Journal of Financial Stability 71 (2024) 101233

Contents lists available at ScienceDirect

Journal of Financial Stability

journal homepage: www.elsevier.com/locate/jfstabil

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

Régis Gourdel[a,d], Irene Monasterolo[b,*], Nepomuk Dunz[c], Andrea Mazzocchetti[d], Laura Parisi[e]

[a] Vienna University of Economics and Business (WU), Institute for Ecological Economics, Welthandelsplatz 1, Vienna, 1020, Austria
[b] Utrecht University, School of Economics (USE), Kriekenpitplein 21-22, Utrecht, 3584 EC, Netherlands
[c] World Bank, 1818 H Street NW, Washington DC, 20433, USA
[d] Ca' Foscari University of Venice, Department of Economics, Cannareggio 873, Venice, 30121, Italy
[e] European Central Bank, Sonnemannstraße 20, Frankfurt am Main, 60314, Germany

ARTICLE INFO

JEL classification:
B59
Q50

Keywords:
Double materiality
NGFS climate scenarios
Climate sentiments
Policy credibility
Stock-Flow Consistent model

ABSTRACT

We analyse the double materiality of climate physical and transition risks in the euro area economy and banking sector. First, by tailoring the EIRIN Stock-Flow Consistent behavioural model, we provide a dynamic balance sheet assessment of the Network for Greening the Financial System (NGFS) scenarios. We find that an orderly transition achieves early co-benefits by reducing CO_2 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 a disorderly transition with higher physical risks, real GDP decreases by 12.5% in 2050 relative to an orderly transition. Second, we analyse how firms' expectations about climate policy credibility (climate sentiments) affect investment decisions in high or low-carbon goods. Firms that trust an orderly policy introduction do anticipate the carbon tax and 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.

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, 2018, 2021; Kreibiehl et al., 2022). Delays in climate policy action became a reason of concern for 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

☆ The peer-review for the present article was conducted outside of Elsevier's submission system. A record of this review was kept, and has been reviewed by the Publisher to ensure conformity with Elsevier's and the journal's standards for quality and ethics. Dates of submission and acceptance reflect the dates on which the final versions were uploaded to our submission system. The timeline for peer-review is available upon request. The Journal has now changed its policy to ensure that all peer review is conducted using Elsevier's Editorial Manager submission system.

☆☆ All authors want to thank Stefano Battiston (University of Zurich and Ca' Foscari university of Venice), Marco Raberto (University of Genoa), Christoffer Kok (European Central Bank), Doyne Farmer (University of Oxford), Marco Bardoscia (Bank of England), the participants to the European Association for Evolutionary Political Economy (EAEPE) annual conference 2022, and the participants to the European Economic Association (EEA) annual conference 2023 for their precious comments and suggestions on earlier versions of the manuscript. We thank the editor and two anonymous reviewers from the Journal of Financial Stability for their useful comments.

ND, AM and IM acknowledge the support of the 11th ACRP call [GreenFin, Klimafonds grant number KR18ACOK14634]. IM acknowledges the financial support from the European Union's Horizon 2020 research and innovation programme [CASCADES, grant number 821010] and of the Horizon 2020 research and innovation programme [TranspArEEnS, grant number 101033869]. RG and IM acknowledge the financial support of the Erasmus+/Knowledge Alliance project [GrEnFin, grant number 612408-EPP-1-2019-1-EPPKA2-KA].

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* Corresponding author.
E-mail addresses: regis.gourdel@wu.ac.at (R. Gourdel), i.monasterolo@uu.nl (I. Monasterolo), ndunz@worldbank.org (N. Dunz), andrea.mazzocchetti@unive.it (A. Mazzocchetti), laura.parisi@ecb.europa.eu (L. Parisi).

https://doi.org/10.1016/j.jfs.2024.101233
Received 16 February 2022; Received in revised form 15 September 2022; Accepted 15 November 2022
Available online 3 February 2024

Bertram, 2019; Dunz and Power, 2021; Basel Committee on Banking Supervision, 2021; Brunetti et al., 2021), also supported by a growing body of research (see e.g. Dietz et al., 2016; Battiston et al., 2017; Mercure et al., 2018).

The climate finance literature focused so far on the feedback from climate change and the low-carbon transition to the economy and to finance. However, the opposite feedback, i.e. from finance to the economy (via adjustments in expectations, risk assessment and lending decisions) and to decarbonization scenarios received much less attention (Battiston et al., 2021). Considering both feedbacks is crucial to assess the "double materiality" of climate risks (EC, 2019; ESMA, 2020; Oman et al., 2021; Robins et al., 2021; Boissinot et al., 2022), and to understand the role of finance in the low-carbon transition.[1]

Indeed, investors who look at climate scenarios may revise their expectations about the 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 et al., 2021). Adjustments in firms' cost of capital, in turn, influence firms' investment decisions for high- and low-carbon goods. Further, if firms deem the introduction of a climate policy (e.g. a carbon tax) credible, they would anticipate its impact in their Net Present Value (NPV) calculations, and thus switch earlier from high-carbon to low-carbon investments.

Our paper contributes to filling 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. To do so, we build on the climate scenarios provided by the Network for Greening the Financial System (NGFS) (NGFS, 2020), which includes over 130 central banks and financial regulators worldwide.[2] The NGFS scenarios were developed to support the analysis of climate-related financial risks of investors and financial authorities. The scenarios provide climate transition pathways coherent with a given temperature target (e.g. 1.5 or 2 °C) and the corresponding carbon budget, and 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), and so does a growing number of central banks and financial regulators.[3] For instance, in 2021, the European Central Bank (ECB)'s economy-wide climate stress test used the first vintage of NGFS scenarios to assess the implications of climate transition and physical risk on a set of approximately 4 million companies and 1600 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)'s report analysed the impact of NGFS scenarios on corporates and financial institutions (ECB/ESRB Project Team on climate risk monitoring, 2022).

In our study we embed the NGFS scenarios NGFS (2021) into the EIRIN Stock-Flow Consistent behavioural model (Monasterolo and Raberto, 2018, 2019; Dunz et al., 2021a). EIRIN is a macro-financial model populated by a limited number of heterogeneous, interacting agents of the economy and finance. EIRIN' agents embed adaptive expectations, enabling us to capture the effects of firms' and investors' expectations on the materialization of the climate scenarios.

Our approach complements the climate scenarios analyses and climate stress tests of central banks and financial authorities, e.g. the ECB economy-wide climate stress test (Alogoskoufis et al., 2021). In particular, while we adopt the same NGFS climate scenarios used by the ECB in its climate stress test, our analysis differs concerning the modelling solution, the climate risk adjustment of banks, the treatment of expectations, and the 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 et al., 2021b) to firms, and we analyse how firms' expectations about climate policy credibility affect their investments in high or low-carbon goods, and the implications on economic decarbonization.

Our results show that an orderly transition, i.e. a situation in which a carbon tax is early announced and implemented before 2030, 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, i.e. a situation in which a carbon tax is introduced after 2030 and suddenly, 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, firms that have climate sentiments anticipate the carbon tax scenarios and switch earlier to low-carbon investments. This, in turn, contributes to tame the magnitude of carbon stranded assets in the economy, and for the banking sector.

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 analysed here, and how chronic physical risk and transition risks scenarios are introduced in the EIRIN model. Section 5 presents the transmission channels from climate physical and transition risks to the agents and sectors of the economy and finance. Section 6 details the calibration of the EIRIN model to the EA. Section 7 discusses the simulation results while Section 8 concludes with the implications of our results for green finance policies at central banks and financial supervisors.

2. Review of the state of the art

2.1. Climate risks and financial stability

Central banks and financial regulators identified two main channels of climate risk transmission to the economy and finance (Carney, 2015; Batten et al., 2016; Hilaire and Bertram, 2019): *climate physical risk*, including both chronic risks and acute risks, and *climate transition risk*, referring to the impacts of climate policies or technological and behavioural changes introduced to foster the transition to a low-carbon economy. Climate physical and transition risks are interconnected. Indeed, delaying the introduction of climate policies, and the decarbonization of the economy, leads to increasing physical risks and the overall risk of carbon-stranded assets (Monasterolo, 2020a).

In the last decade, several studies investigated the macroeconomic and financial impacts of climate physical and transition risks, and on the impact of climate policies, including:

- the conditions for and impact of carbon pricing on the transition (Dafermos et al., 2017; Stolbova et al., 2018; Naqvi and Stockhammer, 2018; Bovari et al., 2018b);
- the trade-offs that governments may face by 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);

[1] The double materiality concept was introduced in 2019 by the European Commission (EC, 2019) and considers both the impact of climate change on firms and finance, as well as the impact of finance on firms' investments and through that on the climate.

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

[3] See for instance the climate stress tests by 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).

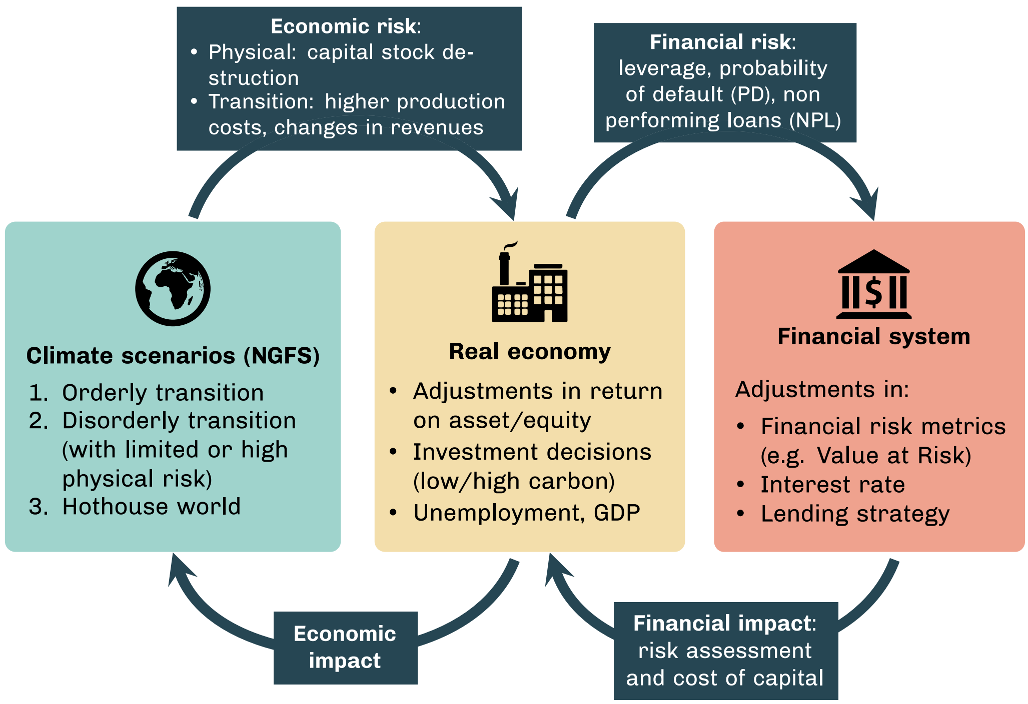

Fig. 1. Double materiality of climate risks in the economy and finance. The figure shows the two opposite feedback loops that characterize the double materiality of climate risks, as analysed in the EIRIN model. The top loop (Feedback 1) goes from the climate scenarios (here, the NGFS ones) to firms and the economy, and from here to the banking sector. The bottom loop (Feedback 2) starts from investors' expectations and risk assessment and affects firms' investment decisions, and from here the materialization of climate scenarios.

- the interplay between feed-in tariffs and carbon pricing (Ponta et al., 2018);
- the role of finance in supporting green innovation (D'Orazio and Valente, 2019) and its potential unintended effects on the 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 et al., 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 dynamics induced by a sudden introduction of low-carbon transition policies (Bovari et al., 2018a);
- the role of green macroprudential policies, e.g. implemented via a Green Supporting Factor that affects banks' capital requirements (Carattini et al., 2023; Dunz et al., 2021b; Dafermos and Nikolaidi, 2021; Lamperti et al., 2021);
- the impact of the transition on the realization of carbon-stranded assets in the energy sector (Mercure et al., 2018, 2021);
- the impact of high-end carbon-intensive scenario consistent with a Representative Concentration Pathway (RCP) 8.5 on economic crises (Lamperti et al., 2018).

These studies addressed the feedback from climate change and the low-carbon transition to the economy and/or the financial sector. Nevertheless, the opposite feedback, starting from the financial sector, via adjustments in investors' expectations and risk assessment, and affecting firms' investment decisions and climate the scenarios, is still missing.

2.2. Contribution to the state of the art

Our paper contributes to filling this gap by providing a methodological framework to assess the double materiality of climate risks in the economy and finance, with an applcation to the EA economy and banking sector. The framework is depicted in Fig. 1 were, starting from the top of the figure, the first feedback runs from the NGFS climate scenarios to the economy and from here to the financial system. Climate risks affect firms' performance, leading to adjustments in firms' profitability, NPV investment decisions, and overall economic performance (GDP, unemployment, inflation, etc.). Financial actors (e.g. banks) that invested via securities and loans in the firms affected by climate risks, experience adjustments in their probability of default (PD), Non-Performing Loans (NPL), and financial risk metrics, such as the Value at Risk (VaR). The second feedback originates from investors and considers their expectations about the transition, in terms of timing of climate policies, and phyisical risk, across scenarios. Banks that look at climate scenarios (e.g. characterised by an early introduction of a carbon tax), and trust them, adjust their risk assessment of firms based on their climate risk exposure, leading to adjustments in the cost of capital. However, firms can also form expectations about the materialization of climate scenarios, and adjust their investment decisions in high-carbon to low-carbon activities based on their expected performance. As a result, the interplay of investors' expectations and climate policy credibility can foster or hinder the low-carbon transition, affecting the materialization of physical risk.

In particular, we contribute to the state of the art by:

(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.

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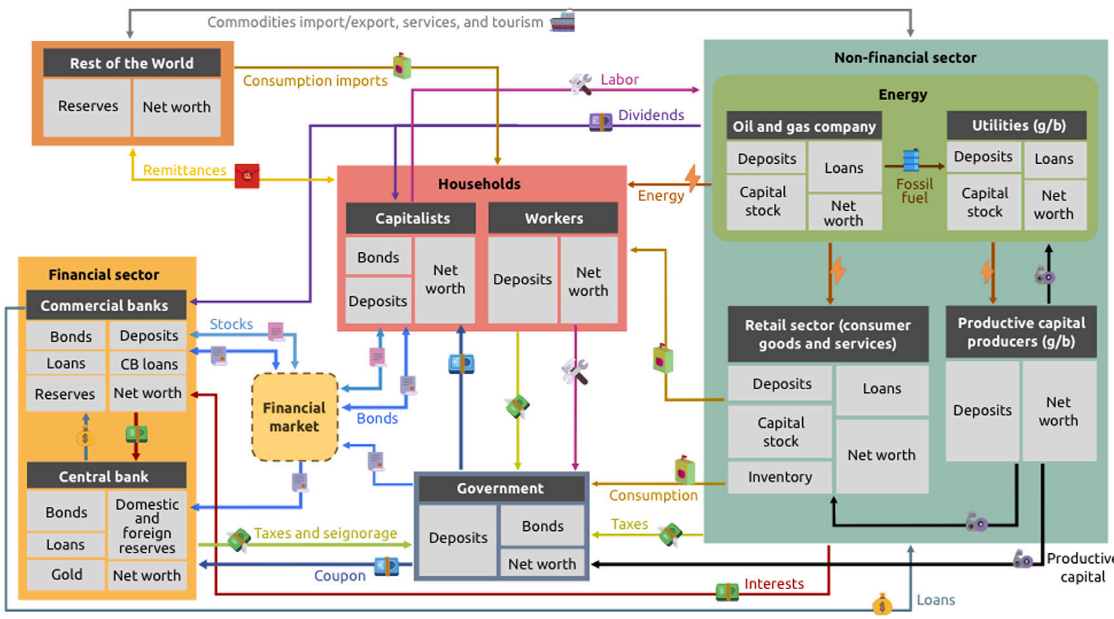


Fig. 2. The EIRIN model framework: capital and current account flows of the EIRIN economy. For each sector and agent of the economy and finance, a representation in terms of assets and liabilities is provided. For utilities and capital producers, "g/b" indicates that the sector is divided between a low-carbon (green) firm and a high-carbon (brown) one, whose balance sheets are separate but with similar compositions.

