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An analytical framework for assessing climate transition risks: an application to France

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Abstract

This paper proposes an analytical framework to quantify the impacts of climate transition narratives on a consistent set of macroeconomic, sectoral and financial variables required for financial risk assessment. Focusing on transition risks, our set-up relies on a suite of models, calibrated on the high-level reference scenarios of the Network for Greening the Financial System (NGFS). Its modular structure and variable coverage ensure a comprehensive assessment of the financial implications of disorderly transition scenarios to a low-carbon economy, from the identification of climate-sensitive sectors to the quantification of the impacts on financial metrics. An application to France evaluates the impacts on financial markets and credit risk parameters. Results indicate that the sectoral disruptions associated with a disorderly transition to a low-carbon economy can be substantial and translate in material financial risks. The study offers further grounds for encouraging policy-makers and financial institutions to support and prepare for an early and orderly transition.

Keywords Climate change · Central banking · Financial supervision · Scenario analysis · Financial stability

JEL Classification C60 · E44 · E50 · G32 · Q40 · Q54

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The views expressed in this paper are those of the authors and should not be interpreted as reflecting the views of the Banque de France, the Autorité de Contrôle Prudentiel et de Résolution (ACPR) or the European Central Bank.

1 Introduction

Climate change is likely to have severe impacts on the economy and the financial system, possibly posing risks to financial stability. This is acknowledged by the Network for Greening the Financial System (NGFS), a group of central banks and supervisors launched in 2017, which recommends "integrating climate-related risks into financial stability monitoring and micro-supervision" (NGFS, 2019), and by most standard-setting bodies. It identifies scenario analysis as an appropriate tool to explore the financial implications from climate change and the transition to a low carbon economy (NGFS, 2020b). To assess the stability of the financial system and highlight the possible weaknesses of the financial institutions, central banks and supervisors need plausible scenarios that are sufficiently adverse and detailed.

Focusing on transition risks, this paper presents an analytical framework to design transition scenarios for financial risk assessment.[1] While the NGFS has released a set of high-level climate scenarios to help integrate climate risks into financial stability monitoring and supervision, we go one step further, providing a method to compute the necessary disaggregated economic and financial information, since aggregate macroeconomic figures might hide sectoral and infra-sectoral shocks. Our framework allows estimating the impacts of transition risks on some key disaggregated variables, such as sectoral value added, equity prices, corporate credit spreads and probabilities of default for non-financial corporations (NFCs). It has been applied for the first time for the pilot exercise conducted by the *Autorité de Contrôle Prudentiel et de Résolution* (ACPR), the French supervisor, in 2020 and 2021.[2] In our application to France, results indicate that the financial risks related to a disorderly transition can be material when accounting for the sectoral disruptions that such a transition would entail. In both our "delayed" and "sudden" transition scenarios, we identify a number of winners and losers, pointing to the need of using granular infra-sectoral information to disentangle impacts. *Petroleum*, *Mining* and *Agriculture* are among the most impacted sectors in terms of value added, default probability and equity price whereas *Electricity* and more generally services sectors are less affected or may even gain from the transition.

The proposed analytical framework allows to make structured assumptions about different possible future pathways and to build hypothetical scenarios, typically with at least two options, such as a baseline scenario including commonly accepted assumptions and an alternative scenario. The modelling framework proposed here

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[1] Climate change-related financial risks are usually distinguished between those stemming from the transition to a low-carbon economy (transition risks) and those related to global warming and its associated climate disasters (physical risks).

[2] This early application explains why this paper builds on the NGFS Climate scenarios released in June 2020.

uses the NGFS set of reference scenarios as starting point to model key climate-economy relationships (NGFS, 2020a).[3] These scenarios provide key information on mitigation policies, emissions, temperature, the climate-energy-land transitions (e.g. Weyant 2017) and GDP for major economic areas with a time horizon extending until 2050. Financial stability assessments however require in addition more detailed information on key macro-financial variables at a more granular level.

In order to meet our financial stability-oriented objective, we deploy a suite-of-model approach that links climate-economy, macroeconomic, sectoral and financial modelling, capitalising on different streams of literature detailed below. The analytical framework developed in this paper includes a multi-country macroeconomic model, a sectoral model (accounting for 55 sectors), and various financial market modules providing infra-sectoral information (using corporate firm-level data). This choice is in line with suite-of-model approaches already implemented in the financial stability assessment literature, where macroeconomic variables are mapped into bank-related indicators using satellite or auxiliary models.[4]

Our modelling framework contributes to the literature on three aspects: by (i) providing an articulated and coherent assessment of climate transition impacts for financial stability, (ii) over an extended time horizon, (iii) at macroeconomic, financial, sectoral and firm-level. In doing so, we account both for multi-country macroeconomic dynamics, but also for more granular and uneven impacts on sector- and firm-level credit risk metrics. We thus identify sensitive sectors from a financial risk perspective as well as provide a full set of consistent projections of macroeconomic, sectoral and financial variables required for stress-testing exercises or scenario analysis. Our soft-linked modelling approach however does not allow to account for the possible retroaction from the financial sector to the macroeconomy highlighted in Battiston et al. (2021) and Battiston et al. (2021).

Related literature Initial work has mainly focused either on the wider macroeconomic impact of climate change or on specific sensitive sectors and individual markets (Harrison et al., 2003; Bosello et al., 2006; Ibarrarán et al., 2009).[5] Regarding financial stability implications, the potential for stranded assets to create market risk or credit risk has been another stream of work of earlier studies (Covington and Thamotheram, 2014). There has been since emerging research that takes these risks channels all the way through to the impact on individual institutions (BCBS, 2021).

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[3] In doing so, we rely on previously developed Integrated Assessment models (IAMs). See for instance REMIND-MAgPIE, MESSAGEix-GLOBIOM and GCAM. See the NGFS Technical documentation here for more details on these IAMs.

[4] See Foglia (2009). Stress-testing authorities typically rely on suite-of-model infrastructures linking a macroeconomic model to "satellite" models relating macroeconomic variables to variables measuring banks' asset quality. Macroeconomic models can either be structural (e.g. NiGEM in van den End et al. 2006; a DSGE model in Andersen et al. 2008) or VAR-based models (e.g. a standard VAR with macroeconomic variables in Jimenez and Mencia 2009; a Global VAR modelling cross-country interactions in Castren et al. 2010).

[5] Interesting exceptions include Heinkel et al. (2001) or Chava (2014), who reports for instance higher interest rates on loans to firms for which there are environmental concerns.

For instance, Jung et al. (2021) develop a stress testing procedure to test the impact of a climate stress scenario on expected capital shortfall, similarly concluding that sharp transition could lead to a substantial increase in financial risks but analysing impacts directly at financial firm level. This paper contributes to this stream of literature by assessing upstream real economy impacts along these transmission channels up to the financial implications for corporates. It however does not build on financial firms' data as it aims precisely to be used by these firms to run their own risk assessment.

Besides these early studies, the literature on the financial implications of climate change is rapidly expanding, with research related to scenario analysis on the one side, and on model development on the other side. The use of scenario analysis for climate-related financial risk assessment have been pioneered by studies based either on network approach (Battiston et al., 2017) or using a step-wise strategy similar to our approach (Vermeulen et al., 2018). These seminal studies highlight both the importance and uncertainties of conducting climate-related risk assessment, focusing over short-term horizons. While such short-term assessments are useful to check the resilience of financial institutions to nearer-term risks, analyses over longer horizons, as done in our approach, are necessary to identify the key vulnerabilities of the financial system to long-term changes.

As far as model development is concerned, a number of alternative or complementary modelling frameworks exist, including macroeconometric (ME) models, Computable General Equilibrium (CGE) models, Dynamic Stochastic General Equilibrium (DSGE) models, Agent-based models (ABM) and Stock Flow Consistent (SFC) models. Macroeconometric and semi-structural approaches take advantage of the large availability of economic data series.[6] However, ME models project future behaviours and expected changes using historical data, making them possibly less effective in detecting ruptures and disruptions (Fair, 2015). Aiming to design longer-term scenarios that consider the implications of an unprecedented climate transition, this paper needs to go beyond historical observations.

CGE models further disaggregate economic variables, by including multiple sectors and multiple countries, most often with an input–output representation of the production side. While they explicitly model agents' and markets' interactions, they remain mostly static as only a few dynamic versions currently exist (Babatunde et al., 2017). On the opposite side of the model spectrum, climate-extended DSGE models (often called Environmental-DSGEs) present the advantage of being both dynamic and micro-founded and of accounting for uncertainty and risks in dynamic environments. They have been designed to investigate specific issues like optimal environmental tax policy (Golosov et al., 2014), asset stranding (van der Ploeg and Rezai, 2020) or the interactions between environmental and monetary policies in the presence of nominal frictions (Annicchiarico and Di Dio, 2015). These models incorporate energy and associated emissions in both production and consumption but remain usually limited in the disaggregation of the impacts (for instance disentangling only green and non-green sectors) and focusing on a single country. Somewhat related to the previous type of modelling approaches, the G-Cubed model (McKibbin et al., 1992) offers more disaggregation at country and sectoral

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[6] See for instance E3ME, ThreeME and Nemesis.

levels for various transition policies, though remaining limited on financial stability indicators. Our approach aims to bridge the gaps between the various frameworks mentioned above by combining some of them, in particular CGE and semi-structural approaches. More precisely, the proposed framework combines macro-, sectoral-, firm-level models and financial modules to provide long to medium term transition impacts both at the macro level, but also disaggregated into sectoral and firm-level variables that then drive the impacts on financial variables and the financial stability diagnosis.

Last, ABM and SFC models can provide a relevant representation of phenomena such as imitation, contagion, dissemination and competition, which are relevant in the context of adaptation to climate change and assessment of financial impacts. They remain however difficult to calibrate, and the approach proposed in this paper focuses on more standard representations of individual behaviours.

The remainder of the paper is organized as follows. Section 2 explains the specificities of climate-related scenario analyses for financial stability assessment. Section 3 gives an overview of the modelling infrastructure and Sect. 4 presents the narratives of the selected scenarios and the results at macroeconomic, sectoral and infra-sectoral levels, as well as implications for financial variables. Section 5 discusses the limitations of the approach and concludes.

2 Scenarios for financial stability assessment: a very specific exercise

Scenario analysis has long been part of the financial sector toolkit for planning and risk management purposes. There are however a number of specificities and differences between traditional financial stress test scenarios and climate scenarios.

2.1 Understanding scenarios from a financial stability perspective

Central banks and supervisors have developed stress tests as an exercise to assess the adequacy of capital at individual (microprudential stress tests) or system-wide levels (macroprudential stress tests). These stress tests can be “top-down” (i.e. performed in-house by micro or macroprudential authorities) or “bottom-up” (in this case, financial actors assess themselves the impact of a set assumptions provided by the authorities and report back to the authorities). They are based on the design of scenarios that translate a set of adverse yet plausible events into their economic and financial implications. These scenarios usually include outcomes on key macroeconomic and financial variables, such as the GDP, inflation, unemployment, asset prices, or bond yields, and are supposed to be internally consistent (i.e., conditionally to the trajectory of the other variables) and focus on the “tail risks”, such as deep recessions or severe financial crises that could result in important credit and market losses at the level of financial institutions and systemic risks at the level of the financial system as a whole. For instance in a “bottom-up” approach to microprudential stress test, the set of variables that constitute the scenarios are usually provided by the regulator to the supervised entities, which then assess the impacts of these hypothetical changes on their risk parameters.

Scenarios also play a significant role in the analysis of climate change. However, these differ fundamentally - in both nature and usage - from financial stability-oriented scenarios. While the latter are meant to capture plausible but low probability adverse scenarios, climate scenarios revolve around the ideas of likely changes and desired outcomes. They represent probable future evolution profiles of greenhouse gas (GHG) concentrations and various adaptation/mitigation strategies associated with them (Carter et al., 2001). They tend to illustrate possible (and, in some case, aim to design optimal) pathways to achieve an overarching policy goal. The climate scenarios developed in this paper are however of a different kind. First, they rely on a number of plausible but hypothetically adverse assumptions designed for the purpose of assessing the resilience of the financial system. Second, as financial firms cannot integrate directly climate risk factors in their internal risks models (for assessing credit, market or counterparty risk), our analytical framework aims precisely to generate the associated economic and financial risk factors that can be introduced in their models to conduct of a climate-related financial risk assessment exercise.

Another challenge to be addressed is the severity of the transition risk scenarios. Policies yet to be implemented or potential changes in behaviours might be abrupt and happen in a disorderly manner. The stress therefore needs to be sufficiently severe to impact financial institutions and generate significant financial losses. On the other hand, over a 30-year horizon, financial firms will have time to adapt and change the structure of their portfolios and balance sheets, while fiscal policies, generally used to trigger the transition, will have distributional effects, dampening macroeconomic consequences. Overall, and by contrast with traditional stress-test exercises, the focus of these long term scenarios is more on the strategic adaptation of financial firms to transition risks than on their solvency risks.

2.2 The specificities of climate scenarios for financial risk assessment

Climate change-related stress test scenarios involve also some changes compared to the standard stress test framework defined above. First, a new diverse set of climate-related scenario drivers needs to be considered. Although some standard financial shocks, such as changes in asset prices or risk premia, may remain relevant, new factors may lead to financial tipping points for which financial institutions need to be prepared. These factors can relate to environmental conditions (e.g. weather events), longer-term physical impacts (e.g. impacts on infrastructure), climate policy (e.g. change in carbon pricing or regulation), technology (the development of renewable sources of energy) or change in consumers' or investors' sentiments.

Second, scenarios in standard stress-testing exercises are typically calibrated on past negative events, such as severe financial crises, while there is no precedent from historical experience for climate change-related scenarios. Climate change could represent a regime shift, such that historical observations would offer limited guidance.

Third, stress-testing financial institutions requires a forward-looking analysis that typically does not expand beyond 3–5 years. On the contrary, climate change-related exercises may require to conduct assessments over longer-term horizons because of the possible long run dimension of both transition processes and the physical materialisation of climate change. Although the horizon may be expanded compared to standard stress tests, climate change-related analyses should also integrate short- to medium-term effects. The transition to a low-carbon economy could happen sooner than expected, especially if forward-looking asset prices suddenly change in response to shifts in expectations or sentiment about the transition path. Short-term shifts in market sentiment induced by awareness of future climate risks could also lead to economic shocks.

