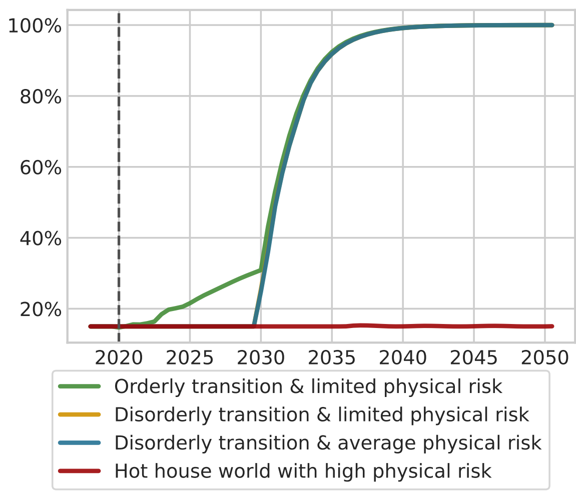


FIGURE 19: Reconstruction costs to GDP.
The *x*-axis displays the simulation time, and the *y*-axis displays the ratio to GDP of government expenses dedicated to climate damage compensation, i.e. what the government spends in emergency relief to real economy sectors to compensate them for their losses due to climate physical shocks.



(A) Consumption goods sector



(B) Service sector

FIGURE 20: Ratio of green capital in investment.
The x-axis displays the simulation time, and the y-axis displays the investment in green capital as a ratio of total investment.

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