We focus on three research questions:

- Through which channels do climate physical and transition risks affect the EA economy, public and private finance?
- What are the impacts of the NGFS scenarios on the EA economic performance and banking sector, in the short- to mid-term? (Feedback 1)
- To what extent do investors' and firms' expectations about climate policy credibility affect the decarbonization of the economy and climate mitigation in the EA? (Feedback 2)

3. Model description

We provide here a description of the core structural and behavioural characteristics of the EIRIN model, as well as 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 interacting agents of the real economy and finance. Agents are heterogeneous with regards to their preferences, source of income, wealth, skills, environmental impact and market power. Agents include wage and capital-income earning households, energy firms characterised by fossil fuels and renewable energy technologies, capital goods producers, consumer goods producers, a bank, the government, the central bank (which mimics the ECB), and a foreign sector (Rest of the World). The economy is backtested, initialized, and calibrated on real data.[5]

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

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

EIRIN's agents are represented as a network of interconnected balance sheet items. This rigorous accounting framework enables us to display the dynamics of agents' balance sheets, and to identify: *(i)* the direct impact of the shock on economic agents, at the level of balance sheet entry, *(ii)* the indirect impact of the shock on macroeconomic variables (e.g. GDP, unemployment, interest rate), on financial risk variables (e.g. PD, NPL and leverage), and *(iii)* the feedback generated by investors' expectations' adjustments that could amplify the original shocks, leading to cascading economic impacts. In addition, the SFC model characteristics make it possible to trace a direct correspondence between stocks and flows, thus increasing the transparency of the shock transmission channels and their statistical validation.

EIRIN is a behavioural model, in which agents' decisions are informed by behavioural rules and heuristics. EIRIN's agents are endowed with adaptive expectations about the future, i.e. they make projections based on past information and internalize policy changes. Agents do not have priors on the duration and persistency of policy or other types of shocks. In response to a shock, agents adapt to the new conditions. Agents' reactions are heterogeneous and may not be fully coordinated. While these characteristics can lead to long-lasting effects on the *levels* of the variables, such as GDP and prices, the variables' *growth rates* return to the baseline value in the mid-to-long run. The departure from rational expectations is an important feature because it enables us to consider agents that take into account the uncertainty of climate scenarios. Indeed, in the context of rational expectations, agents fully anticipate the climate shock (e.g. carbon pricing) in their investment and consumption decisions, leading to impacts on GDP that are usually very small, and likely unrealistic.

Fig. 2 presents the capital and current account flows of the model. The model is composed of five sectors: 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 (E_b and E_g, high-carbon and low-carbon respectively) that supply energy to households, and to firms as an input factor for production (orange line in Fig. 2);

(b) An oil and mining firm that extracts and supplies $\mathrm{E}\mathfrak{b}$ with fossil fuels (brown line);
(c) A capital-intensive and a labour-intensive consumer goods producers (service, tourism, agriculture) that supply heterogeneous consumer goods to households (golden lines);
(d) Two capital producers, $\mathrm{Kp}\mathfrak{b}$ and $\mathrm{Kp}\mathfrak{g}$, high-carbon (i.e. high emissions and resource intensity) and low-carbon (i.e. low-emissions profile and resource intensity) respectively, which supply the sectors listed in *(a)*, *(b)* and *(c)* (black lines).

The energy firms and the consumer goods producers require capital as an input factor for production. The energy sector includes a high-carbon (brown) utility operating with fossil fuels and a low-carbon (green) one producing renewable energy. To build up their capital stock, they invest in capital goods produced either by the low-carbon or the high-carbon capital goods producer.

To finance investment expenditures, firms can borrow from the commercial bank (steel blue 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 offers refinancing lines.

The government pays public employees (pink line) and provides emergency relief and subsidies to firms in the real economy. The government collects tax revenues from households and firms (green line) and finances its current spending by issuing sovereign bonds (blue line). Sovereign bonds can be bought by capitalist households, the commercial bank, and the central bank. The government pays coupons on sovereign bonds (dark blue line).

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

The rest of the world receives remittances (yellow line), exports consumer goods to households (golden line), and resources to firms as inputs for the production factors (grey line). The rest of the world generates tourism flows and spending in the country, and exports of the service sector and industry goods (grey line).

3.2. Markets and sequence of events

EIRIN 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, capital income, corporate earnings, and 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 reduce their investment and production plans accordingly.
3. *Real markets* open in parallel. They include the market for *consumer goods and services*, the *energy* market, the *labour* market, and the *raw materials* market. Prices of the exchanged goods and services are determined. Then, the nominal and real demand and supply are provided by the relevant agents 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 low-carbon 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 mutually independent at any given simulation step. In the credit market, demand depends on the investment that is not covered out-of-pocket. Demand rationing affects the effective demand for capital goods by firms. In each market, the supply side sets prices 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' behaviours

We detail here the model 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 $Q_{i,j}$ is the part of it that is given to j. We also denote by M_i the liquidity of i, akin to cash holdings, and by K_i its stock of productive capital where applicable.

Building on Goodwin (1982), we divide **households** into two classes, i.e. the capitalist and the working class. Income class heterogeneity allows assessing the distributive effects of the policies introduced in the low-carbon transition. The working class (Hw) lives on wages, with gross revenues

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

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 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 (details in Appendix A.3). It also determines the salary level $w_i(t)$ paid by i, based on the required skills of employing firms.

In contrast, the capitalist class (Hk) earns its income out of financial markets through government bonds' coupons and corporate 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, $\mathfrak{c}$ is the coupon's rate, and $S_{i,j}$ the number of securities issued by i and held by j. Both households are then taxed, with τ_{Hw} the rate of the income tax, and τ_{Hk} the tax rate on capital profits. Furthermore, both household classes receive net remittances Rem_i from abroad, negative in the case of the EA, and they pay their energy bill $p_{\mathrm{En}} Q_{\mathrm{En},i}$. This leaves them with Y_i^{disp} as net disposable income:

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

Households' consumption plans 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:

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

In particular, consumers spend more than their net income if their actual liquid wealth to income ratio is higher than the target level, and vice versa. This results in a quasi-target wealth level that households pursue. Then, households split their consumption budget C_i between consumer goods and services, also importing a share β_0 from the rest of the world:

$$D_{\mathrm{Fl},i} = (1-\beta_0)\times\beta_1\times C_i \tag{5}$$

$$D_{\mathrm{Fk},i} = (1-\beta_0)\times(1-\beta_1)\times C_i. \tag{6}$$

The **service firm** Fl (also called labour intensive) and **consumer 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:

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

By 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 output level. In the short- and medium-term time horizons, which are crucial to capture key dynamics of transition (e.g. the shock driven by the introduction of a carbon tax and climate policies, and the recovery phase), it is difficult to substitute labour with capital, mainly due to technological, business and regulatory constraints. The latter is particularly relevant in the context of the euro area, where employment protection is stricter than most countries, such as the US.[6]

In addition, we consider the substitution of production factors that matter the most for our analysis, distinguishing between high- and low-carbon energy and capital, which can be substituted, although at a limited pace due to frictions (as in the real world).[7]

The two firms set their price as a markup μ_j on their labour costs w_j/γ_j^N, capital costs $\kappa_j L_j$, energy $p_{\mathrm{En}}Q_{\mathrm{En},j}$ and resource costs $p_R Q_{R,j}$, such that

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

The price can be affected by firms' interest rates κ_j on loans, and by more expensive imports (p_R), energy and/or wages. Higher prices of consumer goods and services constrain households' consumption budgets, thus contributing to decreased aggregate demand (a counterbalancing mechanism).

The minimum between the real demand of the two consumer goods and the real supply (Eqs. (9) and (10)) determines the transaction amount $\tilde{q}_j$ that is traded in the goods market. The supply of capital-intensive consumer goods also takes the firms' inventories ($\mathrm{IN}_{\mathrm{Fk}}$) into account. In case 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 inventory stock of Fk's inventories ($\mathrm{IN}_{\mathrm{Fk}}$). Finally, both consumer goods producers make a production plan $\hat{q}_j$ for the next simulation step based on recent sales and inventory levels.

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

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

The **energy sector** (En), which is divided into low-carbon and high-carbon energy producers (E𝔤 and E𝔟 respectively), produces energy that is demanded by households and firms for consumption and production, respectively. We assume that all demand is met, even if E𝔟 may buy energy from the foreign sector, such that $\mathbf{Q}_{\mathrm{En}} = \mathbf{D}_{\mathrm{En}}$. Households' energy demand is inelastic (i.e. the daily uses for heat and transportation), while firms' energy demand is proportional to the production. The fossil fuel energy company requires capital stock and oil as input factors for production and only productive capital for its low-carbon counterpart but in higher quantity. The energy price is endogenously set from the unit cost of both firms (see details 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 markups on their unit costs to their customers (Eq. (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. The **oil and mining** company MO supplies E𝔟 in oil and exports to the rest of the world as well. The mining company faces no restriction on extraction, but it requires a proportional amount of productive capital to operate.

In EIRIN we consider both price and wage stickiness. In particular, prices are set by the supply side and are based on a markup on unit production costs (see e.g. Blanchard, 2017). Each unit cost evolves endogenously in the model, based on agents' and sectors' interactions. In this context, the price stickiness can arise due to endogenous adjustments in response to a shock or a policy and can be further amplified by supply-side constraints. Regarding the wages, they do not adjust immediately in response to a shock. In particular, the speed of adjustment accounts for the level of employment and inflation at the previous time step, and can be moderated by a parameter (see Appendix A.3).

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 $I_j^{\dagger}$ 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

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

Differently from supply-led models (e.g. Solow, 1956), in EIRIN investment decisions are fully endogenous, and they are based on firms' NPV. Firms' NPV 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 $I_j^{\star}(t) = \left(\varphi_j\cdot M_j(t-1)+\Delta^{+}L_j(t)\right)/p_{\mathrm{Kp},j}(t)$, 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 $p_{\mathrm{Kp},j}$ is the average price of capital, which depends on the ratio of low-carbon and high-carbon, at unit prices $p_{\mathrm{Kp}\mathfrak{g}}$ and $p_{\mathrm{Kp}\mathfrak{b}}$ respectively. The NPV allows 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 between low-carbon and high-carbon capital, that is, for a level ι of investment, the related NPVs are

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

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

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 that is set by the commercial bank. The final realized investment

[6] See for instance https://ec.europa.eu/info/sites/default/files/european-semester_thematic-factsheet_employment-protection-legislation_en.pdf.

[7] It is worth recalling that here we analyse how different NGFS scenarios impact firms' decision to invest in low-carbon capital (driven by NPV), the implications on the ratio of low- and high-carbon investments, and the adjustment in the capital mix.

$I_i(t)$ is divided into low-carbon and high-carbon capital such that $I_i = I_i^{\mathfrak{g}} + I_i^{\mathfrak{b}}$. Then, it is potentially constrained by the supply capacity of the producers.

The **capital goods producers** (Kp, divided into low-carbon and high-carbon capital producers, Kp$\mathfrak{g}$ and Kp$\mathfrak{b}$ respectively) supply productive capital to fulfil the production capacity of Fl, Fk, and En:

$$\mathbf{Q}_{\mathrm{Kp}\mathfrak{b}} = I_{\mathrm{Fl}}^{\mathfrak{b}} + I_{\mathrm{Fk}}^{\mathfrak{b}} + I_{\mathrm{E}\mathfrak{b}} \leq \mathbf{D}_{\mathrm{Kp}\mathfrak{b}}, \quad \mathbf{Q}_{\mathrm{Kp}\mathfrak{g}} = I_{\mathrm{Fl}}^{\mathfrak{g}} + I_{\mathrm{Fk}}^{\mathfrak{g}} + I_{\mathrm{E}\mathfrak{g}} \leq \mathbf{D}_{\mathrm{Kp}\mathfrak{g}}. \tag{14}$$

Newly produced capital goods will be delivered to the consumer goods producers and the energy firm at the next simulation step. Capital goods producers rely on energy and high-skilled labour as input factors. Low-carbon and high-carbon capital goods differ in terms of production and use. Regarding production, the low-carbon capital requires more skilled labour than the high-carbon one, as well as more materials imported from the rest of the world, e.g. rare metals for batteries. Therefore, a unit of low-carbon capital is more expensive than a unit of high-carbon capital (for the same productive capacity).

However, in its use, low-carbon capital is the most interesting per unit for the service sector and the consumer goods producer (the ones that can choose which type of capital to use). This is due to lower usage of raw material and energy, resulting in a lower bill per unit of capital used, and lower related GHG emissions.

Capital good prices $p_{\mathrm{Kp}\mathfrak{b}}$ and $p_{\mathrm{Kp}\mathfrak{g}}$ are set as a fixed markup μ_{Kp} on unit costs:

$$\forall i \in \{\mathrm{Kp}\mathfrak{g}, \mathrm{Kp}\mathfrak{b}\}, \quad p_i = (1 + \mu_{\mathrm{Kp}}) \times \frac{w_{\mathrm{Kp}} N_i + Q_{\mathrm{En},i} p_{\mathrm{En}}}{\mathbf{Q}_i} \tag{15}$$

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 loan). This is consistent with the most recent literature on endogenous money creation by banks (McLeay et al., 2014). The money supply in the EIRIN economy 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 grants loans to finance firms' investment plans. The bank sets sector-specific interest rates that affect firms' capital costs and NPV calculations. The commercial bank provides credit in compliance with existing regulatory capital requirements. When this does not happen, credit is rationed and firms have to scale down their investment plans. In this situation, the commercial banks react by retaining part of their 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 that influence firms' activity and investments can become sources of financial instability.

The credit market is characterized by the *level of credit, the cost of credit, and the level of NPLs*. The *level of credit* represents 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 CAR parameter $\mathfrak{R}_{\mathrm{CAR}}$, to comply with regulatory provisions. Other relevant information includes the demand for new credit $\mathbf{D}_{\mathrm{BA}}(t)$ and the credit level at the previous period $\mathbf{L}(t-1)$. 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 keeps the CAR higher than $\mathfrak{R}_{\mathrm{CAR}}$:

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

The *cost of credit* is the interest rate applied by the bank to the borrowers. The interest rate is sector-specific and based on macroeconomic indicators. 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[8] of i. The PDs are computed following Alogoskoufis et al. (2021), that is $\mathrm{PD}_i = \alpha + \beta_1 \Delta^{\%}\mathrm{ROA}_i + \beta_2 \mathrm{Leverage}_i + \mathrm{GICS}_i$, where $\Delta^{\%}$ denotes the growth operator, ROA stands for returns on assets, and GICS_i is a sector-specific constant.