Finally, climate change analyses need a much higher level of disaggregation than standard stress test scenarios. Usual stress tests have often focused on macro-financial aggregates. For climate-related risks, it is important to study effects at least at the sectoral level. As a general principle, industries that emit a high amount of CO_2 and cannot easily substitute high-carbon energy inputs, or fossil fuel producers will be more severely hit if a price is imposed on carbon emissions. Yet, even within sectors, some actors might be more advanced than others and able to benefit earlier than others from the induced changes.

Initial approaches to climate change-related stress test had focused, at best, on cross-sector comparisons and exploring only recently infra-sectoral dynamics as data became more available (FSB/NGFS, 2022). This is an important improvement as companies are increasingly challenged for action on climate change. Some have already strategically invested in emerging related markets. Others are financially very robust and benefit from financial resources that could be invested in new activities better aligned with the transition. These individual climate strategies and financial capacities can significantly influence their vulnerability to climate change within a particular industry and their associated risks. In this paper, on top of a sectoral disaggregation, the impacts on the probabilities of default are estimated at infra-sectoral level using corporate firm-level data. From a financial stress test perspective, this is especially relevant as the low carbon transition might imply an overall reduction of demand, as only the actors most advanced in the transition would efficiently operate in the sector while others would fail as the overall capacity of the sector adjusts downwards.[7]

2.3 Minimum key requirements for financial risk assessment

While climate-related financial risk assessments call for a number of adjustments to be implemented as explained above, scenarios need also to meet the usual

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[7] For physical risks, disaggregation may also be a required feature. As climate change is producing differentiated impacts at the local level, it is important to consider the location of the underlying assets that can be exposed to extreme events (or indirectly, be impaired by deteriorations to nearby infrastructures) or suffer from chronic disruptions (for instance, in the availability of natural resources).

requirements regarding macroeconomic and financial variables. This implies providing a wide spectrum of information, from policy measures and transition features to macroeconomic and financial metrics, some required to be disaggregated by sector. These variables can be global or country-specific. Table 1 provides an overview of some of the key variables required following discussions with banks and insurance companies.

These variables provide the magnitude of the shocks that will characterize the adverse scenarios. Given the wide-ranging number of variables required (including economic and financial as well as climate or energy-specific variables), multiple models or the integration of separate modules are necessary to translate the narratives into the full set of variables. Some of these variables, in particular regarding climate and transition, are available from the NGFS scenario dataset released in June 2020. A number of macroeconomic, sectoral and financial variables were missing at the time of this analysis.[8] The next section will present the modelling suite proposed to recover this information in a consistent approach with the NGFS framework. Please note that the proposed framework focuses on transition risks.

3 The modelling approach

Climate-related scenarios require the projections of a larger number of macro-financial variables over longer time horizons and entail a more granular sectoral disaggregation compared to usual stress testing exercise. Similarly to more conventional exercises, the approach followed here relies on a suite of models, which translates transition scenarios generated from climate models into macroeconomic, sectoral and financial variables.

Figure 1 illustrates the modelling strategy, which relies on a set of tools linked together in a modular approach. It combines climate-economy models – the so-called Integrated Assessment Models (IAMs), a multi-country macroeconomic model – NiGEM, a sectoral model specifically developed,[9] the rating model of the Banque de France and a set of financial modules.

It is worth pointing out that our suite of models can be seen as a cascade of tools going from the most comprehensive models to more specific modules. In other words, each tool disaggregates downstream one aspect already included implicitly in the previous ones. For instance, the IAMs include macroeconomic impacts that are only summarised in GDP trajectories. The macroeconomic model therefore disaggregates these overall impacts into additional variables. In the same spirit, the sectoral model declines the previous results by providing sectoral details and the financial modules give firm-level or market-level information consistent with the upper levels of the cascade. A number of checks ensure consistency across the various models involved. Notably, we apply to all of them the same carbon price trajectories and

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[8] The NGFS has since been updating and improving its reference scenarios published in June 2020, with complementary information in particular on macroeconomic impacts. Most of the sectoral and many of financial variables presented in this paper are still not provided on the NGFS Scenario portal.

[9] See Devulder and Lisack (2020) for more details.

Table 1 List of some key required variables for a climate-related financial risk assessment

General climate variables
Emission pathways (aggregate and disaggregated by region and sector)
Global and regional temperature pathways
Physical risk variables
Frequency and severity of climate-related perils, by region (for non-life insurance)
Mortality / morbidity parameters (for life insurance)
Transition risk variables
Carbon price pathways
Commodity and energy prices, by energy source
Energy mix
Economic variables
GDP (aggregate and disaggregated by region and sector)
Inflation rates
Unemployment rates
Interest rates (short, long, risk-free)
Exchange rates
Public finance information (debt and deficit)
Financial variables
Government bond prices
Corporate bond prices (disaggregated by sector)
Equity prices (disaggregated by sector)

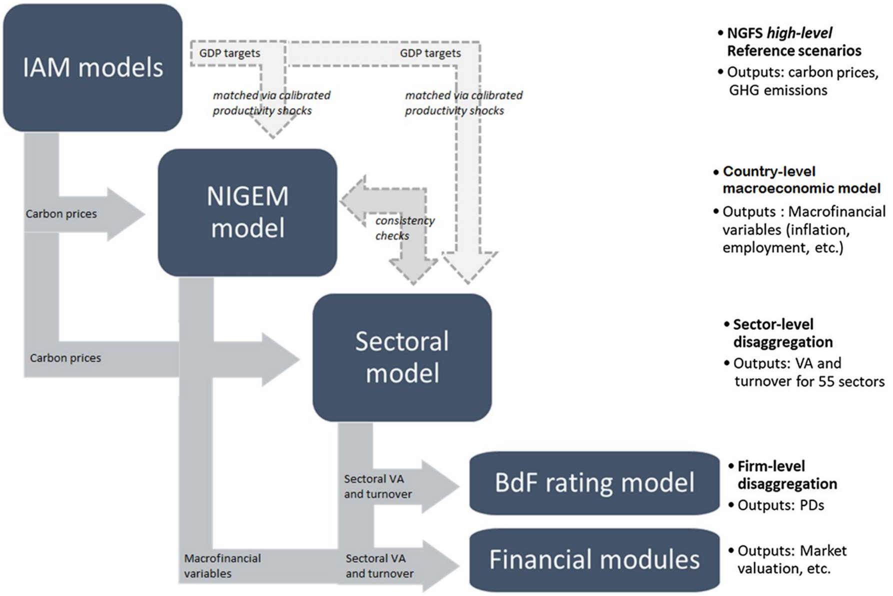

Fig. 1 The modelling architecture

impose that the GDP paths obtained from NiGEM and the sectoral model's aggregated GDP trajectory are identical those from IAMs (using productivity shocks), except in the sudden transition scenario where we depart from IAMs (see Sect. 4.1). We also impose that the tax receipts redistribution is as similar as possible across IAMs, NiGEM and the sectoral model. Lastly, the rating model and the financial modules also rely on the aggregate macro-finance variables and the sectoral value added and turnover obtained from NiGEM and the sectoral model, ensuring that their results (default probabilities, market valuation, etc.) appropriately account for the carbon price and productivity paths.

This section will focus on the presentation of the economic and financial modules developed to assess the final impact on credit risks and market risks.

3.1 Projecting macroeconomic impacts

The initial input comes from the IAMs used to derive the NGFS high-level scenarios. These models provide GDP trajectories,[10] carbon prices and GHG emissions for a number of country blocks (including the EU and the USA). The carbon prices trajectories are used as inputs to set the carbon tax rates in the macroeconomic model, as well as in the sectoral model (see Appendix I for more details on the models coupling).

Most of the macroeconomic variables used in the scenarios are simulated using NiGEM (National institute Global Econometric Model).[11] NiGEM is a global macroeconomic model consisting of individual country models of New Keynesian structure (see Hantzsche et al. (2018) or Barrell et al. (2004) for a detailed introduction). Each country/region is modelled through a dynamic set of equations where agents are generally assumed to have rational expectations.[12] There are also nominal rigidities that slow the process of adjustment to external shocks. Importantly, each country model has a well-specified supply side over the medium term, through a Cobb-Douglas production function that includes capital, labour and energy as inputs. International linkages come from patterns of trade, asset holdings, and the impacts of trade prices and exchange rates on domestic prices. NiGEM's country coverage is quite extensive in that all OECD countries are modelled individually, as well as some large emerging countries, while the rest of the world is modelled through regional blocks. This detailed country coverage allows us to single out France from the other EU countries, derive GDP trajectories compatible with the NGFS regional projections and define other country blocks in a flexible manner. The extensive country coverage of NiGEM as well as its endogenous monetary policy reaction function were among the main reasons justifying our

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[10] The 2020 edition of the NGFS climate scenarios provide information on prices and production for a few sectors, such as agriculture or energy, but no information on Value Added by sector.

[11] NiGEM has been developed by the National Institute of Economic and Social Research (NIESR). More details at: https://nimodel.niesr.ac.uk/.

[12] The model can also be solved for adaptive expectations, which has been used here for computational reasons.

choice of using this model, other than those traditionnally used in France for climate transition assessment.[13]

Although NiGEM is not a climate model, it has benefited from extensions to simulate macroeconomic scenarios for climate transition analysis, mostly associated with public policy action (e.g. carbon tax or border tax adjustment). It was thus particularly appropriate for the purpose of this exercise, complementing the sectoral model with a more refined analysis of demand factors (impact on consumer prices, on public spending) as well as dynamic features allowing to provide long-term trajectories.[14] Note that the production function in NiGEM has a Cobb-Douglas functional form, comprising an energy bundle with fixed shares (see Appendix A). We acknowledge that this is not ideal to study the climate transition and change in energy mix, which is why we use NiGEM in combination with the sectoral model, which has a CES production function (see Section 3.2), or with one of the IAMs used in NGFS scenarios, each time aligning production with either one of the two models through productivity shocks (see the beginning of this section for details on the coupling of models). Finally, the international exposure of global systemically important banks' portfolio requires a global coverage that NiGEM is able to provide, as well as a number of variables other than GDP (inflation, interest rates, public deficits, etc.).

Carbon tax and prices of fossil fuels

Carbon emissions associated with the production process can be introduced in this framework through each country's usage of fossil fuels. Aggregate supply in NiGEM's individual country models is based on a production function with three factor inputs: labour, capital and energy.[15] Energy is decomposed into the three main types of fossil fuels (oil, coal and gas) as well as renewable energy.

Prices of fossil fuels are determined at the international level and depend, among other variables, on world demand for each fossil fuel. Carbon tax is introduced by increasing a country's price so that the effective price of fossil fuel F in country X, P_{XF}, is equal to the international price of the fossil fuel, P_F, plus an extra element representing the country's carbon tax levied on the fossil fuel, CB_{XF}.

$$P_{XF} = P_F + \delta_F CB_{XF}$$

where δ_F is the CO_2 produced per barrel-equivalent of fossil fuel F.

This effective price will then feed into each country's demand for fossil fuel, allowing it to respond to the tax as well as to changes in international prices, which depend on the world demand for fossil fuel. In our exercise, the tax on fossil energy

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[13] Imaclim-R, NEMESIS and Three-ME cover either France only or the EU countries and not the rest of the world. Moreover all three models do not model interest rates using a monetary policy reaction function.

[14] The model version used in this exercise is *v4.19-climate* We thank the team at the NIESR for allowing us to work on this preliminary version of their "climate model extension" at the time when this work was initiated.

[15] See Allen et al. (2020) and Hantzsche et al. (2018) for details.

is calibrated according to a predetermined path of carbon price, the calibration being based on the amount of CO_2 emissions released when burning one unit of fossil fuel. This follows Vermeulen et al. (2018), who use this approach to carry out the DNB's energy risk transition stress tests.[16]

Pass-through to consumer prices

Other than firms' demand for fossil energy in the production process, the carbon tax will also affect consumer demand: first directly through its impact on gasoline prices and later indirectly through its general impact on consumer prices (*second round effects*). In the version of the model used for this exercise, the carbon tax on consumers is introduced in the NiGEM model through an increase in the price of imported fossil fuels once they are consumed in the country (the *effective* price of the imported fossil fuel) in order to exploit the existing pass-through mechanisms of the model for fossil-fuel importing countries like France.[17]

Redistribution of tax proceeds and monetary policy

While the carbon tax has been modelled through an increase in prices of fossil fuels, it also constitutes a source of revenue for the government. An additional step has therefore been added to the standard model to calculate tax proceeds that reflect the specific tax applied by each country as well as the country's current consumption of fossil fuel. Since energy intensity is endogenous in the model, tax proceeds are dynamic and, for a constant level of tax, decrease over time because of the subsequent decrease in the country's demand for fossil fuel. By default, NiGEM includes an automatic fiscal solvency rule that redirects tax proceeds towards the deficit. This rule has been deactivated in our simulations in order to (i) allow for flexibility in the redistribution of tax revenue, and (ii) obtain the effect of the economic simulations on public finances without any further public policy action. In our case, we assume that the tax proceeds are redistributed through a decrease in households' income tax rate, which, in terms of fiscal multiplier in the model, is on the low end of the spectrum of fiscal policies (see de Walque et al. (2015) for a discussion of fiscal multipliers in Euro area countries, including France). Moreover, redistributing the carbon tax through a decrease in the cost of labour (social security contributions here), which is a commonly-used scheme in the carbon tax literature, has a higher multiplier in the model than a change in the household income tax rate. We choose the conservative approach of redistributing the carbon tax proceeds through a channel having among the lowest multipliers in the model in order to present more adverse scenarios in line with our objective of financial risk assessment.

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[16] We use the same calibration as Vermeulen et al. (2018) in terms of CO_2 emissions per barrel or oil-equivalent barrel of fossil fuel burnt, namely 432 kgs for oil, 653 kgs for coal and 316 kgs for gas. A unit conversion coefficient is included to take into account the different unit measures of fossil fuels.

[17] The increase in consumer prices will depend on each country's share of oil, for instance, in its imported consumption basket, see price equation in Appendix A.

Finally, in our scenario simulations, monetary policy is endogenous and therefore reacts to changes in GDP and inflation according to a specific reaction function.[18] Since the shocks simulated are mainly supply shocks with large inflationary effects, monetary policy mainly reflects inflationary developments and interest rates tend to increase despite the contraction in GDP in some adverse scenarios. This has been mitigated through adjustments in the coefficients of the reaction function to account for the fact that central banks tend to look through increases in energy prices when determining their policy stance. Although we make this choice in this simulation exercise, we acknowledge that the issue of optimal monetary reaction in climate transition scenarios is far from resolved and would require further research (see Diluiso et al. (2021)). On the one hand, subsequent scenario simulations within the NGFS framework have shown a relatively low sensitivity of macroeconomic impacts to the choice of the monetary reaction function in NiGEM when working under rational expectations (NGFS, 2022).[19] On the other hand, although the scenarios we model here generally involve an increase in inflation, the inflationary impact of transition scenarios and the subsequent monetary policy trade-off are not clear-cut in the literature on climate transition (see Dees et al. 2023).

3.2 Projecting sectoral impacts

The macroeconomic results from NiGEM are coupled with a multi-country multi-sector framework that gives a disaggregated picture of the economy for a flexibly adjustable number of country blocks/regions (here: France, Rest of the EU, USA and Rest of the World).

The sectoral model is a slightly adjusted version of the work by Devulder and Lisack (2020). It builds on the production network literature developed, among others, by Baqaee and Farhi (2019) and follows the work of Hebbink et al. (2018). As detailed below, the model accounts for carbon taxation in a more detailed fashion than NiGEM, since it features carbon taxes not only on fossil fuel consumption, but also on GHG emissions inherent to the production process (e.g. methane for agriculture).

Our framework features a production network model calibrated using a global input–output matrix to represent the production in each sector in each country as a process involving non-energy and energy intermediate inputs from all countries and domestic labour. All these inputs are substitutable to various degrees, and the

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[18] We use a default two-pillar rule in the model, where the policy rate depends on nominal GDP and inflation:

$$i_t = \gamma i_{t-1} + (1-\gamma)\left(-\alpha \ln\left(\frac{NOM_t^*}{NOM_t}\right) + \beta^i\left(inf_{t+1} - inf_{t+1}^*\right)\right)$$

where i is the short-term nominal interest rate, NOM is nominal output, NOM^* is a specified target for nominal output, inf is inflation expectations and inf^* is the inflation target. The adjustments made were to reduce the inflation coefficient, γ, from 0.7 to 0.2, and to increase inertia by increasing β from 0.5 to 0.9.

[19] This contrasts with the results of Vermeulen et al. (2018) who show the important effects of monetary policy reaction on fixed income assets. This is because NiGEM does not include endogenous risk premiums which would account for a differentiated impact on fixed income assets.

producing firms optimise their intermediate demands given the relative prices of inputs in a perfectly competitive environment. The model is then closed to form a general equilibrium set-up by adding a representative household in each country, which supplies labour inelastically in a frictionless domestic labour market and consumes goods from all countries.

More specifically, in each sector i a representative firm produces a quantity Q_i from labour L_i and intermediate consumptions Z_{ji}, (corresponding to energy inputs for $j \leq N_E$ and to other intermediate inputs for $N_E < j \leq N$, where N is the total number of sectors in the world), using the following CES technology with sector-specific input shares and exogenous sector-specific total factor productivity (TFP) A_i :

$$Q_i = A_i \left(\mu_i^{\frac{1}{\theta}} L_i^{\frac{\theta-1}{\theta}} + \alpha_{Ei}^{\frac{1}{\theta}} E_i^{\frac{\theta-1}{\theta}} + \alpha_{Ii}^{\frac{1}{\theta}} I_i^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}}$$

where:

$$E_i = \left(\sum_{j=1}^{N_E} \left(\frac{\alpha_{ji}}{\alpha_{Ei}} \right)^{\frac{1}{\sigma}} Z_{ji}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}$$

$$I_i = \left(\sum_{j=N_E+1}^{N} \left(\frac{\alpha_{ji}}{\alpha_{Ii}} \right)^{\frac{1}{\epsilon}} Z_{ji}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}$$

Firm i maximises its profit, which can be written as follows:

$$\max_{L_i, Z_{ji}} \pi_i = P_i(1 - \tau_i)Q_i - wL_i - \sum_{j=1}^{N} P_j(1 + \zeta_{ji})Z_{ji}$$

subject to its production technology. In this expression, w is the wage rate in the country where firm i is located, and τ_i and ζ_{ji} are taxes on production and fossil fuel inputs entering as expenditures and described below.

Within this framework, we impose sector-specific carbon taxes proportional to sectoral GHG emissions and declined into three types of taxes. The first type of tax is linked to firm's GHG emissions *excluding* CO_2. It consists in a tax on each sector i's production, proportional to non-CO_2 GHG emissions inherent to its production process (for instance, methane emitted by cows in the agricultural sector). The corresponding tax rate is denoted by τ_i, so sector i's production tax amounts to $\tau_i P_i Q_i$, where P_i is its selling price. Second, each producer pays a tax on its intermediate consumption of refined oil and coke, proportional to its CO_2 emissions (using again the example of the agricultural sector, this is a tax on the gas needed to operate tractors). Let ζ_{ji} be the tax rate on intermediate inputs from sector j entering in sector i's production. Firm i pays $\sum_{j=1}^{N} P_j \zeta_{ji} Z_{ji}$ as taxes on its consumption of intermediate inputs, where all ζ_{ji} corresponding to sectors j other than fossil fuels producers are zero.[20]

Last, the representative household maximizes a CES utility function subject to a budget constraint. Each household pays a tax (at a rate κ) on his consumption of refined oil and coke that is proportional to the households' emissions of GHG - both CO_2 and non-CO_2 (e.g., a tax paid by a household on gas used for their car).

The model assumes perfect international risk-sharing: households trade bonds internationally so that country specific shocks affect households' revenues abroad. All tax proceeds are redistributed as a lump-sum transfer to the household of the country where they are levied to be consistent with what is implemented in NiGEM. Appendix B presents in more details the maximisation programs of the agents and their first-order conditions.

For simplicity, this sectoral framework abstracts from capital and investment. While these variables are key to the low-carbon transition, including them in the sectoral model would have raised a range of issues, notably related to the consistency with investment movements in Nigem, the good composition of the investment bundle specific to each investing sector, and substantially complicate the sectoral model by turning our static set-up into a dynamic one. Given these drawbacks, we decided not to include investment in the sectoral model. Consequently, the impact we obtain for specific investment sectors like cement or construction may be a lower bound, however impacts for other sectors would probably not be very different.

The shares of the inputs used for production in each sector (parameters αs and μs), the relative sizes of the sectors and the shares of the goods in the final consumption are calibrated to match sectoral input–output and final consumption data from the World Input Output Database (WIOD).[21,22] The values of the substitution elasticities θ, σ and ϵ are obtained from the literature (see Appendix C for their calibration and Devulder and Lisack 2020, for a sensitivity analysis). In the selected scenarios, taxes are implemented in all countries. The tax calibration strategy is proportional to the sectoral carbon intensity and is exposed in more details in Appendix D.

To ensure that the coupling with NiGEM is done in a consistent way, we try to match its assumptions as much as possible. The carbon price path applied in the two models is the same, and the tax proceeds are fully redistributed to the households in both models. Since the economic mechanisms embedded in NiGEM and in the sectoral model may differ, we make sure that results are consistent at the macro level

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[20] In this framework, both taxes τ and κ are applied to the value of fossil fuel consumption and not to the quantities consumed. However, robustness checks show that applying them to quantities would not significantly change the results, both at the aggregate and sectoral levels.

[21] World Input Output Database, see Timmer et al. (2015). The sectoral classification is from NACE rev.2 and encompasses 55 sectors per country. The final consumption shares are obtained by grouping all types of final demand reported in the data (household, non-profit organisations and government consumption, GFCF and change in inventories).

[22] The input shares (αs and μs) are fixed in our model, which partially rules out technological change, as the only adjustment possible is via substitution without deep modifications in the production process. We considered the possibility of modifying these shares to allow for innovation over the long run. However, looking at the WIOD data over the entire available time period (2000 to 2014), there was no clear time-trend for the input shares, even when focusing specifically on energy inputs. For this reason, we preferred to keep the αs and μs fixed and have a clean substitution effect due to relative prices only.

by matching real GDP impacts (in % deviation from the baseline) from the latter with the real GDP impacts from the former, at the country level. This is achieved by calibrating the country-wide TFP shocks either in the sectoral model through changes in A_is imposed to be identical for all sectors i located in the same country, or in NiGEM, depending on the scenario.

Given that the main purpose of the sectoral model is to provide a sectoral disaggregation of the country-level results obtained from NiGEM, and that the TFP shocks are homogeneous within sectors of a same country, this matching procedure has a limited impact on the results in terms of sectoral heterogeneity. It mostly shifts upwards or downwards all sectoral impacts within a country. Furthermore, the key information that the sectoral model provides to the rating model and financial modules resides in the sectoral dispersion of real value added and real turnover, while the aggregate value added impact is determined from NiGEM at the country-level. Hence the country-level TFP calibration in the sectoral model only marginally affects the sectoral dispersion – and thus the financial stability results.

3.3 Projecting financial impacts

The coupled macroeconomic and sectoral models described above are complemented with three financial models. The first two are designed to capture the implications of the scenarios on non-financial corporations (hereafter, NFC) credit risks and the last one on the market value of financial assets.

3.3.1 Projecting probabilities of default

The first financial model introduced in the infrastructure is the Banque de France's rating model used to assess credit risk at the firm level. Outputs from the sectoral model are plugged into the Banque de France's rating model to assess and further disaggregate impacts on firms' probabilities of default (PDs). Figure 2 provides a synthetic picture of the transmission process. The financial rating procedure is based on the analysis of key financial ratios, R. Simulated sectoral shocks, S, are transmitted through key financial aggregates to financial ratios, namely liquidity, financial autonomy, profitability, financial structure. As each ratio is assigned to a single financial theme, the sectoral shocks are transmitted to theme-based categorical variables. The latter are then used in a logistic regression to estimate the impacts on the PDs, which in turn can modify the assigned *Statistical Financial Rating*.[23]

The main default variable is the one-year horizon binary default, which complies with Eurosystem standards and is consistent with the definition given by the Basel Committee.[24] The binary default is defined as:

$$d_i^t = \begin{cases} 1 & \text{if firm } i \text{ defaults during year } t \\ 0 & \text{otherwise} \end{cases}$$

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[23] See Appendix G for details on the transmission channels.

[24] See Appendix E for details on the default definition.

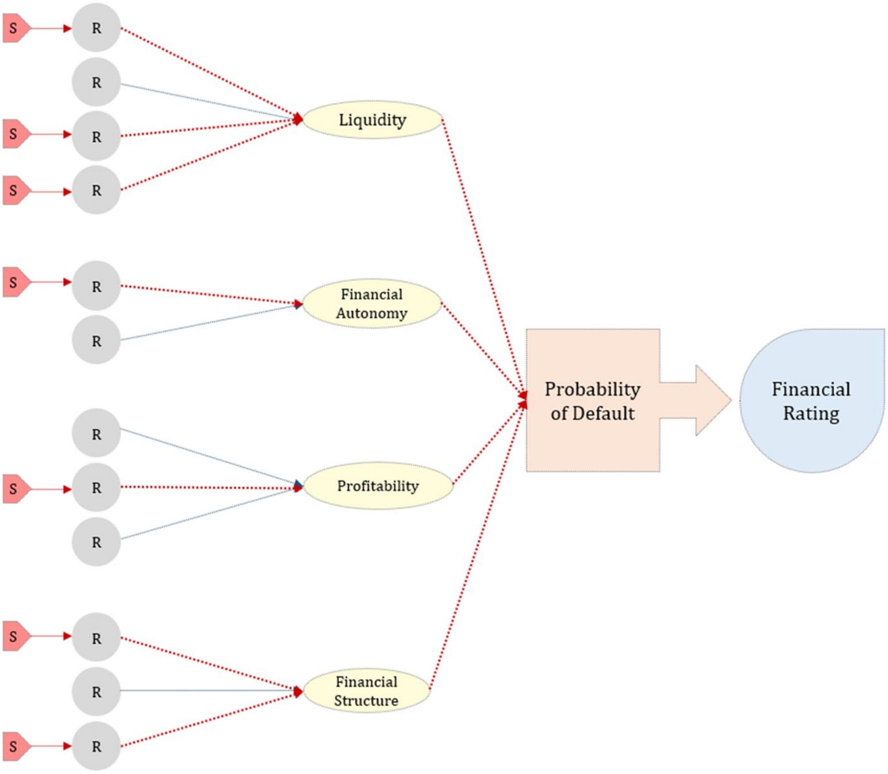

Fig. 2 Overview of the transmission mechanism through the financial rating model

where d_i is the realisation of a random variable D that takes the value 1 with probability $1 - \pi$, and 0 with probability π. The variable D follows a Bernoulli distribution with parameter π, defined by:

$$P\{D = d_i\} = \pi^{1-d_i}(1 - \pi)^{d_i}$$

We estimate the default probability π conditionally on a vector of observed covariates X_i:

$$P(D = 1|X_i) = 1 - \pi(X_i) = E(D|X_i)$$

The estimation of probabilities of default is performed on a macro-sector basis, using a logistic model and the theme-based categorical variables as explanatory variables as follows:[25]

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[25] Only the non-defaulted entities at the beginning of each year are kept, and all firms are clustered into seven macro-sectors.

$$P(D = 1|X_i) = 1 - \pi = \frac{1}{1 + exp(\beta_0 + X_i\beta)}$$

where (β_0,β) are the parameters of the logistic regression and X_i represents the theme-based categorical variables for firm i.

The model uses yearly firm accounting data from the FIBEN database hosted at Banque de France, which is based on firms' accounting statements, supplier and customer trade bill payment incidents, bank loans reported by credit institutions and firm legal information. Payment default data come from the French National Central Credit Register (CCR) operated by the Banque de France.[26] See more details on the Banque de France's rating model in Appendix F and in Auria et al. (2016).