Then, to determine the actual rate applied, we allow bridging only part of the gap between the previous interest rate and the objective one. Thus, 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 interest adjustment speed. With this approach, we analyse financial stability through banks' CAR and loan interest rates.

The *non-performing loans (NPL)* represent the final part of the credit market mechanism. We compute the NPL ratio based on the literature,[9] such that

$$\Delta^{\%}\mathrm{NPL}(t) = \eta + \sum_{j=1}^{2} \boldsymbol{\alpha}_j \Delta^{\%}\mathrm{NPL}(t-j) + \sum_{j=1}^{p} \boldsymbol{\beta}_j \cdot \mathbf{X}(t-j) + \varepsilon(t)$$

where $\Delta^{\%}$ is the quarter-on-quarter growth operator, while η, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ 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.

Each sector i pays interests with rate $\kappa_i(t)$ at t on its total loans of the previous period $L_i(t-1)$. Taking into account the NPL ratio, the total paid interests are[10]:

$$\mathrm{ID}_i(t) = \kappa_i(t) \times L_i(t-1) \times (1 - \mathrm{NPL}(t)) \tag{18}$$

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:

$$\Delta^{-} L_i(t) = \chi_i \times L_i(t-1) \times (1 - \mathrm{NPL}(t)), \tag{19}$$

where χ_i is the constant repayment rate of i (the inverse of what would be its loan length).

The **central bank** (CB) sets the risk-free interest rate ν according to a Taylor-like rule (Taylor, 1993), thus depending on the inflation and output gaps.[11] It is worth mentioning that, while the policy rate in EIRIN is set by the central bank following a Taylor rule, the speed and magnitude of policy rate adjustment can be tailored and calibrated to reproduce the characteristics of countries of interest.

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. Constraints to full

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

[9] We build on Beck et al. (2015) and Tente et al. (2019) with regard to the NPL determinants.

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

[11] 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 solve to equilibrium. This feature is important because it allows us to study the conditions for out-of-equilibrium dynamics to arise and their macro-financial implications. Thus, it would not be logically consistent to adopt a standard Taylor rule and NAIRU.

intertemporal optimization prevent potential crowding-out effects of monetary policies on households' consumption.

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 $\bar{u}$):

$$\nu(t) = \omega_\pi(\pi(t) - \bar{\pi}) - \omega_u(u(t) - \bar{u}) \tag{20}$$

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

$$\pi(t) = \frac{\mathbf{Q}_{\mathrm{FI}}(t)}{\mathbf{Q}_{\mathrm{Fk}}(t) + \mathbf{Q}_{\mathrm{FI}}(t)} \cdot \left(\frac{p_{\mathrm{FI}}(t)}{p_{\mathrm{FI}}(t-m)}\right)^{1/m} + \frac{\mathbf{Q}_{\mathrm{Fk}}(t)}{\mathbf{Q}_{\mathrm{Fk}}(t) + \mathbf{Q}_{\mathrm{FI}}(t)} \cdot \left(\frac{p_{\mathrm{Fk}}(t)}{p_{\mathrm{Fk}}(t-m)}\right)^{1/m} - 1 \tag{21}$$

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 liquid assets shortage.

The **foreign sector** (RoW) interacts through tourism, consumer 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 consumer goods. Raw material, consumer 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 $\mathfrak{M}$, the government issues a new amount $\Delta\mathbf{S}_{\mathrm{G}} = (\mathfrak{M} - M_{\mathrm{G}})/p^{\dagger}_{\mathrm{G}}$ of bonds to cover the gap, where $p^{\dagger}_{\mathrm{G}}$ is the endogenously determined government bond price. Government spending C_{G} is a fixed percentage of revenues from taxes R_{G}. During crises, it contributes to avoiding credit crunch and compensates households and firms' liquidity constraints.

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

4. Climate physical and transition risk scenarios

4.1. The NGFS climate scenarios

The NGFS developed supervisory climate 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, 2022, 2023).

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 IAMs 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; Fricko et al., 2017).

4.1.1. Low-carbon transition scenarios

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 to 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 tax 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 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.

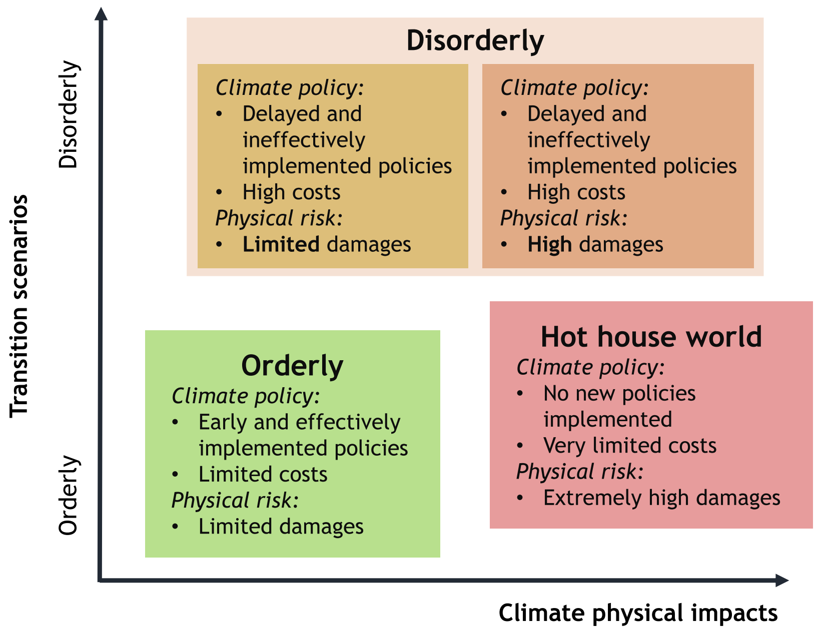


Fig. 3. EIRIN-NGFS scenarios, adapted from Hilaire and Bertram (2019). The *x*-axis indicates the strength of physical risk, and the *y*-axis gives the steepness of climate policy.

4.2. Implementation of the NGFS scenarios in the EIRIN model

We closely follow the scenario design of the NGFS database.[12] 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-minimizing 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 hot house world (NGFS, 2020). Orderly transition scenario refers to the REMIND-MagPie “Immediate 1.5 °C with CDR (Orderly, Alt)” scenario,[13] disorderly transition to the “Delayed 2 °C with limited CDR (Disorderly, Rep)” scenario[14] and a hot house world to the “Current policies (Hot house world, Rep)”.[15]

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 low-carbon technologies (the cheaper the low-carbon 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.

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

[13] Global climate action after 2020 to limit cumulative emissions between 2011–2100 to 400 $GtCO_2$ (67% chance of limiting warming to 1.5 °C).

[14] Global climate action after 2030 to limit cumulative emissions between 2011–2100 to 1000 $GtCO_2$ (67% chance of limiting warming to 2 °C), assuming limited availability of carbon dioxide removal options.

[15] Extrapolation of current national policies implemented.

We implement four scenarios that are characterized by different climate policy targets and climate physical impacts (see Fig. 3). Orderly and disorderly transition scenarios reduce physical risk impacts due to ambitious mitigation policies. The hot house 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 10th percentile of the reported damage distribution in the NGFS scenario database, adjusted for the EA.

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 tax increase trajectory and strong government measures such as green subsidies. Physical climate damages until 2050 are also assumed to be limited, taking the lowest 10th 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 one 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.

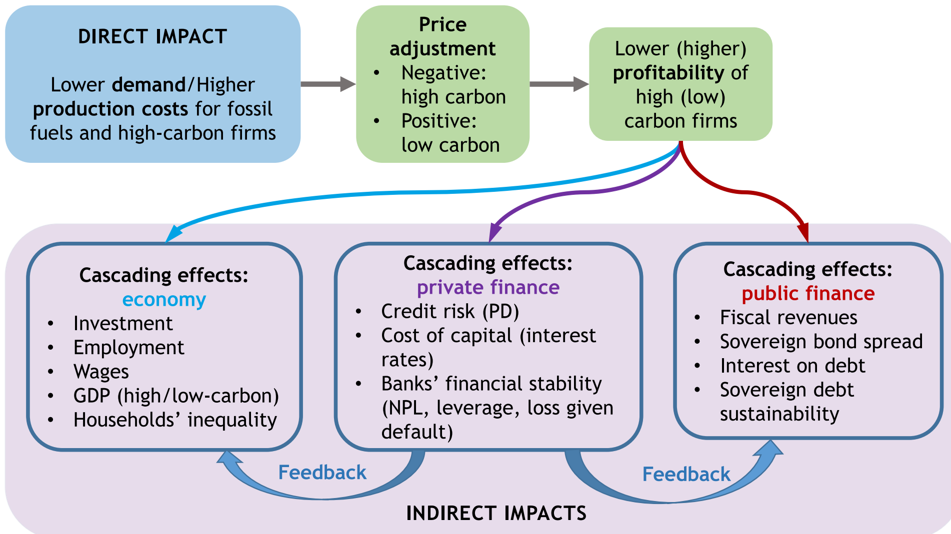


Fig. 4. Channels of transmission of climate transition shocks to the economy and finance. The figure shows the entry point and the direct and indirect impacts of the introduction of a carbon tax on the country economy, on public finance and on private finance (e.g. the banking sector).

Finally, we employ a "Hot House World scenario with high physical risk", where no additional 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 on 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 (see Appendix A.7 for details). 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 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 Section 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 taxation. 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.

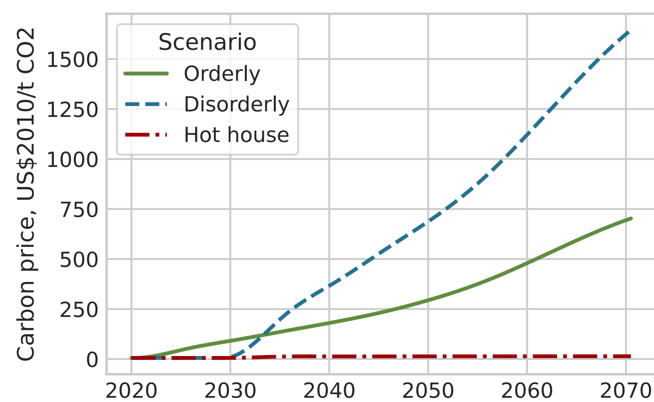


Fig. 5. Carbon price level trajectories from NGFS scenarios. The x-axis displays the years, and the y-axis displays the carbon price level. The scenarios chosen are generated by the model REMIND-MAgPIE 1.7–3.0, where orderly corresponds to "Immediate 1.5 °C with CDR", disorderly to "Delayed 2 °C with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

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

Fig. 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 tax (consistent with the NGFS scenarios) and other climate policies such as green subsidies, negatively affect the demand for fossil fuels-based energy and high-carbon goods via the price channel, and the cost of production of high-carbon firms. On the contrary, positive adjustments in demand and value of low-carbon assets occur. Due to lower demand and higher costs, high-carbon firms start to lay off workers, leading to indirect

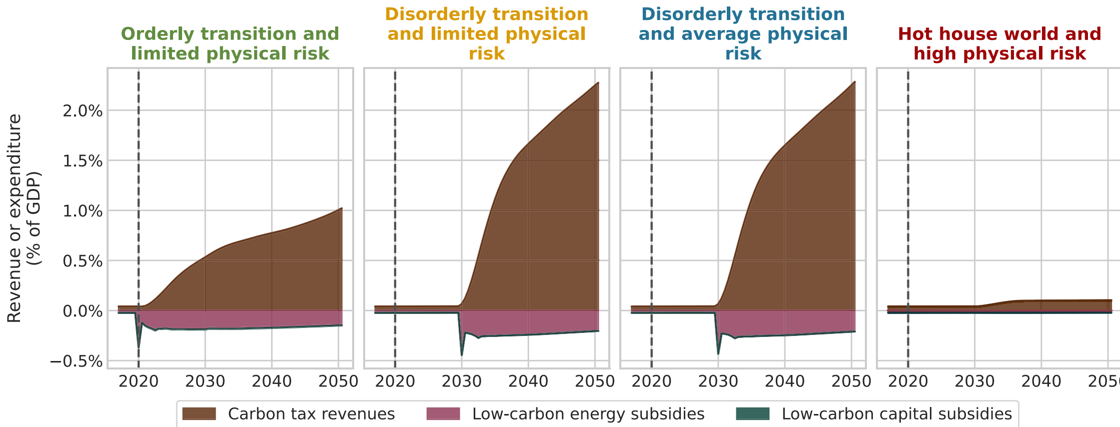


Fig. 6. Nominal revenues and expenditures from climate policies, as a share to GDP. The x-axis displays the simulation timeline, and the y-axis displays the climate policies budgets as ratios to GDP. Policies include the carbon tax, introduced in 5.2.1; the subsidies to renewable energy, introduced in 5.2.2; and the subsidies to low-carbon capital, introduced in 5.2.3. Note that the GDP differs across scenarios.

effects on the economy in terms of investments, unemployment, household consumption, and GDP growth. In turn, adjustments in firms and economic performance also affect banks' financial indicators (NPL, PD, and leverage) and financial stability. Economic and financial shocks affect the fiscal revenues and government budget balance and contribute to the increase of sovereign risk.

5.2. Modelling climate transition risk in EIRIN

We integrate the carbon tax trajectories from the 2020 NGFS scenarios, provided by the REMIND-MagPie model, into the EIRIN model. In the NGFS scenarios, the carbon tax revenues are recycled via the general government budget. In the EIRIN-NGFS, part of those revenues is recycled in 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 between the use of carbon tax revenues by the government (i.e. green subsidies) and the responsiveness of firms' investment decisions in the orderly and disorderly transition scenarios.

5.2.1. Carbon tax

As described in Section 4, and represented in Fig. 5, the government applies a carbon tax on GHG emissions. The carbon tax affects the cost of production and the revenues of fossil fuels and high-carbon firms. In a disorderly transition with delayed climate policy (after 2030) and absent CDR technology, a higher carbon tax is needed to achieve the 2 °C target, due to the more stringent carbon budget. The carbon tax is introduced at time t by a rate $\tau^{GHG}(t)$ such that the revenues paid to the government by a sector i are given by $\mathrm{Em}_i(t) \times \tau^{GHG}(t)$, where Em_i denotes the total carbon emissions of i and covers scope 1 and 2 emissions. In our framework, GHG emissions are calibrated by sector, based on available data.[16] The further calculation of the GHG emissions generated in the economy by activity, and the resulting aggregate emission path, is done within the EIRIN model. In this setting we analyse how the economic composition and its structural change, induced by adjustments in the cost of capital and by firms' expectations, affects the climate.

While in EIRIN the carbon tax is an exogenous policy variable, in REMIND-MagPie its level is the shadow price of the cost-minimization procedure to reach the target emission level. To ensure comparability of the two modelling approaches, we select the same timing of the carbon tax 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 an orderly transition. In contrast, in the disorderly transition scenario, the carbon tax 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.