3.3.2 Projecting corporate credit spreads

The second financial model that captures the implications of the scenarios on the credit risk exposure of NFC is a projection tool for corporate credit spreads. Corporate credit spreads are constructed and projected for each of the relevant scenarios, countries and economic sectors, by exploiting the projections of PDs (for France) from the Banque de France's rating model, and historical data from the Risk Management Institute (RMI) of the National University of Singapore (for all countries or economic areas of interest).[27] The RMI provides monthly PDs data with observations starting, in general, at the beginning of the 1990's and with default horizons τ from 1 month to 5 years. They consider several economic areas, countries and BICS (Bloomberg Industry Classification Standard) economic sectors, and PDs are calculated following the methodology of Duan et al. (2012), generalizing the approach of Duffie et al. (2007).

The credit spread of any country m and sector i at maturity τ, denoted $CS_i^{(m)}(\tau)$, is calculated using the following formula (see, among others, Merton (1974), Black and Cox (1976), Chen et al. (2009) and Feldhutter and Schaefer (2018)):

$$CS_i^{(m)}(\tau) = -\frac{1}{\tau} \ln \left[1 - (1 - RR)N\left(N^{-1}(PD_i^{(m)}(\tau)) + \theta\sqrt{\tau}\right)\right], \tag{1}$$

where $PD_i^{(m)}(\tau)$ is the (historical) default probability for the same country, sector and maturity, $N(.)$ is the cumulative distribution function of a centered and normalized Gaussian distribution; θ is the asset Sharpe ratio fixed at an average level of 0.22 (as

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[26] CCR covers extensively bank exposures to firms on a bank-firm level on a monthly basis.

[27] Given the different definition of default adopted by the Banque de France's rating model and the RMI (see Appendix E for further details), the projections of the 1-year default probabilities of the former have been rescaled in order to match the observations provided by the latter. In addition, while Banque de France's projections cover 55 sectors, the RMI provides time series of default probabilities for 11 BICS (Bloomberg Industry Classification Standard) sectors. We have merged NACE into BICS sectors in order to have the projections of 1-year default probabilities compatible with the observations (details are available upon request from the authors).

empirically suggested by Chen et al. (2009))[28] and RR is the recovery rate assumed constant at 40%. We focus on maturities 1 year, 2 years, 3 years and 5 years, for any given relevant country and economic sector. The projections, for each scenario, of the 1-year maturity credit spreads are calculated from (1) using (for France) and mimicking (for the other countries or economic areas) the projections of the 1-year PDs of the Banque de France's rating model presented above. Given those scenario-based projections of 1-year credit spreads, the projections of the remaining (longer) maturities are obtained in the following way (see also Fig. 11 in Appendix H):

(*i*) for any given country, we estimate a Gaussian VAR(1) process on the state vector $X_t^{(m)} = (M_t^{(m)}, Y_t^{(m)}, CS_t^{(m)})'$, where $M_t^{(m)} = (g_t^{(m)}, \pi_t^{(m)})'$ denotes the vector of country-m macroeconomic variables (year-on-year GDP growth and inflation rate, respectively), $Y_t^{(m)} = (Y_t^{(m)}(6m), Y_t^{(m)}(1y), Y_t^{(m)}(3y), Y_t^{(m)}(5y), Y_t^{(m)}(7y), Y_t^{(m)}(10y))'$ is the vector of country-m sovereign yields with maturities from 6 months to 10 years, while $CS_t^{(m)} = (CS_{t,1}^{(m)}, \dots, CS_{t,I}^{(m)})'$ presents the corporate credit spreads of the I BICS sectors in country m, with $CS_{t,i}^{(m)} = (CS_{t,i}^{(m)}(1y),\ CS_{t,i}^{(m)}(2y),\ CS_{t,i}^{(m)}(3y),\ CS_{t,i}^{(m)}(5y))'$ collecting the credit spreads of the sector i for any relevant maturity;

(*ii*) the sample period is January 1993–December 2019 for France and US, while for the rest of EU countries and Japan the sample period starts in January 1999 and January 1996, respectively;

(*iii*) given the future path, from January 2020 to December 2050, of the observable variables $g_t^{(m)}$ and $\pi_t^{(m)}$ (obtained from NiGEM) and of $CS_{i,m}(1y)$ for any sector $i \in \{1, \dots, I\}$ (obtained exploiting the projections provided by the Banque de France rating model), we calculate the conditional forecasts (projections) of the credit spreads for the remaining maturities and over the same path-like period, using the methodology of Waggoner and Zha (1999).

3.3.3 Projecting dividend streams and asset prices

Finally, our infrastructure is completed with a last financial module, which determines scenario-based asset prices consistently with the other macroeconomic and sectoral information. This module uses a Dividend Discount Model (DDM), to calculate stock prices as the sum of discounted scenario-based dividend streams for each industry and country (or economic area). We assume here that the share of distributed dividends represents 50% of the return on capital and that the latter corresponds to 33% of the gross value-added. Indeed, exploiting yearly observations, from 1993 to 2020, on national accounts of French financial and non-financial

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[28] The average Sharpe ratio of the representative firm is approximately one-half the value of the Sharpe ratio for the market portfolio, given that the average firm volatility is approximately twice the level of the market volatility (see Chen et al. (2009) for further details).

institutions (provided by the INSEE), we find that distributed dividends represent on average 16.7% of gross value-added, which is consistent with our assumption. We therefore consider in this section that distributed dividends represent 16.5% of gross value-added projections (by sector and country) computed by the sectoral model for each scenario. The associated dividend stream is then discounted in our DDM using, for all economic areas, sectors and projection horizons, a discounting rate given by the average index stock return (calculated over the periods January 2001–December 2019) of the country (or area) increased by a projection of a sector-specific risk-correction component mimicking the behavior of the corporate credit spread of the same sector. In other words, we assess the relative stock price change in 2020 as if investors were reevaluating their anticipated dividend stream taking into account the new information associated with the two adverse scenarios (compared to the baseline).

More formally, for a given scenario, we have a country-m and sector-i dividend stream ($D_{i,m}(2025),...,D_{i,m}(2050)$), with:

$$D_{i,m}(t) = 0,5 \times (0,33 \times VA_{i,m}(t))$$

where $VA_{i,m}(t)$ is the projection at date t of the value added of the country m and sector i. The associated time-varying and scenario-based discount factor over the period (s, t) is denoted $(R_{i,m}(s,t))^{-1}$, with $R_{i,m}(s,t) = 1 + \bar{r}_m + rp_{i,m}(s,t)$, where $\bar{r}_m$ is the average index stock return of country m, while $rp_{i,m}(s,t)$ is the relevant risk-premium component. The value of the stock at date $s = 2020$ (the evaluation date) is therefore given by:

$$\begin{aligned} P_{i,m}(2020) = {} & D_{i,m}(2025) \times \left(R_{i,m}(2020, 2025)\right)^{-1} + \dots \\ & + D_{i,m}(2045) \times \left(R_{i,m}(2020, 2045)\right)^{-1} \\ & + \left[\frac{D_{i,m}(2050)}{R_{i,m}(2049, 2050) - 1 - g}\right] \times \left(R_{i,m}(2020, 2050)\right)^{-1}, \end{aligned}$$

where g is the dividend growth rate fixed at one-half the (scenario-based) index stock return (as empirically suggested by Ang and Liu (2004) and Maio and Santa-Clara (2015)). From the last term of the pricing formula, we also observe that the dividend payment $D_{i,m}(2050)$ is assumed constant from 2050 onward and the associated discounting (in 2050) is obtained using the last available yearly discount factor $R_{i,m}(2049, 2050)$.

4 The macroeconomic, sectoral and financial impacts: An application to France

This section presents the application of our analytical framework to a selection of NGFS scenarios, namely a baseline scenario and two adverse variants covering different disorderly transition narratives. Results show the importance of conducting the analysis at a granular sectoral level of analysis. Because this application focuses on France and for simplicity, the world is divided into four blocks of countries/regions: France, the Rest of the EU (RoEU), the USA and the Rest of the world (RoW).

4.1 The selected transition narratives

Building on the NGFS reference scenarios,[29] three narratives focusing on transition risks have been selected. The set of scenarios includes a baseline and two progressively more adverse variants spanning from 2020 to 2050. The two variants reflect different assumptions about the likelihood and timing of government actions, as well as technological developments and their spillover effects on productivity.

More precisely, the proposed scenarios combine assumptions related to: (i) the introduction of a public policy measure (a higher carbon tax); (ii) productivity shocks resulting from the insufficient maturity of technological innovations (higher energy prices, including for low-carbon sources of energy that may not step up to the challenge) and the crowding-out effects on investments in non-energy sectors (lower productivity gains than expected in the baseline). Figure 3 presents the implied CO_2 emission profiles and emission price trajectories of the three scenarios.[30]

Baseline scenario: an orderly transition

A key challenge is to identify which scenario serves as a baseline (or reference scenario). Baseline scenarios are frequently used in risk assessment such as stress testing in order to contrast the results under an adverse scenario. The baseline scenario usually reflects the "business as usual". In the case of climate-related risk, however, this "no transition" or "current policies" scenario describes a situation with limited mitigation efforts as highlighted on Fig. 3, which could in turn lead to severe physical risks.[31] It might thus be more "adverse" in this context than what would be expected from a baseline.[32]

Given the nature of our exercise, it is assumed here that the most appropriate family of scenarios for a baseline is an orderly transition meeting climate challenges. All other families of scenarios are indeed more adverse for one or the other types of the risk. Most of the existing "orderly" scenarios have been designed to meet climate commitments while minimizing the trade-offs between climate and economic

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[29] The NGFS scenarios share many commonalities with other existing climate scenarios, such as the ones collected by the Intergovernmental Panel on Climate Change (IPCC), including the reliance on Integrated Assessment Models (IAMs) to provide transition pathways. The NGFS scenarios are now included in the IPCC set of scenarios.

[30] Note the differences in assumptions regarding the development and deployment of carbon capture and storage technologies, which are more limited in the adverse variants.

[31] Climate scenarios can be designed to reveal the hidden or unrecognized risks of climate change. In that case, the baseline would need to be a scenario that assumes neither transition risks nor physical risks. This approach might be informative but purely theoretical and inconsistent with the climate scientific literature.

[32] A "no transition" scenario has been included in the ACPR pilot exercise as an adverse scenario for the insurance companies (ACPR, 2020).

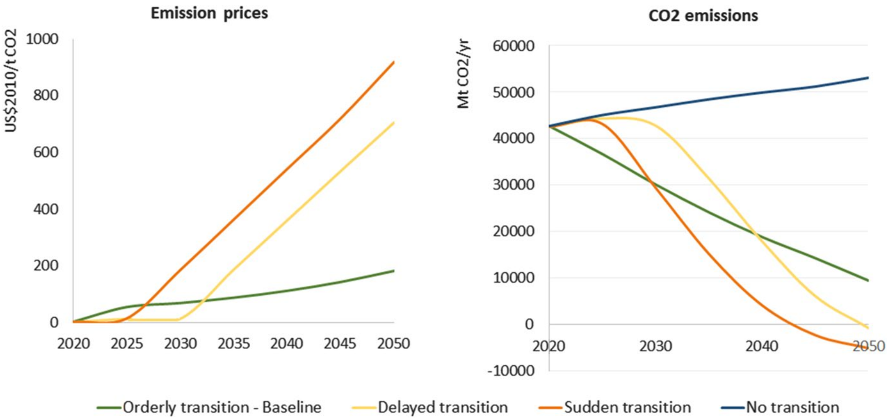

Fig. 3 CO_2 emission profiles and price trajectories by scenario. *Note* The NGFS CO_2 emission trajectory for the sudden transition scenario has been adjusted to reflect the change in narrative proposed for this exercise *Source* NGFS Climate scenarios and authors' calculations

growth objectives, some even translating into more positive economic impacts than the forecasted trends.[33].

Adverse scenario 1: A delayed transition

The first adverse scenario implies delayed policy action and depicts the case of a late introduction of a carbon tax. Following the NGFS narratives, it is assumed in 2030 that the GHG emission reduction target is not met and that carbon capture and storage technologies are not mature. To remain in line with the objective to reach carbon neutrality by 2050, governments decide to revise the carbon price in all four countries/regions.[34] The revisions of the carbon price imply a number of shocks over the period, jumping from \$87 per ton of CO_2 in the baseline to \$219 in 2035 and then continuing on a step upward trend reaching \$704 in 2050 (in the European Union). It translates into overall increases of energy prices, although the effective increase of each individual price depends on the carbon content of each energy product.

Adverse scenario 2: A sudden transition

The second adverse scenario depicts the case of a sudden, earlier than expected, transition, which is made worse because of the immaturity of technological innovations.

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[33] The NGFS orderly transition scenario translates in some transition risks, estimated to reduce World GDP by 2% in 2050 compared to a "business as usual" scenario. Choosing the NGFS "Current Policies" scenario as the baseline would have further minimise the impact of transition risks, as physical risks - estimated by the NGFS at the time to up to 10% by 2050 - already exceed the impacts of a disorderly transition scenarios by the mid of the century according to the NGFS (NGFS, 2020c).

[34] The NGFS provides carbon price trajectories for blocs of countries - including European countries - or countries - including the USA, but the prices converge to similar levels after a few years in the first edition of the NGFS scenarios. The carbon price trajectories are identical in France and in the EU.

It combines an early increase in the carbon price with a negative productivity shock (relatively to the baseline scenario). In this scenario, the carbon price is unexpectedly revised and assumed to reach \$184 per ton of CO2 in 2030, increasing steadily afterwards following the carbon trajectory set in one alternate NGFS reference scenario to reach \$917 in 2050. This scenario departs from the NGFS underlying reference scenario in that it further assumes that, in 2025, low-carbon energy production technologies are not as mature as expected, translating into a more adverse productivity path compared to the baseline scenario.[35] More precisely, it assumes away any productivity gain over the period. This lack of productivity growth could interpreted as the consequence of delays in the adoption, diffusion and operationalisation of low-carbon technologies, but also of disruptive shocks in the supply chains, resource misallocation, inadequate economic institutions, skill shortages or insufficient appropriate infrastructure with regard to the transition. As highlighted in several academic papers (Bergeaud et al., 2018), there has been a broad-based slowdown in productivity growth since the start of the 21st century, with for instance an average of just 1% growth per year for labor productivity in the Euro area since the 2000s (Lopez-Garcia et al., 2021), making the assumption proposed here not unrealistic if this trend was to be be compounded with the effects of a disorderly transition.

4.2 Economic impacts

The macroeconomic impacts of the adverse scenarios given by NiGEM are significant and heterogeneous across countries. In the most severe cases, they can lead up to more than 12% losses in GDP in 2050 relative to the baseline for countries that are the most exposed to transition risks (emerging economies in particular). For France - as well as for most advanced economies - the GDP loss is more limited. Results indicate that under the delayed transition scenario, the longer-term impacts would be around 2% below what it otherwise would have been with an orderly transition, and around 6% below in the sudden transition scenario. Our results for France in the case of a sudden transition are within the range of GDP impacts obtained by other French models who simulate a shock in energy prices (see Boitier et al., 2015). Although the sequence of our shocks differs, our GDP impacts for a similar shock (100% fossil fuel price shock without any redistribution of tax proceeds) yield −2.3% over 5 years and −4.1% after 10 years, when Boitier et al. (2015) obtain a range of GDP impacts between −2.5% and −3.2% after 10 years depending on the model used. Given that we simulate a gradual shock whereas Boitier et al. (2015) simulate a permanent one, we focus on our results somewhere between the 5 year and 10 year horizon, which seem comparable to theirs in terms of order of magnitude. Finally, the macroeconomic impacts may overall seem mild given the magnitude of carbon taxes implemented. This is partly due to the fact that there is no feedback loop within this framework from the financial sector impacts, which will be detailed in the next subsection, to the real economy. Other work have explored this aspect for

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[35] See more details on the alignment on the NGFS high-level scenarios in Appendix I.

Table 2 Impact on the main macroeconomic variables for France in deviation from baseline scenario using NiGEM

	2030	2035	2040	2045	2050
Adverse scenario 1 - Delayed transition					
GDP (%)	0.3	−0.7	−1.3	−1.7	−2.1
Inflation (p.p.)	0.3	0.4	0.2	0.1	0.1
Unemployment (p.p.)	−0.2	0.6	0.2	0.3	0.3
Adverse scenario 2 - Sudden transition					
GDP (%)	0.2	−1.5	−3.2	−4.4	−5.5
Inflation (p.p.)	0.8	0.5	0.4	0.2	0.2
Unemployment (p.p.)	−0.1	0.1	0.3	0.2	0.5

instance by including financial shocks to the disorderly scenarios (NGFS, 2022) or within short term transition scenarios (?).

In more detail, Table 2 shows that under the delayed scenario, the decline in activity occurs from 2035 onward, i.e. when the carbon price increases. Beforehand, as the carbon price is lower than in the baseline scenario, the effects on activity are slightly positive. Overall, the inflation response is positive due to the rapid increase in carbon prices compared to the more gradual path of the baseline scenario. On average, the annual inflation rate is 0.1 to 0.4 percentage points higher than in the baseline scenario. At the end of the horizon, the inflationary effect of higher energy prices is marginal as it is offset by disinflationary pressures coming from the fall in activity. The unemployment rate also increases in line with the decline in GDP.

Under the scenario of a sudden transition, the greater drop in activity is due to both the stronger rise in energy prices and the productivity shock. The impact on inflation is relatively stronger than in the first adverse scenario from 2030 onward, between 0.2 and 0.8 percentage points higher compared to the baseline scenario. The adverse effects on GDP lead to a negative supply shock that yields an additional decline in activity while price levels are higher. The unemployment rate also remains higher between 2040 and 2050.

In all cases, we find that carbon taxes raise prices for consumers and producers have a general recessionary effect and lead to reduced exports and imports in France. Although the macroeconomic costs of the simulated shocks are relatively mild, the sectoral impacts can vary significantly and be more substantial. Figure 4 shows the results for selected sectors and GDP in France across the two adverse scenarios. A country-wide carbon price has differentiated, non-linear impacts on sectoral outputs, depending both on sectoral emissions, substitution possibilities and the sector's upstream or downstream position within the production network (Devulder and Lisack, 2020).

Interestingly, because the policy is introduced later than in the baseline, the most carbon-intensive sectors are better off until 2030. From 2035 onward, these sectors start to be negatively impacted. Overall, industry sectors are more affected than service sectors. The *Manufacture of coke and refined petroleum products* sector

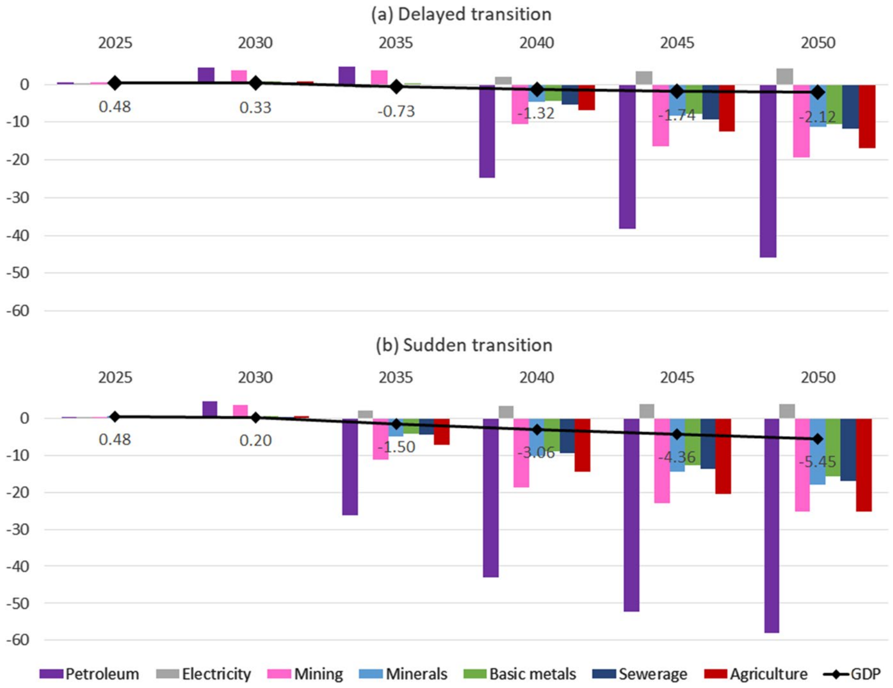

Fig. 4 Impacts on the French GDP and selected sectoral value added, delayed and sudden transition (% deviation from baseline)

(hereafter *Petroleum*)[36] is the most impacted, with its value added decreasing by up to −58% in 2050 in the sudden transition. While fairly intuitive, this result is not due to the GHG emitted for its production, but to the large quantities of GHG emitted when *consuming* its output. Final and intermediate consumers of oil and coke are therefore heavily taxed, incentivising them to flock away towards cleaner energy sources. Given the tri-dimensional tax system (on production, intermediate and final consumption), and thanks to the general equilibrium closing in our framework, these tax and demand effects transmit to all prices via sectoral interlinkages, further reducing the demand for goods that use oil more heavily as an intermediate input. This triggers a strong drop in the demand for *Petroleum*, causing its output in France in 2050 to fall by 47% from the baseline in the delayed transition scenario, and by close to 60% in the sudden transition scenario.

Another interesting indirect effect highlighted by the results is the impact on the *Mining* sector. Because close to 25% of its output is used by the French petroleum industry,[37] the drop in demand affecting *Petroleum* further transmits to the French *Mining* sector. This causes a decrease in *Mining* real value added reaching 25% in the sudden transition in 2050, even though this sector is not heavily taxed. This

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[36] See Appendix J for the key NACE sectors mentioned in this paper and their abbreviations.

[37] This number goes up to 45% when considering intermediate use by all petroleum refining sectors worldwide.

intersectoral transmission is well described by the network structure of the sectoral model that allows for the diffusion of shocks via domestic and international value chains. In a similar fashion, upstream sectors in the production network also tend to be more affected by spillovers across sectors, via the value chains represented in the model. This is for instance the case for the *Basic metals* sector: it includes carbon intensive industries (iron, steel) and is also located very upstream in the production network, both explaining the drop in is real value added by about 10% in 2050 in the delayed scenario.

The introduction of a tax on fossil fuel consumption favours substitution towards greener energy. For instance, in the delayed transition between 2025 and 2050, the share of fossil fuel in the sectoral energy mix shifts from 65 to below 35% in the *Chemicals* sector, from 11 to 0.5% for Paper products, from 85 to 60% in *Land Transport*. Some sectors with a very high dependence on fossil fuels (*Air* and *Water Transport* for instance) face somewhat limited possibilities to shift towards greener energy and their energy mix remains more stable, while their total output significantly decreases. Altogether, this results in an increased demand for *Electricity, gas, steam and air conditioning supply* (hereafter *Electricity*), and the value added of that sector rises by up to 4%.

Last, the *Agricultural* and *Sewerage* sectors are strongly impacted because of their direct non-CO_2 GHG (methane among others) emissions, while the *Minerals* sector include the cement industry that is a heavy CO_2 emitter.

Due to the overall recessionary effect of the transition, there are very few sectors gaining in terms of value added besides *Electricty*. Yet, we can observed that some sectors, despite a lower value added, are faring *relatively* better than the overall economy. This is true for instance for *Retail trade*, *Research and Development* and *Public administration*.

Despite the difficulty to do precise comparisons, the sectoral impacts we obtain seem in line with the literature. Cahen-Fourot et al. (2021) and Godin and Hadji-Lazaro (2020) highlight the importance of inter-sectoral transmission and scope 3 emissions, which our sectoral framework is able to account for via its general equilibrium closure and its tri-dimensional taxes.[38] Using G-Cubed, Fernando et al. (2021) for instance obtain an EU GDP decrease by 1% and a decrease in *Mining* and *Agriculture* productions in the EU by 9% and 1% respectively following a carbon price increase of US$40. They distinguish between the *Coal* and the *Petroleum* sectors and obtain respectively a 70% and 10% output decrease. The transition path considered by Fernando et al. (2021), designed as an orderly transition, is most comparable to our baseline scenario between 2020 and 2030. A carbon price increase by US48$ in 2025 in our framework implies a medium-term (5 years later) drop in *Mining*, *Agriculture* and *Petroleum* by 22%, 9% and 3.7% respectively in the EU, thus fairly close to Fernando et al. (2021)'s results.

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[38] The different methodology and focus on stranded capital in Cahen-Fourot et al. (2021) however triggers important second-round impacts on downstream sectors, while our results rather point to negative spillovers on upstream sectors due to a strong demand effect.

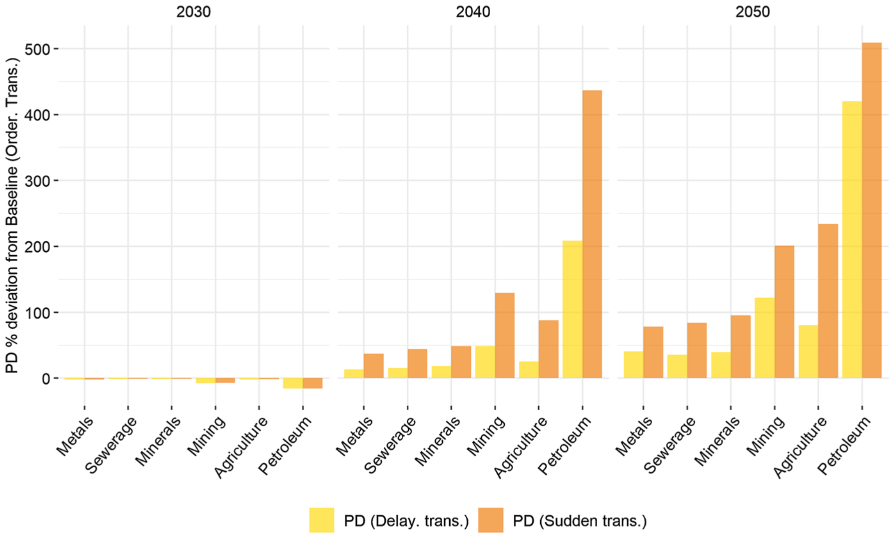

Fig. 5 Probabilities of default for the most impacted sectors (in deviation from baseline)

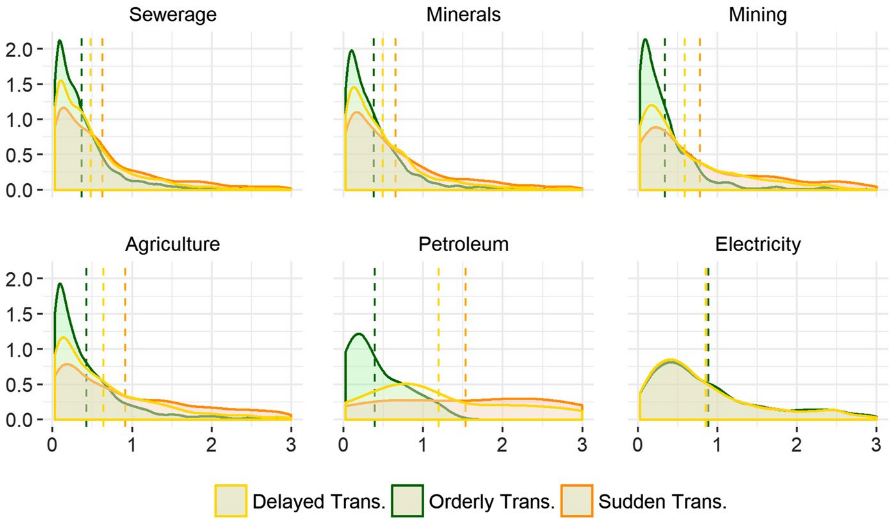

Fig. 6 PDs densities across scenarios (in 2050). *Note* Vertical dotted lines provide the median for each scenario

4.3 Financial impacts

The macroeconomic and sectoral shocks described above translate into significantly negative impacts on financial variables for some sectors. Overall, credit and market risks will deteriorate for the large GHG emitters and the fossil fuel-producing sectors, should the transition to a low-carbon economy occur in a disorderly manner.