5.2.2. Other fiscal policies to support renewable energy investments

An important characteristic of 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,[17] substantially slowing down the needed renewable energy investments.[18]

The energy supply not covered by renewable sources is given by $\mathbf{D}_{\mathrm{En}} - \mathbf{Q}_{\mathrm{Eg}}$. 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 low-carbon energy to a share ξ_{Eg} of the total. The capital efficiency of the low-carbon utility firm is denoted by γ_{Eg}, and the low-carbon utility firm aims to replace a share λ_{Eg} of the non-renewable market. Thus, the quantity of capital to acquire is given by

$$\Delta \hat{K}_{\mathrm{Eg}}(t) = \frac{\lambda_{\mathrm{Eg}}}{\gamma_{\mathrm{Eg}}} \times \left(\xi_{\mathrm{Eg}} \cdot \mathbf{D}_{\mathrm{En}}(t-1) - \mathbf{Q}_{\mathrm{Eg}}(t-1) \right). \tag{22}$$

Note that this component represents only one aspect of the investment by the low-carbon 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_{Eg} represents the time necessary to achieve a climate-aligned energy mix. For example, suppose that the starting point is a ratio of renewable energy of 18%, and we want to achieve 75%, given a maximum[19] of $\xi_{\mathrm{Eg}} = 80\%$, and we have $\lambda_{\mathrm{Eg}} = 0.05$ (supposed, in line with our exercise, to apply to a semester). Then, a numerical application[20] tells us that reaching the target will take 25 years. This

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

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

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

[19] The value retained corresponds to the renewable energy increase of Rogelj et al. (2018) for 1.5 °C trajectories, plus part of its potential for decarbonizing and compensating the rest of its emissions. It assumes a limited capacity for the deployment and carbon removal techniques in the simulation time frame.

[20] Let $u_t = \mathbf{Q}_{\mathrm{Eb}}(t)/\mathbf{D}_{\mathrm{En}}(t) - 1 + \xi_{\mathrm{Eg}}$ be the ratio at t of non-renewable energy over the production that could be ensured by both producers. Then we have $\forall t, u_{t+1} = (1 - \lambda_{\mathrm{Eg}})u_t$ under the assumptions given. Thus, $u_n = u_0 \times (1 - \lambda_{\mathrm{Eg}})^n$ and $n = \ln(u_n/u_0)/\ln(1 - \lambda_{\mathrm{Eg}})$. Taking $u_0 = 0.82 - 0.2 = 0.62$ and $u_n = 0.05$ gives 49.1 semesters.

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

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 and Directorate-General for Taxation and Customs Union, 2021). We assume EA governments to implement a renewable energy subsidy that influences the speed of new investments. This subsidy to the low-carbon energy producer is implemented as a price discount to buy low-carbon 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 scenarios. The subsidy stimulates renewable energy investment by increasing the NPV of the sector, making it more attractive for firms.

5.2.3. Regulatory requirements on low-carbon 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 low-carbon and high-carbon productive capital. Especially at the beginning of the transition, low-carbon capital alternatives, such as green hydrogen steel, are still more expensive, giving a role to the government to create incentives for low-carbon capital use. Thereby the government can support technology improvements, efficiency gains, and scale effects over time. For firms, the key step when making investment decisions is the computation of the NPV associated with the purchases of low-carbon and high-carbon capital, respectively. Several parameters influence the NPV calculation, including the carbon tax that makes high-carbon production more expensive.

Nonetheless, the carbon tax alone might not be sufficient to make the low-carbon NPV more favourable than the traditional one. Therefore, the government introduces a minimum share in low-carbon capital investments, as long as the NPV is positive (see Fig. 7). This weight parameter differs between the orderly and disorderly transition scenarios. Increasing it between the initial period and the transition allows for greening to occur in the production of the two sectors affected. Note that the low-carbon capital is not necessarily greener at the point of its production, and it may require more energy[21] or more raw materials. The advantage of low-carbon capital stands in its lower emissions when used in production.

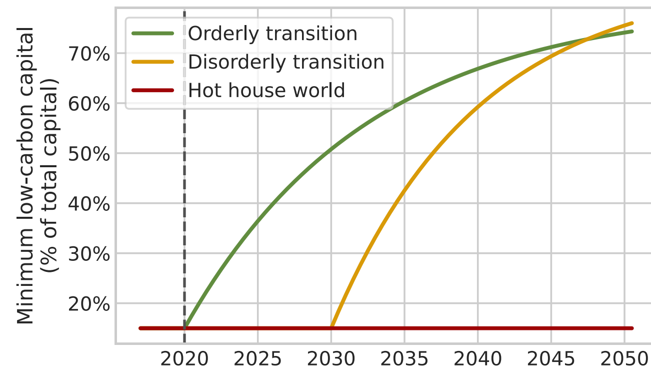


Fig. 7. Low-carbon capital weight across scenarios. The x-axis displays the simulation time, and the y-axis displays the low-carbon capital weight, which is indicative of the minimum share of low-carbon capital that the labour-intensive and capital-intensive sectors have to buy, provided that the low-carbon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

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

In EIRIN, GDP is a fully endogenous outcome variable. Hence, we cannot apply exogenous GDP impacts as an input in the EIRIN model. Thus, we use the impacts from physical risks on agents or sectors' balance sheets as an input, and we analyse their effects on macro-financial and sectoral outcomes[22] in EIRIN (see Fig. 8).

Fig. 9 shows how climate physical risk is introduced in the EIRIN model, including the direct and indirect impacts of natural hazards in the economy and finance. Consider the example of floods, which represent a common acute physical risk for EA countries. Floods enter the country economy through the destruction of 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 the input factors, and thus 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 adjustments in banks' financial performance and financial risk metrics, and on banks' financial stability. Finally, the climate shock can affect sovereign risk via changes in tax revenues and sovereign debt.

6. Model dimensioning and calibration

We initialize, calibrate, and empirically validate the EIRIN model to selected characteristics and real EA data, to ensure that the simulations are quantitatively meaningful. We rely on official data provided by Eurostat, the ECB data warehouse, and by the OECD.[23]

The model depends on more than 100 parameters, and the calibration is split into 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). The Appendix provides a list of key parameters, see Table A.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 many 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 sector value added, the energy

21 Note that the accompanying emissions depend on the share of renewable energy at the time of the investment.

22 The application of disaster risk modelling (e.g. those in Dunz et al., 2020) can provide a more accurate estimation of disaster impacts on productive capital stock at the disaggregated sector and geographical level.

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

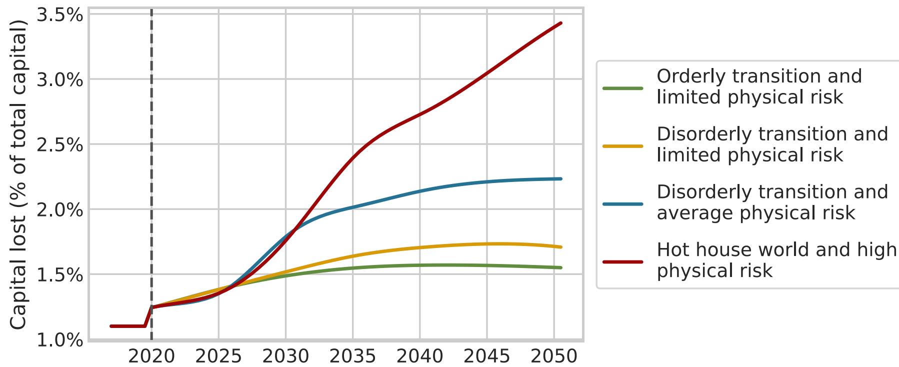


Fig. 8. Physical risk trajectories across scenarios. The *x*-axis displays the simulation time, while the *y*-axis shows the share of capital affected by physical damages at each period and that is used as an input in the model.

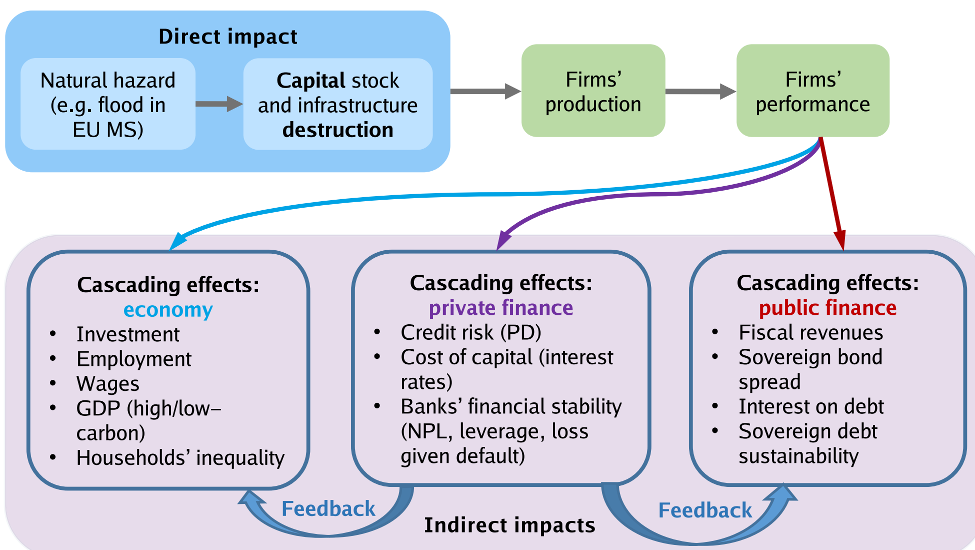


Fig. 9. Channels of transmission of climate physical shocks to the economy and finance. The figure shows the entry point and the direct and indirect impacts of a natural hazard (e.g. flood) on the country economy, on public finance and on private finance (e.g. the banking sector).

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 the model's indicator means with observed data means during six years, which serve as benchmark values to calibrate the model.

This first regional application of the EIRIN model represents an advancement on previous applications and required a tailoring. Indeed, the calibration of a model to a region that includes several countries is complex and requires going beyond standard national statistics. In some cases, overall EA values are available. Otherwise, when national-level statistics are available, we use the mean across EA countries. For example, consider the case of the replacement rate, i.e. what determines the revenues given by the government to the unemployed labour force. Since this amount is set by governments at the country level, an EA aggregate is not available. Therefore, we compute an average based on national statistics.

Our double calibration strategy enable us to ensure that the modelled economy produces outcomes that are coherent the observed ones, conditioned to the same policy variables. Furthermore, it is complemented by an extensive sensitivity analysis. For all parameters, it is possible to test the impact of deviations on key outputs, including GDP growth, unemployment, the value added of every sector, and their GHG emissions.

7. Results

In this section, we present the results of the climate physical and transition risk analyses. In 7.1, we compare the scenarios-conditioned output for macroeconomic, environmental, distributional, and financial variables, 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 tax, on their investment decisions.

7.1. Macroeconomic indicators

In Fig. 10(a) we observe different real GDP dynamics between orderly and disorderly transition scenarios concerning the timing and magnitude of impact. Fig. 10(b) shows that the orderly transition scenario implies short-term, yet limited, losses in terms of economic growth (0.3% less by 2025 than in the other scenarios). Then, in the orderly transition GDP outperforms the disorderly and hot house world scenarios already by 2030. In particular, better financing conditions for low-carbon firms in the orderly transition scenario, based on bank's climate 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 bank's financial stability.

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

		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

In contrast, a disorderly transition scenario leads to larger GDP contraction (−2.8% by 2035 compared to the orderly scenario), and 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 hot house 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.

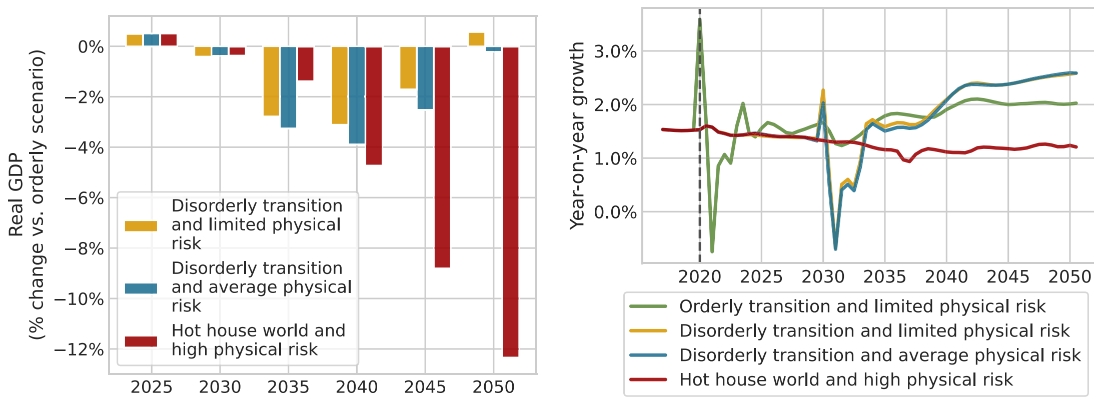
Note that our shock results are large in magnitude and larger than the ones obtained in previous supervisory exercises (see e.g. Alogoskoufis et al., 2021; Allen et al., 2020). However, our shock results should still be considered as a lower bound, and thus conservative, since the NGFS scenarios have important limitations in modelling acute physical risks, and do not consider their potential compounding with other risks risks (Ranger et al., 2022).

A relevant driver of the economic outcomes is the facility with which capital can be replaced.[24] Importantly, the impact of physical risks increases over time, as shown in Fig. 8, representing the average expected damages. Thus, capital has to be replaced more frequently, driving up investment and financing needs in the affected scenarios (Fig. B.20 in the Appendix shows the costs of reconstruction).

In the hot house world scenario, physical risk gradually shifts the economy to a more capital-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. Could capital be replaced immediately, production would only be affected to a low extent.[25] Nevertheless, firms' leverage ratios strongly increase, indicating

[24] Our results are in line with the literature, which finds that developed countries' economies 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).

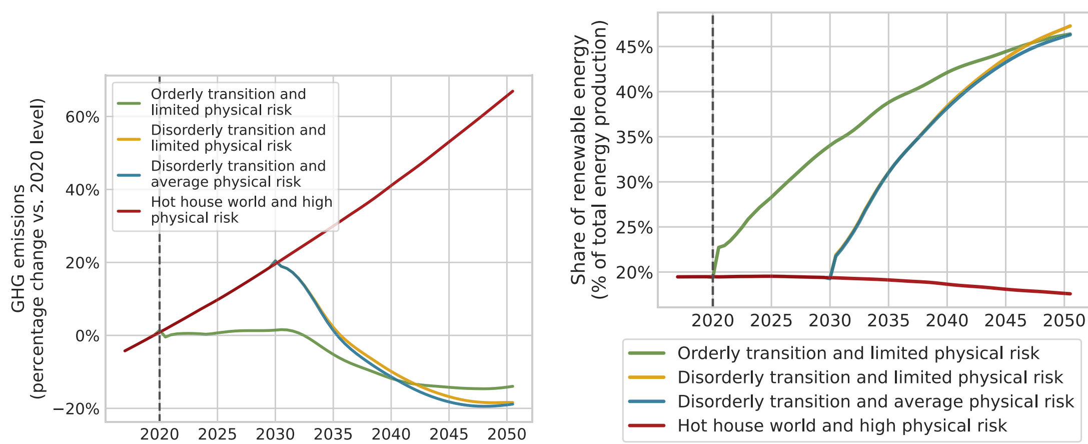
[25] A more realistic type of shock would be considering a stochastic impact of climate physical risk. Capital producers plan their production based on the demand of the previous periods, which is influenced by the strength of past physical shocks. Then, the production level would not be enough to fully 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 a relevant impact. We leave their assessment to further research.



(A) Real GDP comparison to the orderly transition scenario

(B) Yearly growth of real GDP

Fig. 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 percentage point deviation in real GDP of the last three scenarios relative to 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.



(A) Additional GHG emissions compared to the initial value

(B) Ratio of renewables in the energy mix

Fig. 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.

potential financial stability risks that could arise (see credit levels in the Appendix, Fig. B.15(c)).

Large differences in GHG emission trajectories emerge across scenarios (see Fig. 11(a)). GHG emissions increase considerably in the hot house 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 highest 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 to 4% per year to reach Net-Zero targets). Thus, the positive results on GDP decoupling that we observe should be intended as conservative.