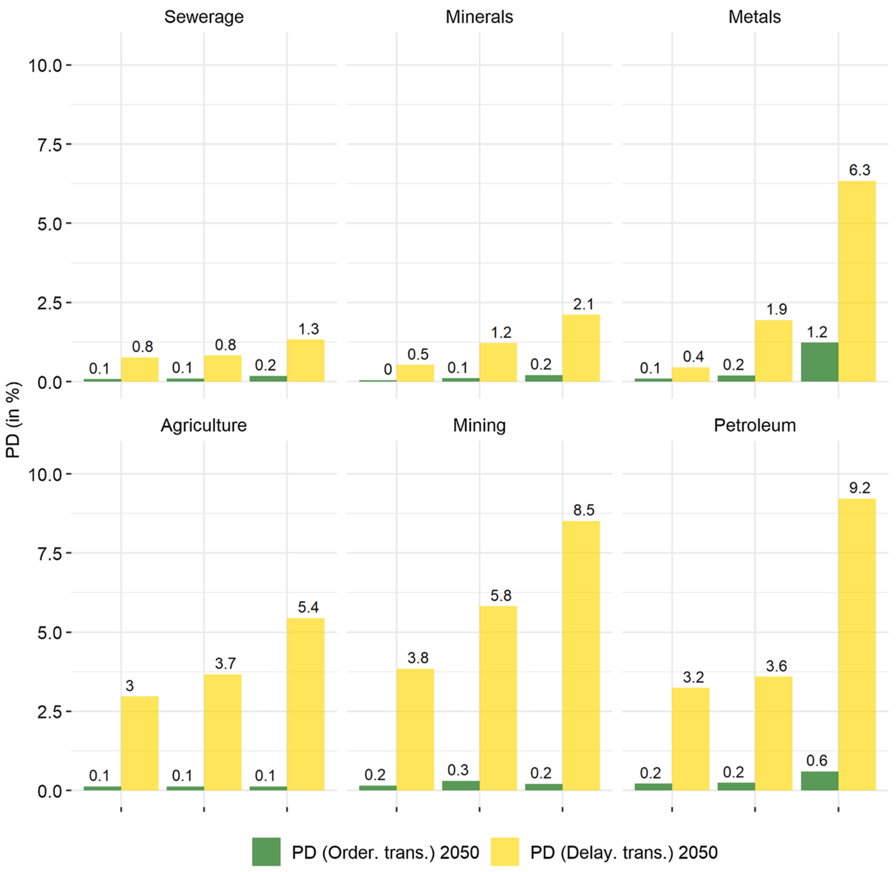

Fig. 7 PDs for top 3 impacted firms (in 2050)

Table 3 Expected variations (in bps) of corporate credit spreads in France from January 2020 to December 2050 (average over 5-year intervals) for Consumer Non-Cyclical and Fossil Energy sectors.

France								
Years/maturity	Consumer non-cyclical				Fossil energy			
	1-year	2-year	3-year	5-year	1-year	2-year	3-year	5-year
2020–2025	0 0	0 0	0 0	0 0	0 1	0 1	0 1	0 1
2026–2030	0 0	0 0	−1 −1	−1 −1	−1 −3	−2 −4	−2 −5	−2 −5
2031–2035	1 0	1 0	1 −1	1 −1	−6 6	−8 7	−8 6	−8 4
2036–2040	1 1	2 0	2 −1	2 −3	5 22	7 25	7 24	7 19
2041–2045	0 2	0 0	0 −2	−1 −5	21 28	25 30	25 28	22 22
2046–2050	1 2	0 −1	−2 −4	−4 −7	24 31	27 32	26 29	21 21

For each period and sector, the cell $x \mid y$ shows the expected variation (with respect to the baseline scenario) under the delayed transition (x) and the sudden transition (y) scenarios

Projections of corporate default probabilities

First, results show that both the delayed and the sudden transitions have recessionary impact on PDs for all sectors except *Electricity* (Fig. 5). Consistent with the scenario narratives, PDs improve until 2030 compared to the baseline.[39] Then, PDs for the most impacted sectors deteriorate, reaching up to 500% degradation in the *Petroleum* industry in 2050. This represents a very significant impact. As a benchmark, similar levels of PDs degradation have been computed for the sectors worst affected by COVID19 in 2020.[40] The increase in the expected PDs is however gradual over a much longer period of time.

Figure 6 presents the densities of the PDs across the three scenarios. The ordering of the impacts across scenarios is as expected, with structural and larger increases in PDs as the transition is more adverse. Interestingly, the distribution of PDs changes quite dramatically across scenarios for some sectors, such as *Petroleum*, with a larger share of the sample in the tail of the distribution as the transition becomes more disorderly. In the *Petroleum* sector, a significant number of firms have PDs above 3%, when it hardly exceeds 1.5% in the orderly scenario.

Looking more specifically at some individual firms, Fig. 7 highlights that some firms can reach highly unsustainable level of PDs, jumping from 0.6% to more than 9%. This degradation of four Credit Quality Steps (corresponding to seven notches in the BdF native rating scale) is a strong negative signal. Note that a $0,6\%$ PD corresponds to the standard of Eurosystem's harmonised requirement for credit assessment collateral eligible to monetary policy operations (collateral is eligible with PDs up to $0,4\%$ in the permanent framework, with a transitional additional credit claims for PDs up to 1%). A PD over 1% is a non eligible assessment and PDs over 5% are mapped to the last and worst credit quality rating.

Projections of corporate credit spreads

Regarding corporate credit spreads, we focus here on two specific BICS sectors in order to empirically compare the impact of the alternative scenarios: Consumer non-cyclical and Fossil energy.[41] We consider these economic sectors in France, while we gather in Appendix K the results for the Rest of Europe (i.e., Germany, Italy, Spain and UK), USA and Japan.

On the basis of the projections presented in Fig. 5, the fossil energy sector is affected by a much larger rise of the default probability than the consumer

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[39] The shocks are introduced in 2025 and 2030, respectively for the sudden and delayed scenarios, with an additional lag of 5 years for the economy to adjust.

[40] PDs degradation computation based on similar approach using Banque de France projections for COVID19 sectoral impacts.

[41] The former is given by the NACE sectors *Agriculture* (A01), *Manufacture of food products* (C10), *Manufacture of beverages* (C11), *Manufacture of tobacco products* (C12), *Manufacture of basic pharmaceutical products and preparations* (C21) and *Human health and social work activities* (Q). The latter includes *Mining* and *Petroleum*. The label *fossil energy* refers to the fact that the NACE electricity sector is included in the BICS utility (instead of energy) sector.

non-cyclical one, over the projection horizon. From Table 3 we observe the following results (in deviation from the baseline):

(*a*) The fossil energy sector shows in general larger (in absolute value) expected variations than the consumer non-cyclical one, under both alternative scenarios. Indeed, if we consider for example the sudden transition, the fossil energy sector is affected by a default probability rise that is around seven times larger than the one of the consumer non-cyclical one.

(*b*) The expected credit spreads of the consumer non-cyclical sector are only marginally affected by the two alternative scenarios. In this sector, we have a downward sloping future path of the default probability for all scenario and the relative rise of the alternative ones is on average of only 10 bps and 15 bps (for delayed and sudden transitions, respectively).

(*c*) Under the delayed transition, the projected variations of credit spreads of the fossil energy sector are slightly negative up to 2035 and then become positive moving up to 25–27 bps between 2045 and 2050. This is in line with a moderate reduction of the projected default probability up to 2035, and then a 240 bps rise between 2035 and 2050 (compared to the baseline trajectory). Under the sudden transition, the relative reduction of the default probability is observed only up to 2030, and then we have a rise of 300 bps up to 2050. Coherently, expected credit spread variations range between −3 bps and −5 bps, across the maturity spectrum, from 2026 to 2030, then taking positive values and reaching 30–32 bps between 2045 and 2050.

Estimation of equity price variations

Regarding market risks, the stock pricing module presented in Sect. 3.3.3 provides estimates of the elasticity of equity prices (for a given country and industry) to the structural changes and resulting shifts in the expected stream of dividends for each disorderly scenario. It is therefore important to highlight that the elasticity, measured as the percentage price deviation (impact) from the baseline scenario, is associated to a current-period readjustment due to expectation corrections, rather than an evolution along the transition like the default probability variations discussed in the previous sub-section. Figure 8 shows the elasticities for climate relevant economic sectors in France (the percentage price variations for the RoEU, the USA and the RoW are in Appendix L).

In line with sectoral shocks, for any given alternative scenario revealing, at the evaluation date, an associated new expected dividend stream and discount factor (with respect to the baseline), markets would revise their expectations leading to significant repricing for some sectors, consistently with the literature on stranded assets (IRENA, 2017). In both disorderly scenarios, fossil fuel producers

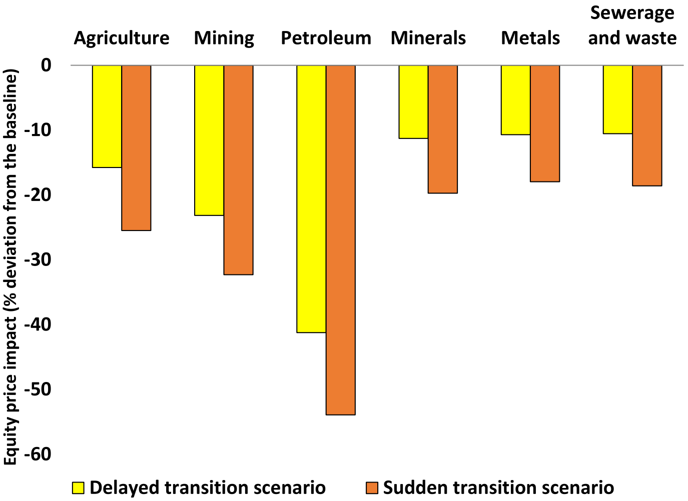

Fig. 8 Equity price impacts across economic sectors - France

and large emitters (in particular those unable to adjust their production processes to the change in policies) are strongly affected. For instance, equity prices for the *Petroleum* sector would be corrected by up to 41% and 54%, respectively, for delayed and sudden transitions in France.

The losses due to these asset repricings could affect banks' trading books, as well as insurers and investment funds. Investors in investment funds might redeem their funds altogether, which would create further losses due to liquidity mismatches and leverage. In addition to these first-round effects, the reassessment of a large range of assets could be aggravated by investors adapting their portfolios to new risk-return profiles in the same direction. Investors deciding to sell the same assets at the same time would lead to second-round losses on these assets.

5 Conclusion

This paper proposes a suite of models to translate climate policy and transition narratives into the economic and financial quantitative information necessary for financial stability assessment. The modular approach provides a flexible and efficient architecture, compartmenting the numerous modelling challenges and allowing for further enhancement. It includes firm-specific financial information, usefully complementing existing studies with infra-sectoral information and key credit parameters.

Building on the NGFS reference scenarios, the framework is applied to three scenarios: a baseline case and two adverse scenarios. The proposed scenarios describe a hypothetical set of events selected and modelled specifically for financial stability assessment. They are neither forecasts predicting what will happen nor normative scenarios indicating what should happen. The estimates reported provide important information on the structural change related to the transition toward a low-carbon economy.

The results show the materiality of the negative economic and financial impacts of disorderly transitions. Given the 30-years time horizon of the simulations, allowing for economic and financial actors to adapt, the effects at macroeconomic and financial market levels remain somewhat limited compared to more usual solvency assessments. The impacts on the sectors exposed to the transition policies simulated are however substantial. In both disorderly transition scenarios, large emitters and fossil fuel producers could see their activities impacted by up to 50% and 60% respectively by the end of the period, leading to asset repricing of the same magnitude as market participants revise their expectations. The magnitude of the shocks and the heterogeneity across sectors highlight that the risks to financial stability are potentially much more pronounced than macroeconomic impacts would suggest. Yet, many uncertainties remain as to the size of the financial impacts.

Despite these uncertainties, this paper emphasizes the potential vulnerabilities of the financial sector that could amplify the consequences of a disorderly transition towards a low-carbon economy. Five axes can be identified: i) firm risk and default probabilities; ii) equity price shocks and market volatility; iii) financial stability risks; iv) impact on credit spreads and interest rates; and v) financial institution resilience. These axes elucidate how abrupt policy changes or reduced productivity might strain the financial sector by elevating firm risk and default probabilities, especially in specific sectors. Additionally, volatility in equity prices and increased market instability within sectors experiencing disorderly transitions might propagate systemic risks across interconnected sectors and institutions. Simulations signaling changes in borrowing costs and lending rates could affect firms' operations and the financial resilience of the broader economy, while a rise in non-performing loans might challenge the resilience of banks. Our paper acknowledges that while macroeconomic and financial market impacts may seem restrained, the potential for pronounced risks within sectors and infra-sectoral entities underscores the need for robust risk management and mitigation strategies in the financial sector.

Going forward, it will be essential to explore other transmission channels not accounted for in this exercise. In particular, these scenarios model the emission prices as the key mitigation policy variable. As acknowledged by the IPCC (2014), this assumption overlooks many dynamics that will be essential to a low-carbon transition, including technological, geopolitical or institutional considerations (Moriarty and Honnery, 2016; Smil, 2017; Zenghelis, 2019). While technological breakthroughs and change in the cost of renewable energy technologies might speed up the transition, also creating some unexpected disruptions, technical limitations may also prevent a smooth transition from occurring. The technological dimension is only partially and imperfectly covered in the proposed framework through the assumptions on productivity improvements.

Additional work on potential contagion channels, interdependencies between industries and amplification effects would be key to provide a robust and comprehensive assessment of the financial risks related to the transition (Hildén et al., 2020). While the amplification of industry-specific shocks (i.e., the aggregate response following a sector specific shock) is covered in the proposed modelling thanks to the production network framework, the proposed approach does not model potential feedback effects between macroeconomic and financial variables. It also does not account for feedback between climate and economic variables, which would also constitute relevant future avenues for research. There may be for instance interactions between banks' financial health and climate change, as a fragile financial system may in turn impede the financing of the transition. Accounting for these second-round effects would be crucial as shown by the recent experience of Covid-19, illustrating how global supply chains can be disrupted in unpredictable ways.

Appendix A Modelling details for NiGEM

We further describe the features of NiGEM most useful for understanding the transmission channels of the economic shocks implemented in the scenario simulations, namely the production function, consumer price equations and monetary policy reaction functions.