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, and shown in Fig. 11(b). 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.[26]

We also explore the impact of climate scenarios on the cost of credit. In Fig. 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

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

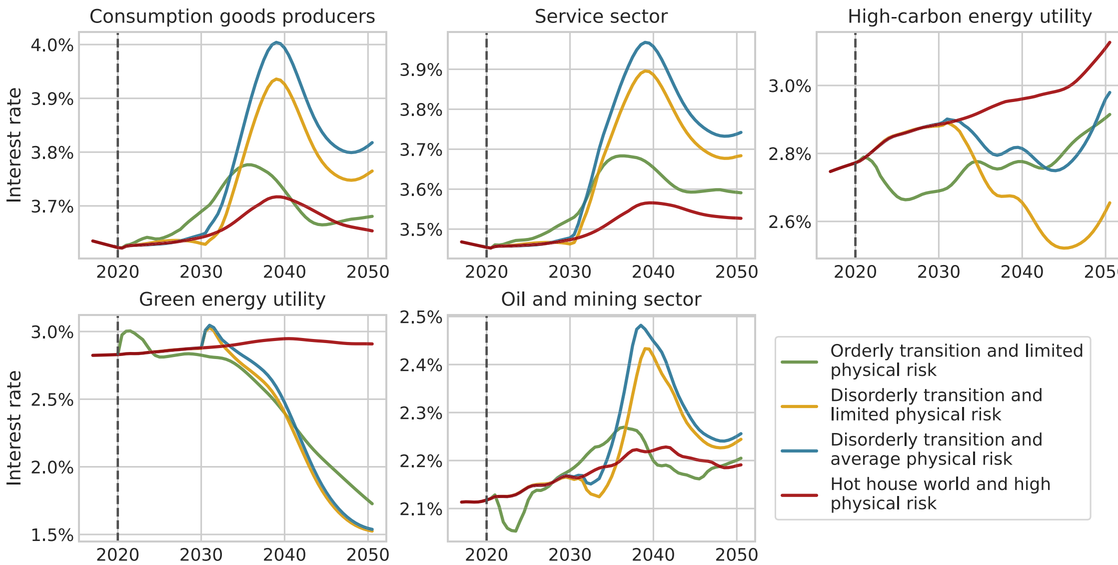


Fig. 12. Interest rates for real economy firms. In each panel, the x-axis displays the simulation time, and the y-axis displays the interest rates (in percentages) that firms pay on their loans in each period.

mining sectors. In the disorderly scenarios, such adjustments occur more abruptly, with implications for financial instability. In contrast, in the orderly scenario, interest rates do not differ considerably from those plotted for the hot house world scenarios, and tend to increase for all firms as a result of extra financing needs due to physical damages. A notable exception is represented by the low-carbon energy producers, for which interest rates drop significantly a few years after the introduction of the climate policies. This result follows a small initial uptake driven by an increase in the leverage. Indeed, the increase in the share of the energy market requires more capital, which is financed through credit.

A large deleveraging, which counteracts reduced profitability, leads to relatively low interest rates for the oil and mining sector and the high-carbon energy producer in the orderly scenario. In the orderly scenario physical damages are low, 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 the 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. Fig. 13 shows the ratio of investment targets that these two sectors can finance. For both, transition scenarios reduce the realized investment, as the carbon tax reduces their expected profitability, even when governments' compensatory measures are implemented to foster the energy sector's transition to low-carbon capital.

While the orderly scenario leads to higher realized investments, due to a lower value of the carbon tax than in the disorderly scenarios, physical risk reduces the ratio of realized investments (see the hot house world scenario).

7.2. Firms' climate sentiments

In this section, we analyse the impact of firms' expectations about climate policy credibility on their investment decisions in high-carbon and low-carbon goods. 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).

Sentiments are implemented as firms' anticipation of the carbon tax trajectories, and related costs for high-carbon production, conditioned to firms' trusting the policy announcement. 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 the current carbon tax), 10 years, 20 years, and 30 years. More specifically, investments by consumer goods producers in low-carbon and high-carbon capital depend on the expected returns. Therefore, when firms internalize the future carbon tax earlier in their NPV, they transition earlier and in a milder way to low-carbon capital.

Two important results emerge. First, if firms trust an orderly transition, i.e. an early introduction of a carbon tax, and start to internalize the scenarios of carbon tax in their NPV assessment, they promote an earlier low-carbon energy transition, as shown in Fig. 14(a). 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 circa 20% fewer emissions in 2035, compared to a case with no anticipation. [27]. The impacts of firms' climate sentiments on GDP growth (see Fig. 14(b)) and unemployment (Fig. 14(c)) are contained, meaning that firms' anticipation of the switching to renewable energy and capital has no meaningful economic trade-off.

Second, the longer the investment horizon of firms, the higher the credit in the initial phase of the simulation. This result is driven by the fact that the price of low-carbon capital is still comparatively high when the carbon tax is introduced, and thus in the short term, investment decisions would be less profitable. Therefore, the benefits for the firms from early carbon emissions abatement appear when the carbon tax rate reaches the anticipated levels.

8. Conclusion

In this paper, we provide a dynamic balance sheet assessment of the double materiality of climate physical and transition risks in the

[27] Changes are more limited beyond that horizon because the carbon tax trajectory then stabilizes in the NGFS scenarios

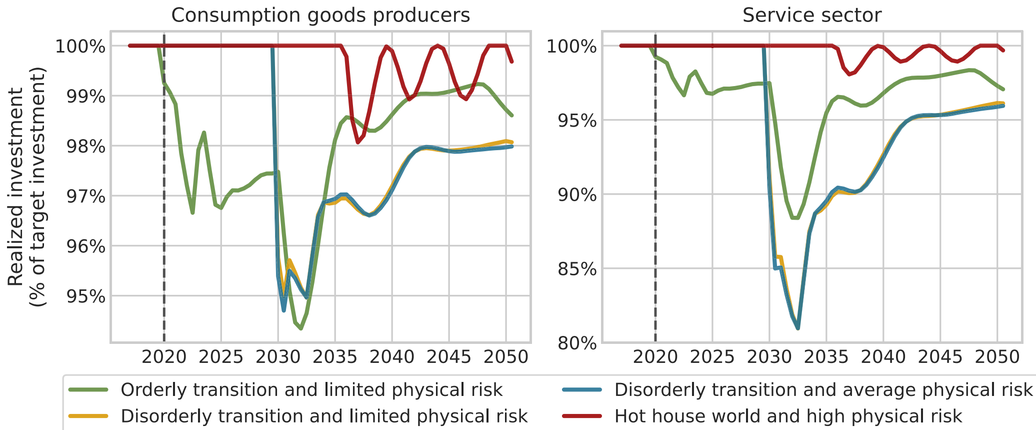
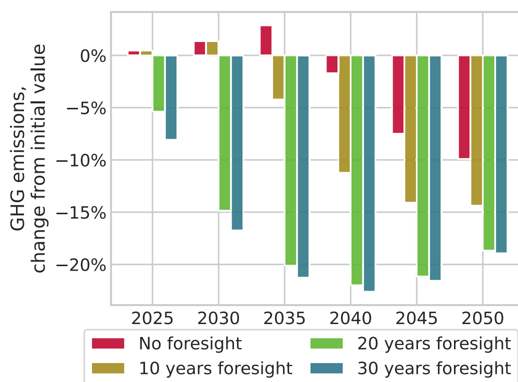
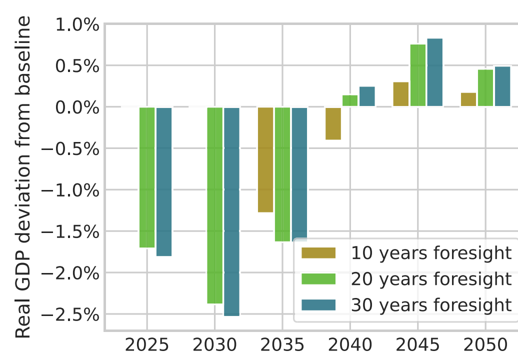


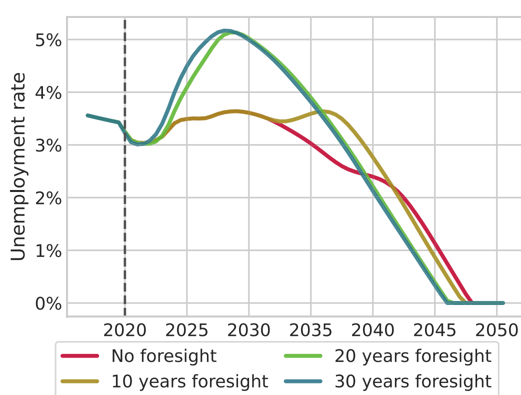
Fig. 13. Ratio of investment achieved by the consumption goods producers and the service sector across the NGFS scenarios. For each sector, the x-axis displays the simulation time, and the y-axis displays the realized investment as a ratio to the target. The realized investments are totals in units of 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 Eq. (11), uses sector-level expectations for both the demand and the deterioration of capital, including from climate damages.



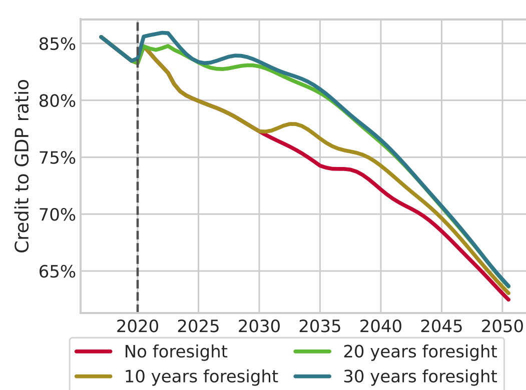
(A) Additional GHG emissions in comparison to the initial level



(B) Real GDP deviation from the baseline with no foresight



(C) Unemployment



(D) Credit to GDP

Fig. 14. Impact of firms' climate sentiments on main macroeconomic and financial variables. 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 ratios in percentages of the overall credit granted to GDP.

EA economy and banking sector. We tailor and calibrate the EIRIN model to the EA, and we embed the NGFS climate scenarios. Importantly, EIRIN links the NGFS scenarios to adjustments in firms' economic and financial performance and investment decisions. This step is fundamental to capture the key transmission channels through which the scenarios impact individual sectors. In addition, we analyse to what extent firms' climate sentiments foster or hinder the low-carbon transition via adjustments in expectations, risk assessment, and investment decisions.

Three main results emerge. First, the ways in which the transition could occur (i.e. orderly or disorderly), or not occur (i.e. the hot house world scenario), have different implications on firms' performance, which in turn affect banks' financial performance and investment decisions. We find that an orderly transition achieves early co-benefits (in terms of GDP, GHG emissions, and firms' financing conditions). In contrast, in the absence of an early and credible carbon tax, the GDP level projected for 2050 is around 12% lower than in transition scenarios. In a disorderly transition scenario, constraints on corporate investments weaken firms' and banks' financial stability through the realization of carbon stranded assets. Indeed, firms' challenges to access credit (high cost of capital) and invest in low-carbon energy technologies foster the materialization of stranded assets, with negative impacts on economic and financial performance. Moreover, inflationary spikes triggered by disorderly policy introduction may reinforce this effect by raising interest rates and compounding with inflationary pressures. These findings show the importance for policymakers to introduce an early and credible carbon tax to limit the negative impacts of stranded assets in the transition, and foster the emergence of co-benefits.

Second, firms' and banks' internalization of climate policies in their investment decisions matters to ensure an orderly low-carbon transition and limit climate physical risks. Banks' climate-adjusted risk assessment is crucial for a strong decoupling of economic development from GHG emissions. In particular, climate policy credibility can foster firms' climate sentiments and the low-carbon transition, with very limited – and temporary – costs for the economy. In this regard, the forward-looking nature of climate risks requires an appropriate policy calibration. This means considering future costs and benefits of the policy not only depending on possible climate scenarios but also on firms' and banks' behaviours, which can ultimately affect the realization of climate scenarios and in turn affect their own risk profiles.

Third, the double materiality of climate risks matters for central banks and financial supervisors, who should consider it in their climate stress test exercises, and potentially in the calibration of prudential measures to internalize such principles. To this aim, the macroeconomic models used by financial supervisors could be strengthened by including: (i) investors endowed with adaptive expectations and subject to imperfect information about future climate risks, considering the endogeneity of risks and the lack of complete markets (e.g. insurance); (ii) dynamic balance sheet relations between agents of the economy and finance, to analyse the implications of emerging dynamics (e.g. in the credit market) in investment decisions and economic decarbonization; (iii) the interplay between investors' expectations and policy credibility, to understand uner which conditions investors, and their financing decisions, can contribute to enable or hinder the low-carbon transition.

CRediT authorship contribution statement

Régis Gourdel: Conceptualization, Data curation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Irene Monasterolo:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Nepomuk Dunz:** Conceptualization, Data curation, Methodology, Writing – original draft. **Andrea Mazzocchetti:** Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Laura Parisi:** Conceptualization, Methodology.

Appendix. Model methodology

A.1. Financial market pricing

We model the secondary security market using a mechanism that builds on that of Dunz 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:

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

(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 the desired allocations. Importantly, the mechanism is liquidity preserving because of this last step. The new liquidity of agents after trading is given by

$$\forall i, \quad M_i(t) = M_i(t-1) + \sum_j \underbrace{\left(S_{i,j}(t-1) - S_{i,j}(t)\right)}_{\Delta S_{i,j}(t)} p^\dagger_j(t), \tag{A.2}$$

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 define as

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

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

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

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 $\Delta\hat{q}_j(\imath)$ the additional expected production (and sale), and $\hat{p}_j$ is the expected sale price. The latter is adjusted for VAT, which is assumed constant. They are given by

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

with γ^K_j 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

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

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

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

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 $\hat{p}_{\text{En}}$, and the additional quantity $\Delta D_{\text{En},j}$ of energy required to match the additional production capacity due to investments. We get

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

where π_{En} 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 follows from the use of high-carbon capital bought and the consumption of energy that accompanies the surplus of production. For the tax rate, the default setting is that the contemporaneous value $\tau_{\text{Em}}(t)$ is used, i.e. agents do not expect it to change. However, this assumption is relaxed in 7.2, where we can use a foresight of u periods, which translates into the use of $\tau_{\text{Em}}(t+u)$ 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

$$\Delta^{\mathfrak{b}} \hat{\text{Em}}_j(\iota,t,s) = \Delta\hat{\mathbf{q}}_j(\iota,t,s) \cdot \theta_j^{\text{Em}} + \Delta^{\mathfrak{b}} \hat{D}_{\text{En},j}(\iota,t,s) \cdot \hat{z}_{\text{E}\mathfrak{b}}(s) \theta_{\text{En}}^{\text{Em}}$$

where θ_j^{Em} and $\theta_{\text{En}}^{\text{Em}}$ are the carbon intensity of the sector production and energy use respectively, and $\hat{z}_{\text{E}\mathfrak{b}}(s)$ 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 low-carbon energy producers intend to, based on the mechanism in 5.2.2, as it assumes a constant energy demand and stable damages. Moreover, $\lambda_{\text{E}\mathfrak{g}}$ is not necessarily known to other agents, while $\xi_{\text{E}\mathfrak{g}}$ would be in general. Therefore, the theoretical value $\lambda_{\text{E}\mathfrak{g}}$ is replaced by an estimation $\tilde{\lambda}_{\text{E}\mathfrak{g}}$ in the above, such that

$$\hat{z}_{\text{E}\mathfrak{b}}(s) = 1 - \xi_{\text{E}\mathfrak{g}} + (1-\tilde{\lambda}_{\text{E}\mathfrak{g}})^{s-t} \cdot (\xi_{\text{E}\mathfrak{g}} - \mathbf{q}_{\text{E}\mathfrak{g}}(t)/\mathbf{q}_{\text{En}}(t)).$$

Note that in practice the endogeneity arises in how some of these variables will be defined. In particular, as detailed in Eq. (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 $Y_j = (1-\delta_j)/(1+\kappa_j)$. Then, the set of conditions for the NPV to be properly defined is

$$Y_j(1+\pi_j) < 1, \quad Y_j \frac{1+\pi_{w,i}}{1+\dot{\gamma}^N} < 1, \quad Y_j(1+\pi_R) < 1, \quad \text{and} \quad Y_j(1+\pi_{\text{En}}) < 1. \tag{A.3}$$

When conditions (A.3) are verified, from the formula for sums of geometric series we get

$$\begin{aligned}\frac{\text{NPV}_j^{\mathfrak{b}}(\iota,t)}{\iota} &= -p_{\text{K}p\mathfrak{b}}(t) + \gamma_j^K \left(\frac{p_j(t)/(1+\tau_{\text{VAT}}(t))}{1-Y_j(1+\pi_j)} \right. \\ &- \frac{w_j(t)/\gamma_j^N(t)}{1-Y_j\frac{1+\pi_{w,i}}{1+\dot{\gamma}^N}} - \frac{p_R(t)\phi_j^R}{1-Y_j(1+\pi_R)} \\ &- \frac{p_{\text{En}}(t)\phi_j^{\text{En}}}{1-Y_j(1+\pi_{\text{En}})} - \frac{\tau^{\text{GHG}}(t)}{1-Y_j}\left[\theta_j^{\text{Em}} + \theta_{\text{En}}^{\text{Em}}\phi_j^{\text{En}}(1-\xi_{\text{E}\mathfrak{g}})\right] \\ &\left. - \frac{\tau^{\text{GHG}}(t)\theta_{\text{En}}^{\text{Em}}\phi_j^{\text{En}}}{1-Y_j(1-\tilde{\lambda}_{\text{E}\mathfrak{g}})}\left[\xi_{\text{E}\mathfrak{g}} - \frac{\mathbf{q}_{\text{E}\mathfrak{g}}(t)}{\mathbf{q}_{\text{En}}(t)}\right]\right).\end{aligned}$$

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 invested. The calculation for the low-carbon NPV is similar, with the following equations:

$$\text{NPV}_j^{\mathfrak{g}}(\iota,t) = -p_{\text{K}p\mathfrak{g}}(t)\cdot\iota + \sum_{s=t+1}^{+\infty} \frac{\text{CF}_i^{\mathfrak{g}}(\iota,t,s)}{(1+\kappa_j)^{s-t}}$$

$$\begin{aligned}\text{CF}_j^{\mathfrak{g}}(\iota,t,s) &= \frac{\hat{p}_j(s)}{1+\tau_{\text{VAT}}(t)} \cdot \Delta\hat{\mathbf{q}}_j(t) - \hat{w}_j(s)\cdot\Delta N_j(\iota,t,s) - p_R(s)\cdot\Delta^{\mathfrak{g}}\hat{q}_{R,j}(\iota,t,s) \\ &- \hat{p}_{\text{En}}(s)\cdot\Delta^{\mathfrak{g}}\hat{D}_{\text{En},j}(\iota,t,s) - \Delta^{\mathfrak{g}}\hat{\text{Em}}_j(\iota,t,s)\times\tau_{\text{Em}}(t)\end{aligned}$$

where the differences in the terms of the cash flows are due to lower consumption of energy and raw materials when using low-carbon capital (with constant discount rates given by $\eta_{\text{En}}^{\mathfrak{g}}$ and $\eta_R^{\mathfrak{g}}$ respectively), as well as an absence of GHG emissions from the use of capital. This gives us the following:

$$\begin{aligned}\Delta^{\mathfrak{g}}\hat{q}_{R,j}(\iota,t,s) &= \Delta\hat{\mathbf{q}}_j(\iota,t,s)\times\phi_j^R(1-\eta_R^{\mathfrak{g}}) \\ \Delta^{\mathfrak{g}}\hat{D}_{\text{En},j}(\iota,t,s) &= \Delta\hat{\mathbf{q}}_j(\iota,t,s)\times\phi_j^{\text{En}}(1-\eta_{\text{En}}^{\mathfrak{g}}) \\ \Delta^{\mathfrak{g}}\hat{\text{Em}}_j(\iota,t,s) &= \Delta^{\mathfrak{g}}\hat{D}_{\text{En},j}(\iota,t,s)\cdot\theta_{\text{En}}^{\text{Em}}\cdot\mathbf{q}_{\text{E}\mathfrak{b}}(t)/\mathbf{q}_{\text{En}}(t).\end{aligned}$$

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

$$\begin{aligned}\frac{\text{NPV}_j^{\mathfrak{g}}(\iota,t)}{\iota} &= -p_{\text{K}p\mathfrak{b}}(t) + \gamma_j^K \left(\frac{p_j(t)/(1+\tau_{\text{VAT}}(t))}{1-Y_j(1+\pi_j)} \right. \\ &- \frac{w_j(t)/\gamma_j^N(t)}{1-Y_j\frac{1+\pi_{w,i}}{1+\dot{\gamma}^N}} - \frac{p_R(t)\phi_j^R(1-\eta_R^{\mathfrak{g}})}{1-Y_j(1+\pi_R)} \\ &- \phi_j^{\text{En}}(1-\eta_{\text{En}}^{\mathfrak{g}})\left[\frac{p_{\text{En}}(t)}{1-Y_j(1+\pi_{\text{En}})} + \frac{\tau^{\text{GHG}}(t)\theta_{\text{En}}^{\text{Em}}}{1-Y_j}(1-\xi_{\text{E}\mathfrak{g}}) \right. \\ &\left.\left. + \frac{\tau^{\text{GHG}}(t)\theta_{\text{En}}^{\text{Em}}}{1-Y_j(1-\tilde{\lambda}_{\text{E}\mathfrak{g}})}\left(\xi_{\text{E}\mathfrak{g}} - \frac{\mathbf{q}_{\text{E}\mathfrak{g}}(t)}{\mathbf{q}_{\text{En}}(t)}\right)\right]\right).\end{aligned}$$

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

$$\text{NPV}_{\text{E}\mathfrak{g}}(\iota,t) = \sum_{s=t+1}^{+\infty} \frac{\hat{p}_{\text{En}}(s)\cdot\Delta\hat{\mathbf{q}}_{\text{E}\mathfrak{g}}(\iota,t,s)}{(1+\tau_{\text{En}})(1+\kappa_{\text{E}\mathfrak{g}})^{s-t}} - (1-\eta_K)p_{\text{K}p\mathfrak{g}}(t)\cdot\iota$$

where $\Delta\hat{\mathbf{q}}_{\text{E}\mathfrak{g}}(\iota,t,s) = \iota(1-\delta_{\text{E}\mathfrak{g}})^{s-t}\cdot\gamma_{\text{E}\mathfrak{g}}^K$ 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 Eg. Let $Y_{\text{E}\mathfrak{g}} = (1-\delta_{\text{E}\mathfrak{g}})/(1+\kappa_{\text{E}\mathfrak{g}})$. If $Y_{\text{E}\mathfrak{g}}(1+\pi_{\text{En}}) < 1$ then the series in the above sum converges, and we get

$$\frac{\text{NPV}_{\text{E}\mathfrak{g}}(\iota,t)}{\iota} = \frac{\gamma_{\text{E}\mathfrak{g}}^K\hat{p}_{\text{En}}(t)/(1+\tau_{\text{En}})}{1-Y_{\text{E}\mathfrak{g}}(1+\pi_{\text{En}})} - (1-\eta_K)p_{\text{K}p\mathfrak{g}}(t).$$

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

$$\text{NPV}_{\text{E}\mathfrak{b}}(\iota,t) = -p_{\text{K}p\mathfrak{b}}(t)\cdot\iota + \sum_{s=t+1}^{+\infty}\frac{\text{CF}_{\text{E}\mathfrak{b}}(\iota,t,s)}{(1+\kappa_{\text{E}\mathfrak{b}})^{s-t}},$$

where we have the expected cash flow 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:

$$\begin{aligned}\frac{\text{CF}_{\text{E}\mathfrak{b}}(\iota,t,s)}{(1-\delta_j)^{s-t}\cdot\iota} &= \frac{\hat{p}_{\text{En}}}{1+\tau_{\text{En}}}\cdot\frac{\gamma_{\text{E}\mathfrak{b}}^K}{1+\rho_{\text{E}\mathfrak{b}}} - \hat{p}_{\text{MO}}\cdot\frac{\gamma_{\text{E}\mathfrak{b}}^K}{\gamma_{\text{E}\mathfrak{b}}^o} \\ &- \tau_{\text{Em}}(t)\gamma_{\text{E}\mathfrak{b}}^K\left(\theta_{\text{E}\mathfrak{b}} + \rho_{\text{E}\mathfrak{b}}\hat{z}_{\text{E}\mathfrak{b}}(s)\theta_{\text{En}}^{\text{Em}}\right).\end{aligned}$$

so that, if we set $Y_{\text{E}\mathfrak{b}} = (1-\delta_{\text{E}\mathfrak{g}})/(1+\kappa_{\text{E}\mathfrak{g}})$, then the NPV is correctly defined when we verify $Y_{\text{E}\mathfrak{b}} < 1$,

$$\frac{\text{NPV}_{\text{E}\mathfrak{b}}(\iota,t)}{\iota} = -p_{\text{K}p\mathfrak{b}}(t) + \gamma_{\text{E}\mathfrak{b}}^K\left(\frac{p_{\text{En}}(t)/(1+\tau_{\text{En}})}{1-Y_{\text{E}\mathfrak{b}}(1+\pi_{\text{En}})} - \frac{p_{\text{MO}}(t)/\gamma_{\text{E}\mathfrak{b}}^o}{1-Y_{\text{E}\mathfrak{b}}(1+\pi_{\text{MO}})}\right.$$

$$- \frac{\tau^{\mathrm{GHG}}(t)}{1-Y_{\mathrm{E}\mathfrak{b}}}\left[\theta^{\mathrm{Em}}_{\mathrm{E}\mathfrak{b}} + \theta^{\mathrm{Em}}_{\mathrm{En}}\rho_{\mathrm{E}\mathfrak{b}}(1-\xi_{\mathrm{E}\mathfrak{g}})\right] - \frac{\tau^{\mathrm{GHG}}(t)\theta^{\mathrm{Em}}_{\mathrm{En}}\rho_{\mathrm{E}\mathfrak{b}}}{1-Y_{\mathrm{E}\mathfrak{b}}(1-\tilde{\lambda}_{\mathrm{E}\mathfrak{g}})}\left[\xi_{\mathrm{E}\mathfrak{g}} - \frac{\mathbf{q}_{\mathrm{E}\mathfrak{g}}(t)}{\mathbf{q}_{\mathrm{En}}(t)}\right]\Bigg).$$

A.3. Workers allocation and wages

The 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 friction of moving between sectors or from one 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 at a 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 periods. Those demand expectations then determine firms' production plan $\hat{\mathbf{q}}_j$. For consumption goods producer and service firms, the labour demand $\hat{N}_j$ (with $j\in\{\mathrm{Fl},\mathrm{Fk}\}$) is determined by their production plan $\hat{\mathbf{q}}_j$, their capital endowment K_j and by the Leontief technology, such that

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

where γ^K_j and γ^N_j 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 $\gamma^N_{\mathrm{Fl}} < \gamma^N_{\mathrm{Fk}}$ but employs low-skilled workers only, receiving low wages w_{low}. Fk is more capital intensive, meaning that $\gamma^K_{\mathrm{Fk}} < \gamma^K_{\mathrm{Fl}}$ and employs high-skilled workers only, receiving high wages w_{high}.

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

$$\forall i\in\{\mathrm{K}\mathrm{p}\mathfrak{b},\mathrm{K}\mathrm{p}\mathfrak{g}\},\quad \hat{N}_i(t) = \hat{\mathbf{D}}_i(t)/\gamma^N_i$$

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

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

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

$$\forall i,\quad N_i = \hat{N}_i \cdot \frac{N_{\mathrm{priv}}}{\hat{\mathbf{N}}}\left(1+\alpha_N\frac{w_i-\tilde{w}}{w_{\mathrm{high}}-w_{\mathrm{low}}}\right) \tag{A.4}$$

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, so as to verify $\sum_{i\neq\mathrm{G}} N_i = N_{\mathrm{priv}}$. Moreover, we want to verify $N_i\in[0,\hat{N}_i]$, hence, for every sector i,

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

Then, notice that $\forall i, -1\le \frac{w_i-\tilde{w}}{w_{\mathrm{high}}-w_{\mathrm{low}}}\le 1$. Therefore, a sufficient condition is $\alpha\le\min\left(1,\hat{\mathbf{N}}/N_{\mathrm{priv}}-1\right)$. Thus, we set $\alpha_N = \min\left(\hat{\alpha}_N, \hat{\mathbf{N}}/N_{\mathrm{priv}}-1\right)$, 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,[28] which is provided by the high-carbon capital producer and is subject to depletion. In the new setting, the high-carbon energy producer is similar to its low-carbon counterpart in the way it 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.[29]

Second, the total power that the sector produces is computed to take into account its own contemporaneous consumption.[30] Let $\tilde{\mathbf{d}}^{\mathrm{En}}$ be the energy demand from sectors other than E$\mathfrak{b}$. We have:

$$\begin{cases} \mathbf{Q}_{\mathrm{En}} = \tilde{\mathbf{D}}_{\mathrm{En}} + D_{\mathrm{En,E}\mathfrak{b}} \\ D_{\mathrm{En,E}\mathfrak{b}} = \rho_{\mathrm{E}\mathfrak{b}} \times \mathbf{Q}_{\mathrm{E}\mathfrak{b}} \\ \mathbf{Q}_{\mathrm{E}\mathfrak{b}} = \mathbf{Q}_{\mathrm{En}} - \mathbf{Q}_{\mathrm{E}\mathfrak{g}} \end{cases},$$

where $\rho_{\mathrm{E}\mathfrak{b}}\in[0,1)$ is the parameter indicating how many input units of energy are necessary for E$\mathfrak{b}$ to produce one unit output of energy. As $\tilde{\mathbf{d}}^{\mathrm{En}}$ and $\mathbf{Q}_{\mathrm{E}\mathfrak{g}}$ are already determined, we obtain $\mathbf{Q}_{\mathrm{E}\mathfrak{b}}$, $D_{\mathrm{En,E}\mathfrak{b}}$ and $\mathbf{Q}_{\mathrm{En}}$, starting from $\mathbf{Q}_{\mathrm{E}\mathfrak{b}} = (\tilde{\mathbf{d}}^{\mathrm{En}} - \mathbf{Q}_{\mathrm{E}\mathfrak{g}})/(1-\rho_{\mathrm{E}\mathfrak{b}})$.