The Production function

The production function is based on an underlying constant-returns-to-scale CES production function with labour-augmenting technical progress, which is embedded within a Cobb-Douglas relationship to allow the factors of production (labour and capital) to interact with energy usage.

$$Ycap = \gamma\left(\delta K^{-\rho} + (1-\delta)\left(Le^{\lambda t}\right)^{-\rho}\right)^{\frac{\alpha}{\rho}} M^{1-\alpha} \tag{2}$$

where *Ycap* is real output, K is the total capital stock, L is total hours worked, M is energy input, and λ is the rate of labour-augmenting technical progress.

In the standard version of the model, energy is decomposed into the three main types of fossil fuels: oil, coal and gas, proportionately according to each country's usage. In the extended version used for the simulations, renewable energy has been added to the energy input in order to account for the share of renewables in each country's economy, but demand and supply of renewables have not been modelled at this stage.

Price equations

In NiGEM, consumer prices are a function of unit total cost (and therefore wages through the wage-price loop), import prices and indirect taxes (VAT-type).

$$\begin{aligned}\Delta log\left(ced_t\right) = {} & \Delta log\left(1 + itr_t\right) \\ & + \alpha\left(log\left(\frac{ced_t - 1}{1 + itr_t - 1}\right) + \beta log\left(pm_t\right) + (1-\beta) log\left(utc_t - 1\right)\right) \\ & + (short\ run\ dynamic)\end{aligned} \tag{3}$$

where *ced* is the country consumption deflator, *itr* is the indirect tax rate, *pm* is the price of imports, *utc* is unit total costs and *short run dynamic* includes import prices, unit total costs and inflation expectations.

Prices of imports are a weighted sum of commodity import prices and non-commodity import prices, and commodity import prices are themselves a weighted sum of import prices of energy (oil, coal, gas and renewables), basic metals, food, beverage and agricultural raw materials. Commodity import prices are global prices, taken from market quotations for energy prices and from IMF International Financial Statistics database for non-energy commodity prices.

In the version of the model used for this exercise, the carbon tax on consumers is introduced in the model through an effective import price of fossil fuel consisting in the global price to which is added a country-level carbon tax. This effective import price enters the price equation in replacement of global commodity prices. In subsequent versions of the model, the carbon tax directly feeds into consumer prices through an indirect energy tax rate that is calibrated on the country CO_2 emissions.

Moreover, company profits are reduced by the proportion of the carbon tax levied on the corporate sector.

Monetary policy

Monetary policy in NiGEM mainly operates through the setting of the short-term nominal interest rate, using a simple feedback rule depending on inflation, the output gap, the price level, and nominal output. Different monetary policy rules are defined, but the default one is a *Two-pillar rule*, where the policy rate is function of the ratio of the nominal GDP target to nominal GDP, the difference between inflation expectations and the inflation target and lagged policy rate:

$$i_t = \gamma i_{t-1} + (1-\gamma)\left(-\alpha \ln\left(\frac{NOM_t^*}{NOM_t}\right) + \beta^i\left(inf_{t+1} - inf_{t+1}^*\right)\right)$$

where i is the short-term nominal interest rate, NOM is nominal output, NOM^* is a specified target for nominal output, inf is inflation expectations and inf^* is the inflation target.

Appendix B Modelling details for the sectoral model

Production

For ease of presentation, we present the production side of the model without country indices, only specifying sectoral indices i taken from the global set of sectors $\{1, \dots, N\}$, with N the number of countries times the number of sectors per country.[42] The N production sectors consist of $N_E < N$ energy sectors and $N - N_E$ non-energy sectors. Without loss of generality, we re-order the sectors such that the energy sectors correspond to sectors $1, 2, \dots, N_E$. In each sector $i \in \{1, \dots, N\}$, firms

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[42] This sector-country joint indexation is enough to specify the production function of each sector. The only exception is labour cost, which is country specific. With some abuse of notation, we omit country indices in the description of the production side for convenience.

use intermediate inputs $\{Z_{ji}\}$ from all sectors $j \in \{1, \dots, N\}$ and labour L_i to produce the sectoral good in quantity Q_i. We further assume that firms are operating in a perfectly competitive environment within each sector, with one representative firm per sector. The production technology is modelled as nested CES functions, with two intermediate input bundles: energy inputs E_i on one side, non-energy inputs I_i on the other side, that are combined with labour to obtain sectoral output. σ, ϵ and θ are the respective elasticities of substitution in each aggregation step. This specification defines the production function below, for a firm in sector $i \in \{1, \dots, N\}$:

$$Q_i = \left(\mu_i^{\frac{1}{\theta}} L_i^{\frac{\theta-1}{\theta}} + \alpha_{Ei}^{\frac{1}{\theta}} E_i^{\frac{\theta-1}{\theta}} + \alpha_{Ii}^{\frac{1}{\theta}} I_i^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}} \tag{4}$$

$$\text{where} \qquad E_i = \left(\sum_{j=1}^{N_E} \left(\frac{\alpha_{ji}}{\alpha_{Ei}} \right)^{\frac{1}{\sigma}} Z_{ji}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{5}$$

$$I_i = \left(\sum_{j=N_E+1}^{N} \left(\frac{\alpha_{ji}}{\alpha_{Ii}} \right)^{\frac{1}{\epsilon}} Z_{ji}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}} \tag{6}$$

Parameters α_{ji} correspond to the share of input j in output i; α_{Ei} is the total energy share, α_{Ii} the total non-energy share and μ_i the labour share used by sector i such that:

$$\alpha_{Ei} + \alpha_{Ii} + \mu_i = 1; \qquad \sum_{j=1}^{N_E} \alpha_{ji} = \alpha_{Ei}; \qquad \text{and} \sum_{j=N_E+1}^{N} \alpha_{ji} = \alpha_{Ii}.$$

The representative firm in sector $i \in \{1, \dots, N\}$ maximises its profit, namely:

$$\begin{aligned} &\max_{L_i, Z_{ji}} \pi_i = P_i(1 - \tau_i)Q_i - wL_i - \sum_{j=1}^{N} P_j(1 + \zeta_{ji})Z_{ji} \\ &\text{s.t. Eqs. (4), (5), (6) are verified;} \end{aligned} \tag{7}$$

where $P_i(1 - \tau_i)$ is the amount obtained by sector i's producers for their output, once the sales tax τ_i is deducted, and w is the wage faced by the firm.[43] ζ_{ji} represents a tax on sector i's intermediate input of good j. Relatively to the three types of carbon tax mentioned above, τ_i is meant to charge the GHG emitted during the production process besides energy input consumption, whereas ζ_{ji} pertains to CO_2 emitted when burning fossil energy inputs for production.

This program implies the optimality conditions below in each sector $i \in \{1, \dots, N\}$:

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[43] As detailed in the upcoming household and market clearing sections, there is one labour market per country, so that firms (sectors) face different wages depending on their production location. For notations simplicity, we abstract from this when detailing the producer's program.

$$\frac{L_i}{Q_i} = \mu_i \left(\frac{P_i(1 - \tau_i)}{w} \right)^{\theta} \tag{8}$$

$$\frac{Z_{ji}}{Q_i} = \begin{cases} \alpha_{ji} \frac{(P_i(1-\tau_i))^{\theta}}{(P_j(1+\zeta_{ji}))^{\sigma}} P_{Ei}^{\sigma-\theta} & \forall 1 \leq j \leq N_E \\ \alpha_{ji} \frac{(P_i(1-\tau_i))^{\theta}}{(P_j(1+\zeta_{ji}))^{\epsilon}} P_{Ii}^{\epsilon-\theta} & \forall N_E + 1 \leq j \leq N \end{cases} \tag{9}$$

where price indices are defined for the energy and non-energy intermediate input bundles in each sector i as:

$$P_{Ei} = \left(\sum_{j=1}^{N_E} \frac{\alpha_{ji}}{\alpha_{Ei}} (P_j(1 + \zeta_{ji}))^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \tag{10}$$

$$P_{Ii} = \left(\sum_{j=N_E+1}^{N} \frac{\alpha_{ji}}{\alpha_{Ii}} (P_j(1 + \zeta_{ji}))^{1-\epsilon} \right)^{\frac{1}{1-\epsilon}} \tag{11}$$

We further assume free-entry so that producers make zero profit, implying for each sector i:

$$P_i(1 - \tau_i) = \left(\mu_i w^{1-\theta} + \alpha_{Ei} P_{Ei}^{1-\theta} + \alpha_{Ii} P_{Ii}^{1-\theta} \right)^{\frac{1}{1-\theta}} \tag{12}$$

Final demand

To present the households' program, we turn back to multi-country notations with a set of countries $\mathcal{C}$. Final demand is modelled with a representative household in each country $A \in \mathcal{C}$. He consumes a CES bundle of goods from all sectors and all countries, with elasticity ρ, and inelastically supplies a fixed amount of labour L_A. His preferences are represented by a constant-relative-risk-aversion utility function:

$$u_A = \frac{C_A^{1-\varphi}}{1 - \varphi} \quad \text{where} \quad C_A = \left(\sum_{j=1}^{N} \gamma_{jA}^{\frac{1}{\rho}} C_{jA}^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}}$$

The parameter $\varphi > 0$ refers to his degree of risk aversion. The consumption shares γ_{jA} are such that $\sum_{j=1}^{N} \gamma_{jA} = 1$.

International financial flows are introduced by assuming that there is a competitive market where representative households from all countries can trade Arrow-Debreu securities for every state of nature. In our static model, this amounts to imposing an internationally efficient allocation in the long run.

In addition to financial flows, country A household's resources include labour income $w_A L_A$ and lump-sum transfers from her government T_A. Labour is assumed to be perfectly mobile across sectors within countries, but immobile across countries, so that the wage w_A differs across countries but is the same across sectors within a given country. As is the case for producers, households in each country pay a tax κ_{iA} on their final consumption of good i. The country A household's budget constraint is:

$$\sum_{j=1}^{N} P_j(1+\kappa_{jA})C_{jA} = w_A L_A + T_A + \Phi_A \tag{13}$$

where Φ_A refers to net financial flows from security trading.[44]

Households choose consumption of all goods and security purchases to maximize their lifetime utility. Solving for the optimal decisions, the first order conditions of the household's program boil down to the relative demand and the perfect international risk-sharing conditions below:

$$\forall A \in \mathcal{C},\ \forall j \in \{1,\dots,N\}, \qquad \frac{C_{jA}}{C_A} = \gamma_{jA}\left(\frac{P_j(1+\kappa_{jA})}{P_A}\right)^{-\rho} \tag{14}$$

$$\forall B \in \mathcal{C}, \qquad \frac{C_B}{C_A} = \nu_{AB}\left(\frac{P_A}{P_B}\right)^{\frac{1}{\varphi}} \tag{15}$$

where P_A is the consumption price index of the household's consumption basket in country A:

$$P_A = \left(\sum_{k=1}^{N} \gamma_{kA}\left[P_k(1+\kappa_{kA})\right]^{1-\rho}\right)^{\frac{1}{1-\rho}} \tag{16}$$

The parameters $\{\nu_{AB}\}_{B\in\mathcal{C}}$ determine relative aggregate consumption sizes across countries in the initial steady state.

Market clearing

The market clears for each sectoral good $i \in \{1,\dots,N\}$ and for labour in each country $A \in \mathcal{C}$. Importantly, we assume no international migrations: labour is perfectly mobile across sectors within each country but immobile across countries. The market clearing conditions are hence:

$$\forall i \in \{1,\dots,N\}, \qquad Q_i = \sum_{j=1}^{N} Z_{ij} + \sum_{A\in\mathcal{C}} C_{iA} \tag{17}$$

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[44] See Devulder and Lisack (2020) for an explicit description of financial markets.

$$\forall A \in \mathcal{C}, \qquad L_A = \sum_{j \in \mathcal{S}_A} L_j \tag{18}$$

where $\mathcal{S}_A \subset \{1, \ldots, N\}$ is the subset of sectors located in country A.

The government is not explicitly modelled here, but it is implicitly collecting the taxes and redistributing them to the household in a lump-sum fashion. To keep the set-up parsimonious, there are neither government consumption nor public goods. Transfers are taken as given by the household, and are computed as follows for each country $A \in \mathcal{C}$:

$$T_A = \sum_{j \in \mathcal{S}_A} \tau_j P_j Q_j + \sum_{j=1}^{N} \kappa_{jA} P_j C_{jA} + \sum_{i \in \mathcal{S}_A} \sum_{j=1}^{N} \zeta_{ji} P_j Z_{ji} \tag{19}$$

Market clearing for international securities implies the following resource constraint for the world economy:

$$\sum_{A \in \mathcal{C}} P_A C_A = \sum_{A \in \mathcal{C}} w_A L_A + \sum_{A \in \mathcal{C}} T_A \tag{20}$$

It is straightforward to show from the product market clearing Eq. (17), the profit Eq. (7) and the household budget constraints (13) that international trade balances each country's representative household budget constraint:

$$\forall A \in \mathcal{C}, \quad T_A + w_A L_A = P_A C_A + X_A - M_A$$

with country A's nominal imports and exports respectively defined as:[45]

$$M_A = \sum_{i \notin \mathcal{S}_A} \sum_{j \in \mathcal{S}_A} P_i Z_{ij} + \sum_{i \notin \mathcal{S}_A} P_i C_{iA}; \qquad X_A = \sum_{i \in \mathcal{S}_A} \sum_{j \notin \mathcal{S}_A} P_i Z_{ij} + \sum_{i \in \mathcal{S}_A} \sum_{B \neq A} P_i C_{iB}$$

Equilibrium

We can now define the equilibrium. To have well defined prices, we choose units of labour in country 1 as the numeraire and thus normalise w_1, the wage in country 1, to 1. Note that aggregate labour supply in each country $\{L_A\}_{A \in \mathcal{C}}$ is also normalised to define the scale of the model and the relative size of each country within the model. An equilibrium in this model corresponds to a set of quantities $\{Q_i, L_i\}_{i=1}^N$, $\{Z_{ij}\}_{i,j=1}^N$, $\{\{C_{iA}\}_{i=1}^N\}_{A \in \mathcal{C}}$, $\{C_A, T_A\}_{A \in \mathcal{C}}$ and prices $\{P_i, P_{Ei}, P_{Ii}\}_{i=1}^N$, $\{P_A\}_{A \in \mathcal{C}}$, $\{w_A\}_{A \in \mathcal{C} \setminus \{1\}}$ such that Eqs. (8) to (12), (14) to (20), are verified. We solve for the equilibrium numerically (see Devulder and Lisack 2020 for the solution method).