The price is then set taking into account the unit cost of both sectors, denoted as $\mathrm{UC}_{\mathrm{E}\mathfrak{b}}$ and $\mathrm{UC}_{\mathrm{E}\mathfrak{g}}$. These values take into account the basic production needs and the costs linked to debt and capital acquisition. Thus, for E$\mathfrak{b}$ we get

$$\mathrm{UC}_{\mathrm{E}\mathfrak{b}} = \frac{p_{\mathrm{MO}}}{\gamma^0_{\mathrm{E}\mathfrak{b}}} + p_{\mathrm{En}}\times\rho_{\mathrm{E}\mathfrak{b}} + \frac{(\kappa_{\mathrm{E}\mathfrak{b}}+\chi_{\mathrm{E}\mathfrak{b}})L_{\mathrm{E}\mathfrak{b}} + \tau_{\mathrm{Em}}\mathrm{Em}_{\mathrm{E}\mathfrak{b}} + p_{\mathrm{Kp}\mathfrak{b}}K_{\mathrm{E}\mathfrak{b}}(\delta_{\mathrm{E}\mathfrak{b}}+\hat{\xi})}{\mathbf{Q}_{\mathrm{E}\mathfrak{b}}},$$

[28] 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.

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

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

Table A.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.

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%

where κ_i is the interest rate on loans $L_{\mathrm{E}\mathfrak{b}}$, with $\chi_{\mathrm{E}\mathfrak{b}}$ the repayment rate, and $\gamma^o_{\mathrm{E}\mathfrak{b}}$ the oil efficiency. For E$\mathfrak{g}$ we get

$$\mathrm{UC}_{\mathrm{E}\mathfrak{g}} = \frac{(\kappa_{\mathrm{E}\mathfrak{g}} + \chi_{\mathrm{E}\mathfrak{g}})L_{\mathrm{E}\mathfrak{g}} + p_{\mathrm{K}p\mathfrak{g}} K_{\mathrm{E}\mathfrak{g}}(\delta_{\mathrm{E}\mathfrak{g}} + \hat{\xi})}{\mathbf{q}_{\mathrm{E}\mathfrak{g}}}.$$

Finally, the price is computed as a generalized mean of the unit costs. It is controlled by a unique parameter α_{En} that can be interpreted as the degree of competition imposed by the regulator. More precisely, we set

$$p_{\mathrm{En}} = (1+\tau_{\mathrm{En}}) \times (1+\mu_{\mathrm{En}}) \times \left(\frac{\mathbf{Q}_{\mathrm{E}\mathfrak{b}}}{\mathbf{Q}_{\mathrm{En}}} \cdot \mathrm{UC}_{\mathrm{E}\mathfrak{b}}^{\alpha_{\mathrm{En}}} + \frac{\mathbf{Q}_{\mathrm{E}\mathfrak{g}}}{\mathbf{Q}_{\mathrm{En}}} \cdot \mathrm{UC}_{\mathrm{E}\mathfrak{g}}^{\alpha_{\mathrm{En}}} \right)^{1/\alpha_{\mathrm{En}}},$$

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

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 $\alpha_{\mathrm{En}} > 1$ 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. $\alpha_{\mathrm{En}} > 20$, this would get close to taking simply the maximum of the two. On the other hand, a value $\alpha_{\mathrm{En}} < 1$ 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 A.2 the set of parameters used explicitly in the model taken from the data.

A.6. Matrices for stocks and flows

To complement the mechanisms described in Section 3, we provide in Table A.3 the balance-sheet matrix, i.e. the stock view. Moreover, Table A.4 gives the transaction-flow matrix, which includes the summary of all flows occurring during one period in the model.

A.7. Physical risk data integration

The NGFS database provides the climate physical risk impacts used in the scenarios. It reports the 10th, 50th, or 90th percentile of the expected damage distribution on global GDP, taken from Kalkuhl and Wenz (2020). In Kalkuhl and Wenz (2020), the authors empirically estimate historic climate impacts on gross regional products amongst 1500 regions in 77 countries. They employ a wide range of regression techniques to identify impacts on productivity levels and productivity growth. Expected climate damages are heterogeneous across world regions. For instance, Africa is affected by higher temperature changes and more frequent and extreme weather events than Europe. As such, the global estimates from Kalkuhl and Wenz (2020) need to be adapted to resemble expected damages in Europe, which is the focus of this study. Therefore, we apply the methodology and data by Alogoskoufis et al. (2021), using firm-level physical risk data in 2050, provided by 427 for 6 million firms worldwide. For the same 11 world regions as in REMIND-MagPie, average risk scores from the 427 data are calculated. Those average risk scores we use to assign a relative weight to global climate change damages, with regions with a lower average risk score assumed to have a lower climate damage impact in 2050. At the same time, damage size exposure to climate change increases with a larger economy and higher levels of productive capacity. To account for the damage exposure effect, relative global GDP shares of the different regions until 2050 are also used to adjust reported global GDP damage impacts. The combined effects constitute the GDP damage time series for Europe, which we interpolate to generate biannual time steps.

Appendix 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 Fig. B.15(a) 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 in light of two mechanisms. First, capital replacement due to physical damages reduces the profitability of companies and hence the amount is 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 (Fig. B.15(b)). 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 outcome is consistent with the benefits for employment from the low-carbon transition already identified in the literature (e.g. Füllemann et al., 2020). It eventually dominates in the case of disorderly scenarios as well, but the more abrupt implementation first causes

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

	Hw	Hk	Fk	Fl	Kp$\mathfrak{b}$	Kp$\mathfrak{g}$	E$\mathfrak{b}$	E$\mathfrak{g}$	BA	CB	G	MO	RoW	Total
Tangible capital														
- high-carbon			$p_{\mathrm{Kp}\mathfrak{b}} K^{\mathfrak{b}}_{\mathrm{Fk}}$	$p_{\mathrm{Kp}\mathfrak{b}} K^{\mathfrak{b}}_{\mathrm{Fl}}$	$p_{\mathrm{Kp}\mathfrak{b}} \mathrm{IN}_{\mathrm{Kp}\mathfrak{b}}$		$p_{\mathrm{Kp}\mathfrak{b}} K^{\mathfrak{b}}_{\mathrm{E}\mathfrak{b}}$							$p_{\mathrm{Kp}\mathfrak{b}} \mathbf{K}^{\mathfrak{b}}$
- low-carbon			$p_{\mathrm{Kp}\mathfrak{g}} K^{\mathfrak{g}}_{\mathrm{Fk}}$	$p_{\mathrm{Kp}\mathfrak{g}} K^{\mathfrak{g}}_{\mathrm{Fl}}$		$p_{\mathrm{Kp}\mathfrak{g}} \mathrm{IN}_{\mathrm{Kp}\mathfrak{g}}$		$p_{\mathrm{Kp}\mathfrak{g}} K^{\mathfrak{g}}_{\mathrm{E}\mathfrak{g}}$						$p_{\mathrm{Kp}\mathfrak{g}} \mathbf{K}^{\mathfrak{b}}$
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			$-L_{\mathrm{Fk}}$	$-L_{\mathrm{Fl}}$			$-L_{\mathrm{E}\mathfrak{b}}$	$-L_{\mathrm{E}\mathfrak{g}}$	$\mathbf{L}$			$-L_{\mathrm{MO}}$		0
CB's loan									$-L_{\mathrm{CB}}$	L_{CB}				0
Bank's deposits	M_{Hw}	M_{Hk}	M_{Fk}	M_{Fl}	$M_{\mathrm{Kp}\mathfrak{b}}$	$M_{\mathrm{Kp}\mathfrak{g}}$	$M_{\mathrm{E}\mathfrak{b}}$	$M_{\mathrm{E}\mathfrak{g}}$	$-\mathcal{D}$		M_{G}	M_{MO}		0
CB's reserves									M_{BA}	$-\mathcal{M}_{\mathrm{fiat}}$		M_{RoW}		0
Equity (net worth)			$-E_{\mathrm{Fk}}$	$-E_{\mathrm{Fl}}$	$-E_{\mathrm{Kp}\mathfrak{b}}$	$-E_{\mathrm{Kp}\mathfrak{g}}$	$-E_{\mathrm{E}\mathfrak{b}}$	$-E_{\mathrm{E}\mathfrak{g}}$	$-E_{\mathrm{BA}}$	$-E_{\mathrm{CB}}$	$-E_{\mathrm{G}}$	$-E_{\mathrm{MO}}$	$-E_{\mathrm{RoW}}$	$-E_{\mathrm{EIRIN}}$
Total			0	0	0	0	0	0	0	0	0			

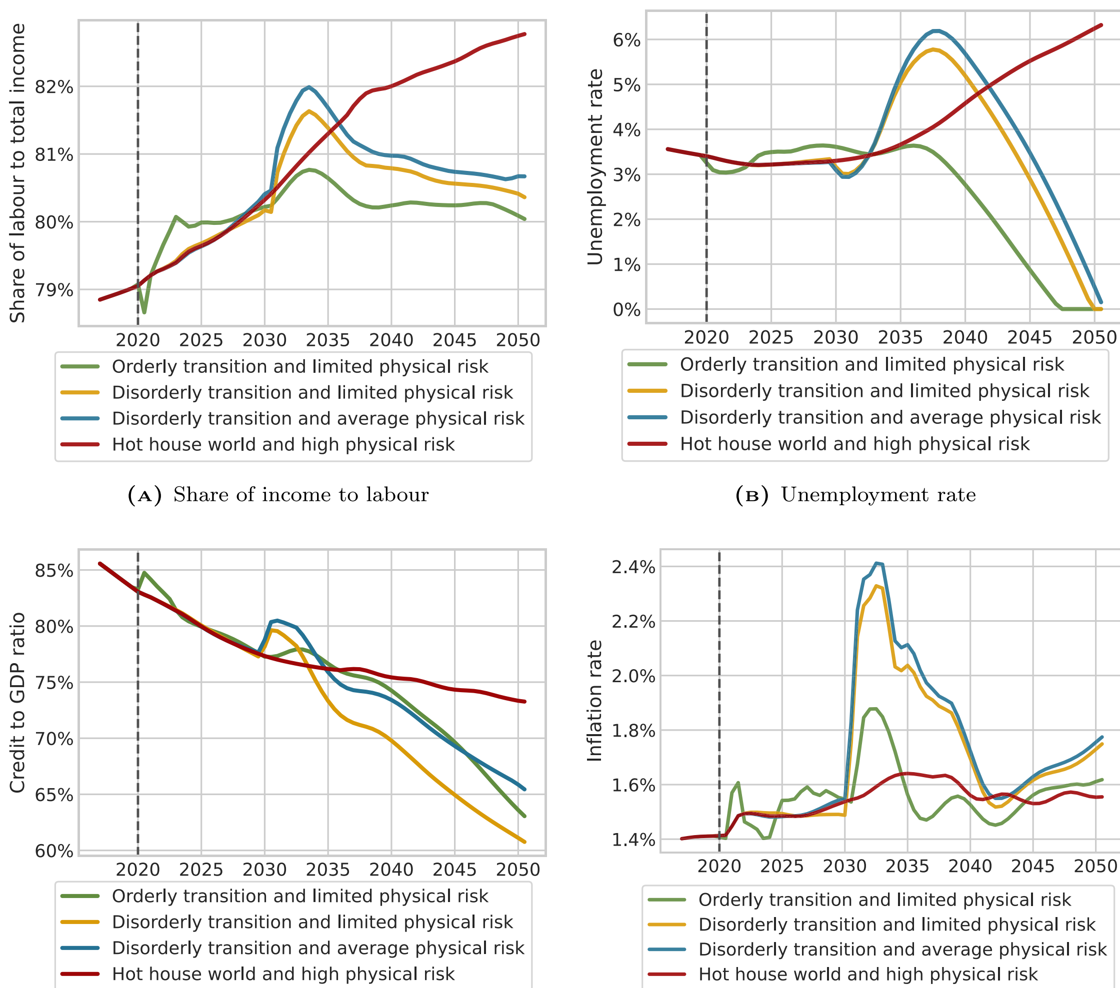


Fig. B.15. Additional simulation results. For all figures, the x-axis displays the simulation time. For the top-left figure, the y-axis shows the income share of working households that is derived from labour (i.e. excluding social transfers), taken as its ratio in total households' labour and capital income per period. For 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. For the bottom-right figure, the inflation rate is computed based on the evolution of the price of goods and services, with a representative basket defined by how much households consume.

an increase in unemployment. This is in line with the generally higher volatility of these scenarios.

Now, on the financial aspect, we represent in Fig. B.15(c) the credit level as percentage 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 low-carbon technologies. However, this effect reverses after a few years, such that transition scenarios show strong trends of decreasing credit levels in the medium term. One explanation already mentioned in Section 7.1 is that there is a deleveraging of high-carbon sectors, 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 normally would.

When examining inflation across different scenarios, we see that the yearly rate observed in the model is relatively sticky, and does

Table A.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.

Cash flows from:	Hw	Hk	Fk	Fl	$Kp\mathfrak{b}$	$Kp\mathfrak{g}$	$E\mathfrak{b}$	$E\mathfrak{g}$	MO	BA	CB	G	RoW
Consumption of:													
- goods	$-p_{Fk} Q_{Fk,Hw}$	$-p_{Fk} Q_{Fk,Hk}$	$p_{Fk} \mathbf{Q}_{Fk}$								$-p_{Fk} Q_{Fk,G}$	$-p_{Fk} Q_{Fk,RoW}$	
- tourism and services	$-p_{Fl} Q_{Fl,Hw}$	$-p_{Fl} Q_{Fl,Hk}$		$p_{Fl} \mathbf{Q}_{Fl}$								$-p_{Fl} Q_{Fl,G}$	$-p_{Fl} Q_{Fl,RoW}$
- energy	$-p_{En} Q_{En,Hw}$	$-p_{En} Q_{En,Hk}$	$-p_{En} q^{En}_{Fk}$	$-p_{En} Q_{En,Fl}$	$-p_{En} Q_{En,Kp\mathfrak{b}}$	$-p_{En} Q_{En,Kp\mathfrak{g}}$	$p_{En}(\mathbf{Q}_{E\mathfrak{b}} - Q_{RoW,E\mathfrak{b}})$	$p_{En} \mathbf{Q}_{E\mathfrak{g}}$					$p_{En} Q_{RoW,E\mathfrak{b}}$
Remittances	Rem_{Hw}	Rem_{Hk}											$-Rem_{Hw} - Rem_{Hk}$
Wages	Y_{Hw}		$-N_{Fk} w_{high}$	$-N_{Fl} w_{low}$	$-N_{Kp\mathfrak{b}} w_{high}$	$-N_{Kp\mathfrak{g}} w_{high}$			$-N_G \hat{w}$		0		
Bonds' coupons		$\mathfrak{c} S_{G,Hk}$					$\mathfrak{c} S_{G,BA}$	$\mathfrak{c} S_{G,CB}$	$-\mathfrak{c} \mathbf{S}_G$		0		
Loan interests			$-r_D L_{Hk}$	$-r_D L_{Fl}$		$-r_D L_{En}$	Y_{BA}						
CB's loan							$-r_{CB} L_{CB}$	$r_{CB} L_{CB}$					
Income tax	$-T_{Hw}$	$-T_{Hk}$	$-T_{C_k}$	$-T_{Fl}$	$-T_K$	$-T_{En}$			T_G		0		
Dividend payouts		$\sum_i \mathfrak{d}_i S_{i,Hk}$	$-\mathfrak{d}_{Fk} \mathbf{S}_{Fk}$	$-\mathfrak{d}_{Fl} \mathbf{S}_{Fl}$	$-\mathfrak{d}_{Kp\mathfrak{b}} \mathbf{S}_{Kp\mathfrak{b}}$	$-\mathfrak{d}_{Kp\mathfrak{g}} \mathbf{S}_{Kp\mathfrak{g}}$	$-\mathfrak{d}_{E\mathfrak{b}} \mathbf{S}_{E\mathfrak{b}}$	$-\mathfrak{d}_{E\mathfrak{g}} \mathbf{S}_{E\mathfrak{g}}$	$\sum_i \mathfrak{d}_i S_{i,BA} - \mathfrak{d}_{BA} \mathbf{S}_{BA}$				
Seigniorage										$-Sgn$	Sgn		
Investment in capital			$-p_{Kp\mathfrak{b}} Q_{Kp\mathfrak{b},Fk} - p_{Kp\mathfrak{g}} Q_{Kp\mathfrak{g},Fk}$	$-p_{Kp\mathfrak{b}} Q_{Kp\mathfrak{b},Fl} - p_{Kp\mathfrak{g}} Q_{Kp\mathfrak{g},Fl}$	$p_{Kp\mathfrak{b}} \mathbf{Q}_{Kp\mathfrak{b}}$	$p_{Kp\mathfrak{g}} \mathbf{Q}_{Kp\mathfrak{g}}$	$-p_{Kp\mathfrak{b}} Q_{Kp\mathfrak{b},E\mathfrak{b}}$	$-p_{Kp\mathfrak{g}} Q_{Kp\mathfrak{g},E\mathfrak{g}}$	$-p_{Kp\mathfrak{b}} Q_{Kp\mathfrak{b},MO}$				
Δ Loans			ΔL_{Fk}	ΔL_{Fl}		ΔL_{En}	$-\Delta L_{BA} + \Delta L_{CB}$	$-\Delta L_{CB}$			0		
Bond issuance		$-p^{\dagger}_G \Delta S_{G,Hk}$					$-p^{\dagger}_G \Delta S_{G,BA}$	$-p^{\dagger}_G \Delta S_{G,CB}$	$p^{\dagger}_G \Delta \mathbf{S}_G$		0		
Change in bank deposits													
Change in CB's reserves							$-\Delta M_{BA}$	ΔM_{fiat}		$-\Delta M_{RoW}$	0		

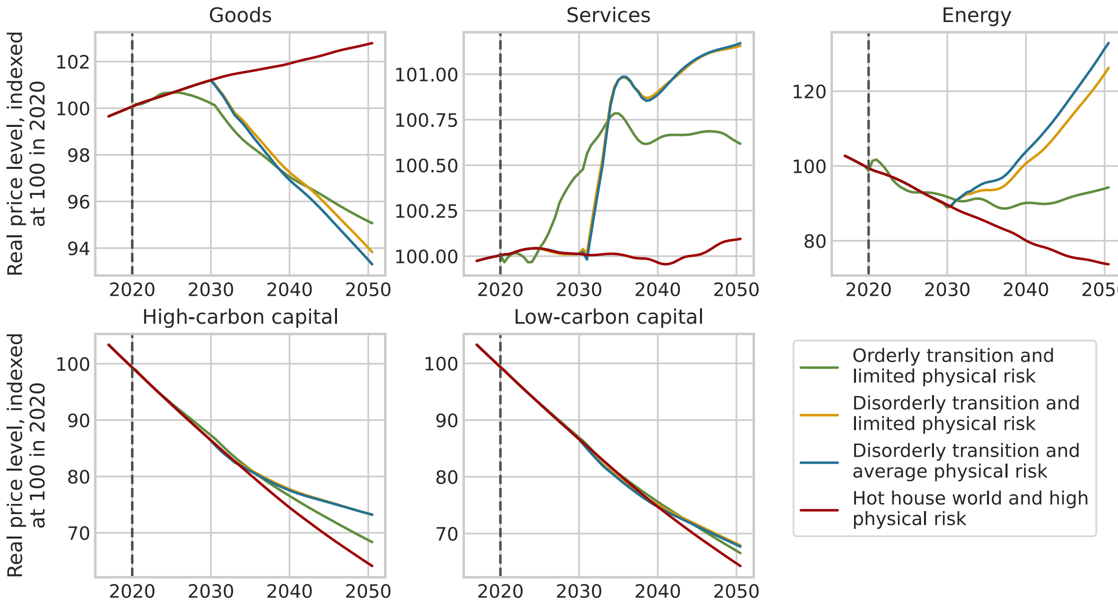


Fig. B.16. Real prices across scenarios. The x-axis displays the simulation time, and the y-axis displays the prices of the different real economy goods, indexed at 100 at the start of 2020. The benchmark inflation rate used to compute real prices is taken from a basket of goods and services with time-varying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

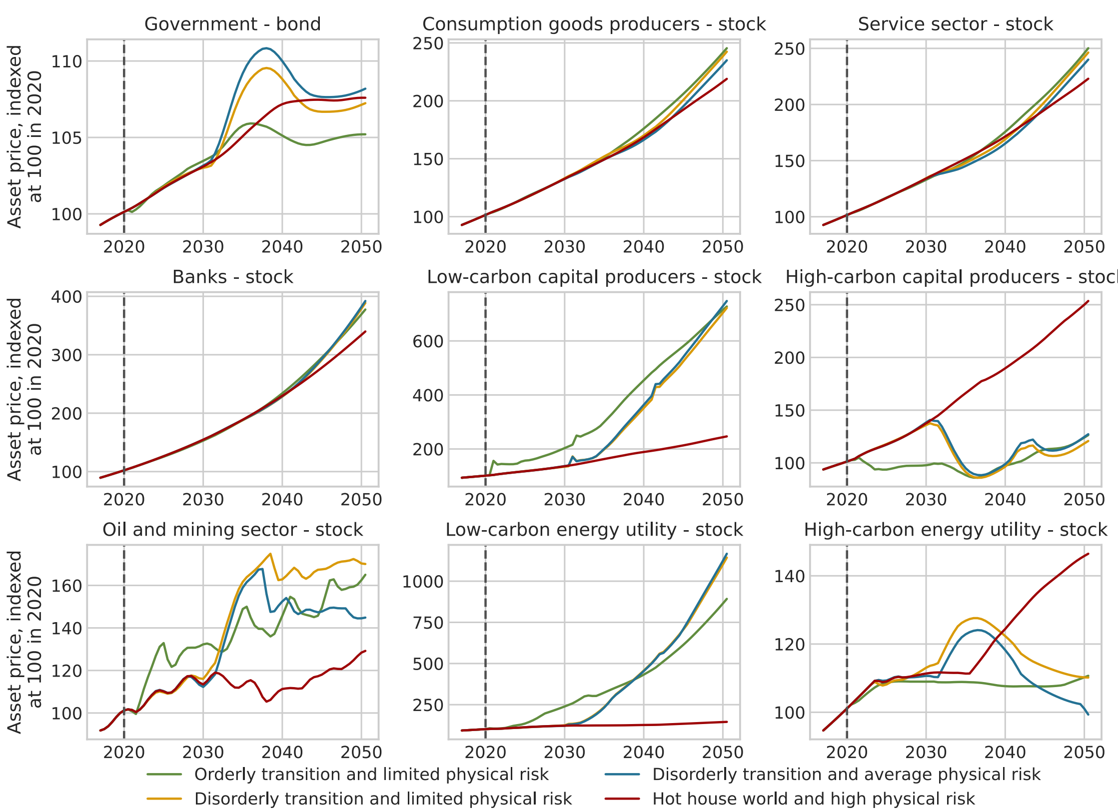


Fig. B.17. Evolution of asset prices on the secondary market. For each plot, the x-axis displays the simulation time, and the y-axis displays the prices of the plot's financial security, indexed at 100 at the start of 2020. Asset prices are mostly the result of how banks and capitalist households value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

not deviate excessively from the baseline rate. Some inflationary effects can be observed at the introduction of green policies, which are most significant in the disorderly scenario (up to 1% higher than the initial inflation rate), reflecting potential "greenflationary" concerns, as indicated in a recent speech by the ECB board member Isabel Schnabel (Schnabel, 2022). This effect creates financial volatility but is transitory, with a time frame of about ten years to go back to its normal level. In an orderly transition scenario, these inflationary pressures are modest, as firms have time to adapt production capacities accordingly. It should be noted, however, that we do not consider more detailed supply chain dynamics and other occasional disruptions that can compound with the effect of the low-carbon transition and

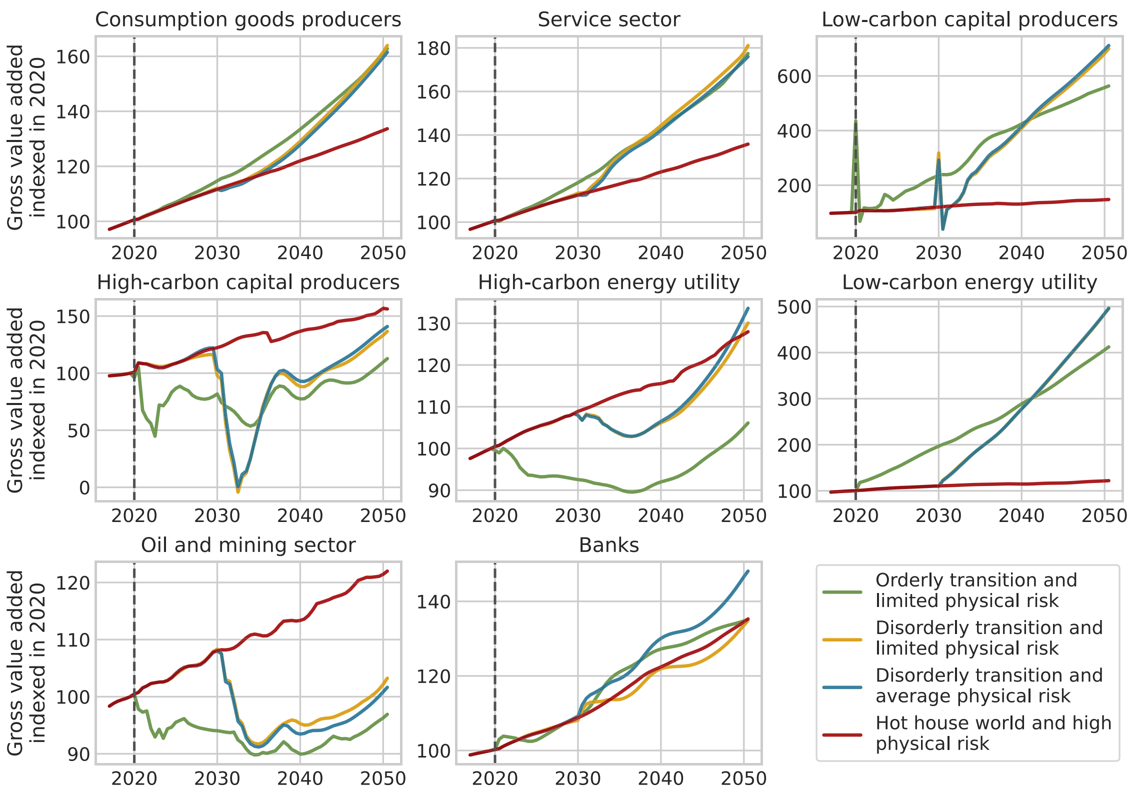


Fig. B.18. GDP components in real terms. For each firm, the *x*-axis displays the simulation time, and the *y*-axis displays the output using the model's internal monetary units.

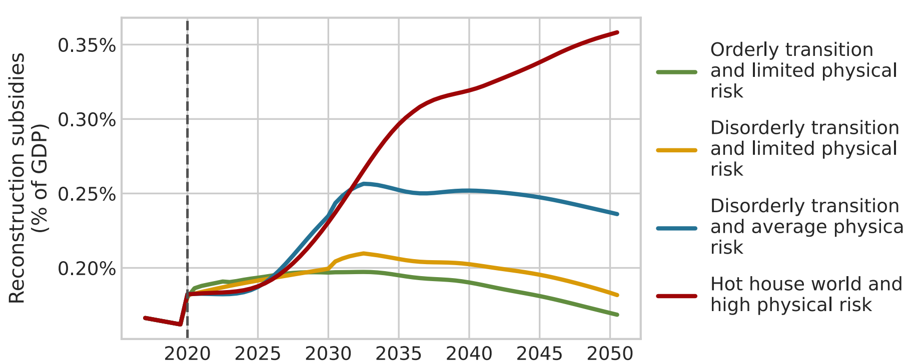


Fig. B.19. Ratio of low-carbon capital in investment. The *x*-axis displays the simulation time, and the *y*-axis displays the investment in low-carbon capital as a ratio of total investment.

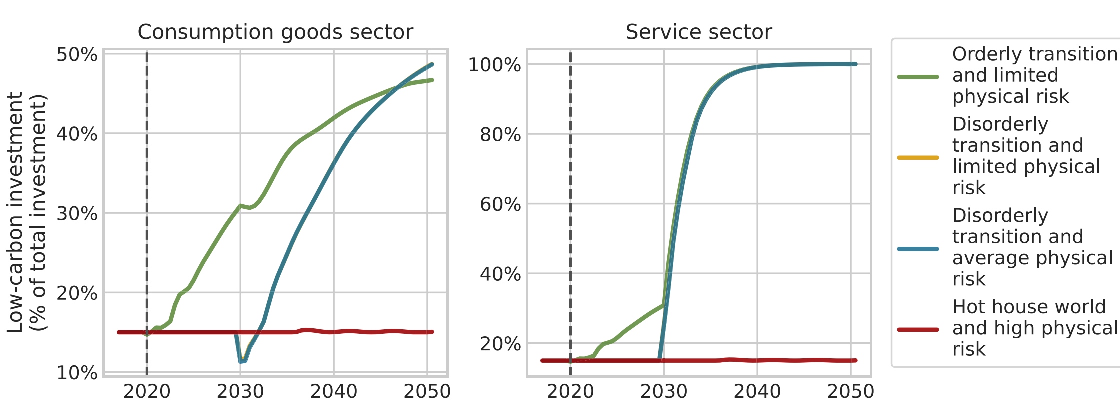


Fig. B.20. Reconstruction subsidies to GDP. The *x*-axis displays the simulation time, and the *y*-axis displays the ratio to GDP of government expenses dedicated to climate damage compensation, i.e. what the government spends in emergency relief to real economy sectors to compensate them for their losses due to climate physical shocks.

thus being another potential driver of inflationary dynamics (Schnabel, 2022).

In complement to the results on inflation, we represent in Fig. B.16 the price level in real terms of different categories of products. Interestingly, we see that consumption goods become cheaper in all transition scenarios, while they get more expensive in the hot house world scenario. One driver of this effect is the increasing need for capital replacement attributable to physical damages in the hot house world. In contrast, energy is relatively cheap in the hot house world scenario but expensive in both disorderly transition scenarios. This emphasizes that disorderly policies can harm consumers compared to an orderly implementation.

Next, we show in figure Fig. B.17 the evolution of stock prices by sector. Its most notable feature is the massive increase in the valuation of stocks issued by low-carbon firms (the energy and capital producers) in the transition scenarios. This is directly attributable to the increase in value added from these sectors, as represented in figure Fig. B.18, from which we can see that the growth differential between scenarios is mostly due to the low-carbon firms. Fig. B.19 shows how the investment in green capital by the consumption goods and service sectors increases in the transition scenarios. This higher investment is a main driver of the growth of the low-carbon sectors.

Finally, as the government takes part in the financing of reconstruction, following the materialization of climate physical risk, this takes a toll on its budget. Fig. B.20 shows that this cost remains stable as a proportion of GDP in the three transition scenarios. In contrast, the total cost of reconstruction subsidies keeps on increasing in the hot house world scenario, and it is likely to become even more of a burden for public finances beyond 2050.

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