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[45] The taxes ζ_{ij} and κ_{iA} are not included in the nominal imports and exports expressions, as these taxes correspond to domestic (and not international) payments.

Table 4 Sectoral model - Calibration of the elasticities of substitution

Elasticity of substitution across	
Intermediate inputs (ϵ)	0.4
Energy types (σ)	1.5
Labour, Intermediate inputs and Energy (θ)	0.8
Final consumption goods (ρ)	0.9

Appendix C Elasticities of substitution in the sectoral model

We calibrate the elasticity values as in Devulder and Lisack (2020), except for the substitution across energy types: since we are looking at very long-term horizons, it seems reasonable to consider different types of energy as substitute - hence with an elasticity of substitution above 1. Values estimated and calibrated vary across the literature, ranging from 0.5 (Pelli, 2012) to 10 (Acemoglu et al., 2012). We choose 1.5, a relatively conservative value in line with the estimates by Papageorgiou et al. (2017) (Table 4).

For a sensibility analysis in the sectoral model over a range of plausible elasticity values, please refer to Appendix C of Devulder and Lisack (2020). A lower elasticity of substitution across energy types (σ) would deteriorate the GDP outcome, while the results are little sensitive to the elasticity of substitution across intermediate inputs (ϵ), across labour, intermediate inputs and energy (θ) and across final consumption goods (ρ).

Appendix D Tax rates calibration in the sectoral model

We have three sets of tax rates to calibrate: on *Coke and refined petroleum products* (hereafter, *Oil and coke*) intermediate consumption by producers, on sectoral production and on *Oil and coke* final consumption by households. Tax rates are set proportionally to the carbon intensity of household and production activities. So we first need to calibrate the carbon intensity parameters, relying on GHG emissions data.

Calibration of GHG emission parameters

On the production side, the following approach applies for all but two sectors. We attribute total sectoral CO_2 emissions to the use of oil and coal. Sectoral non-CO_2 GHG emissions, obtained by subtracting CO_2 emissions from total emissions expressed in tCO_2e in the data are attributed to the sectoral production process besides the use of energy inputs. Formally, this amounts to setting:

$$g_i = \frac{GHG_i - CO_{2i}}{Q_i^I}; \qquad f_i = \frac{CO_{2i}}{\sum_{j \in \mathcal{F}} Z_{ji}^I}$$

where CO_{2i} is the CO_2 emissions of sector *i*, GHG_i is the total GHG emissions of sector *i*, and and superscript *I* denotes variables values at the initial steady state.

Exceptions are made for the *Other non-metallic mineral products* (hereafter *Minerals*) and *Basic metals* sectors. The large quantities of CO_2 these sectors emit are inherent to their production process (for instance for cement, iron or steel) and only partly result from their fossil energy use (or, if it is the case, in such a way that it cannot be easily replaced by electricity). To reflect this situation in a simple way, we make the extreme assumption that no emissions come from energy use and we set for $i \in$ {Minerals, Basic metals}:

$$g_i = \frac{GHG_i}{Q_i^I}; \qquad f_i = 0.$$

For household emissions, the calibration is straightforward since the latter mostly emit CO_2 through the use of fossil fuel consumption. The emission intensity of the household in country *A* is defined as:

$$h_A = \frac{GHG_h^A}{\sum_{j\in\mathcal{F}} C_{jA}^I}$$

with country *A* household emissions GHG_h^A being obtained as the difference between country *A* total GHG emissions and the sum of GHG emissions from production sectors located in country *A*.

Calibration of tax rates in scenarios

Carbon taxation scenarios are characterized by the price of a ton of CO_2e, denoted by P_{CO_2}, and the set of countries or regions implementing the tax. As made explicit below, tax rates are calibrated such that the corresponding tax proceeds amount to the cost of the targeted GHG emissions at the initial steady state.

Production taxes For each sector *i* located in a country implementing the tax, the rates ζ_{ji} on its intermediate consumption of *Oil and coke* are the same for all *Oil and coke* inputs $j \in \mathcal{F}$, whether bought domestically or imported. They verify:

$$\zeta_{ji} = \begin{cases} 0 & \text{if } j \notin \mathcal{F} \\ \zeta_i & \text{if } j \in \mathcal{F} \end{cases} \text{with} \quad \zeta_i = \frac{P_{CO_2} F_i^I}{\sum_{j\in\mathcal{F}} P_j^I Z_{ji}^I} = P_{CO_2} f_i, \tag{21}$$

since all prices are equal to 1 in the initial steady state. Note that tax rates are set based on the observation of the no-tax steady state equilibrium and are not revised over time. Since prices adjust once the tax is implemented, at the new equilibrium equality (21) will not be exactly verified any more. The same is true for the other taxes τ and κ.

In a similar fashion, the tax rate on sector *i*'s sales is set to:

$$\tau_i = \frac{P_{CO_2} G_i^I}{P_i^I Q_i^I} = P_{CO_2} g_i$$

Household tax In each country A implementing the tax, the rates κ_{jA} are the same for all *Oil and coke* products $j \in \mathcal{F}$, irrespective of their origin countries, and zero for all other products. But they may vary across countries implementing the tax depending on the local household consumption's carbon intensity. For a given CO_2 price, κ_{iA} is calibrated to:

$$\kappa_{jA} = \begin{cases} 0 & \text{if } j \notin \mathcal{F} \\ \kappa_A & \text{if } j \in \mathcal{F} \end{cases} \text{with} \quad \kappa_A = \frac{P_{CO_2} H_i^I}{\sum_{j \in \mathcal{F}} P_j^I C_{jA}^I} = P_{CO_2} h_A$$

Remarks This calibration strategy prompts two observations. First, the tax rates ζ, τ and κ obtained in a given country and sector do not depend on whether other countries are or not implementing a carbon tax. Second, although fossil fuels (aside from gas) are grouped into a single *Oil and coke* sector in the WIOD, the tax rates ζ_i take into account the specificity of sectors' energy mix between fossil fuels: for instance, a sector that uses relatively more coal than oil emits more CO_2 and will hence face a higher tax rate on its purchases of *Oil and coke*.

Appendix E Details on the default definition

Definition of the

Basel default used in infra-sectoral Banque de France's rating model

To calculate default rate in the rating model, we report for each rating year N whether a default occurred in year $N+1$, i.e. between $1/01/N+1$ and $31/12/N+1$ (Fig. 9).

The definition of a default according to Article 178 of the Capital Requirement Regulation (CRR) is as follows: a default shall be considered to have occurred with regard to a particular obligor when either or both of the following have taken place:

a. The institution considers that the obligor is unlikely to pay its credit obligations to the institution.
b. The obligor is more than 90 days past due on any material credit obligation to the institution.

Two other rules, linked to the Banque de France's ICAS status, also apply:

c. A persistence rule: to make sure that the company is truly in default, the default must persist for a 90-day latency period. As a result, the total period between the missed obligation and the bank's report is around six months
d. A materiality rule: the company is deemed to be in default only if the total outstanding amount borrowed from all banks and reported as being non-performing exceeds 2.5% of total external financing.

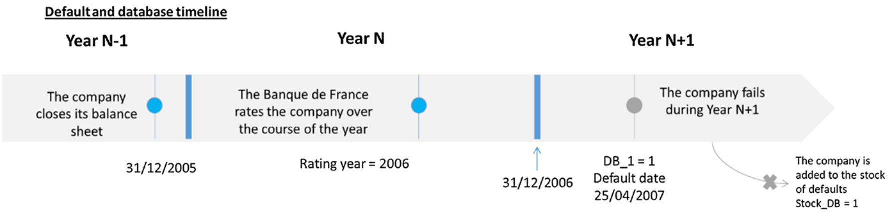

Fig. 9 Definition of the *Basel default* used in infra-sectoral Banque de France's rating model

The notion of failure is also added to the previous definition of default. Failure indicates that legal proceedings have been opened against the company, that is: liquidation, receivership, cancellation of a recovery plan and cancellation of a safeguard plan.

To sum up, for a company *i*, the default definition is:

$$d_i^t = \begin{cases} 1 & \text{if firm } i \text{ defaults during year } t\,, \\ 0 & \text{otherwise.} \end{cases}$$

As far as the RMI is concerned, the default events this institution recognizes are the following: *i*) bankruptcy filing, receivership, administration, liquidation or any other legal impasse to the timely settlement of interest and/or principal payments; *ii*) a missed or delayed payment of interest and/or principal, excluding delayed payments made within a grace period; *iii*) debt restructuring/distressed exchange, in which debt holders are offered a new security or package of securities that result in a diminished financial obligation (e.g. a conversion of debt to equity, debt with lower coupon or par amount, debt with lower seniority, debt with longer maturity).

Appendix F Further details of the Banque de France's rating model - Estimation

Empirically, corporate default signals are low-frequency observations, with default rates that barely attain 1% in some sectors. King and Zeng (2001) underlined the effect of rare events on estimators for the generalized linear model with binomial errors and logit link and the fact that Firth (1993) approach could be used to prevent this first order bias.[46] Heinze and Schemper (2002) compared estimators from Firth's method with ordinary maximum likelihood estimators in several samples, finding that Firth's penalized maximum likelihood ensures consistent estimators. Elgmati et al. (2015) more recently showed that reducing the bias in the estimates of coefficients comes at the cost of introducing a bias in the predicted probabilities.

Puhr et al. (2017) recently proposed a two-step estimation to ensure unbiased predicted probabilities, while leaving unaltered the bias-corrected effect estimates. The first-step consists of a logistic regression with Firth-type penalization to obtain

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[46] Firth's method consists on a systematic corrective procedure that is applied ex-ante to the same score function that is used to calculate the estimated parameters.

the bias-corrected estimates, and the second step is an ex-post re-estimation of the intercept of the model using an ordinary logistic regression with a constrained maximum likelihood, that is:

$$\max_{\gamma_0,\gamma_1} l(\gamma_0,\gamma_1)|D,\hat{\eta}) = \sum_{i=1}^{N} -\log(1+\exp(\gamma_0+\gamma_1\hat{\eta}_i)) + (1-d_i)(\gamma_0+\gamma_1\hat{\eta}_i)$$
$$\text{s.t. } \gamma_1 = 1$$

Such that:

$$P(D=1|\hat{\eta}_i) = \frac{1}{1+\exp(\gamma_0+\gamma_1\hat{\eta}_i)}$$

With

$$\hat{\eta}_i = X_i\beta^{firth}$$

We use this estimation procedure for the ICAS statistical financial rating, and between the first and the second steps, we occasionally apply a prudential adjustment to potential relative-risk reversals between two consecutive categories within the same financial theme. At the end of the estimation procedure, we obtain a coefficient for each category within a financial theme, and a probability of default that is associated to a rating class according to a master-scale that is defined empirically with a smoothing cubic spline:[47]

$$S(.) = argmin \sum_{i=0}^{n} \left(log(\hat{d}_i) - S(\hat{\theta}_i)\right)^2 + \lambda \int_{\hat{\theta}_0}^{\hat{\theta}_n} \left(S''(\hat{\theta})\right)^2 d\hat{\theta}$$

Where $\hat{\theta}_i = \hat{\gamma}_0 + \hat{\eta}_i$ represents the median score and $\hat{d}_i$ the log of the default rate of a group of firms with similar scores (Fig. 10).[48]

Appendix G Detailing transmission channels of turnover and value added shocks in firms' probabilities of default: an accounting approach for microsimulations of shocked balance sheet data

We define a financial ratio as:

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[47] Following Antunes et al. (2016), we define a master-scale to assign probabilities to rating classes, using a smoothing cubic spline. This dynamic approach makes it possible to comply optimally with the requirements of the ECAF, in terms of limit default rates over a one-year horizon for each Credit Quality Step (CQS). This semiparametric curve allows then to determine the probability of default thresholds required to assign firms to a rating class. We define Investment-Grade firms, as firms belonging to CQS 1 to 3.

[48] For each year, we gather groups of companies with similar scores, and we compute their median score and the logarithm of their aggregate default rate. A smooth path across all points is then approximated using a semiparametric-curve, and the degree of smoothing is chosen with the Leave One Out Cross-Validation (LOOCV) criterion initially proposed by Craven and Wahba (1978).

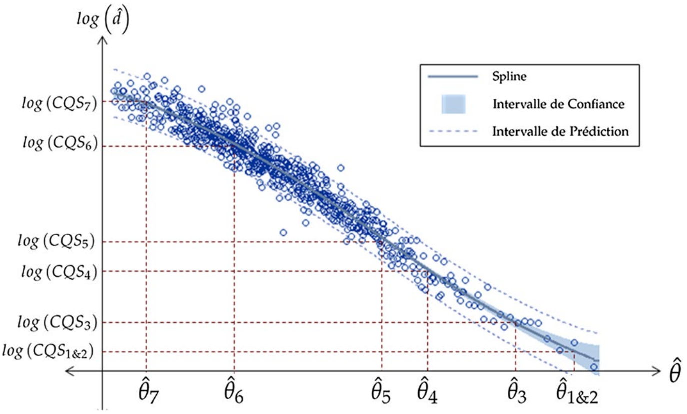


Fig. 10 The Smoothing Cubic Spline and the Empirical delimitation of Credit Quality Steps

$$R = \frac{A_1}{A_2}$$

where A_1 and A_2 are two financial aggregates calculated from firm's financial statements.

The accounting approach consists in finding the accounting expression between the financial aggregates and value added/turnover. In income statements, main financial aggregates can be calculated from value added or turnover in a linear way, for example:

$$A_1 = f(\text{VA}) = \text{VA} - \ldots + \ldots.$$

The microsimulations of shocked balance sheet data will therefore consist on impacting the value added/turnover component of the financial aggregate and reasoning *ceteris paribus* (i.e. holding other balance sheet items constant). The exercise allow us to simulate if the firm has a spare capacity to absorb a value added/ turnover shock, holding other balance sheet items constant. We then obtain after the shock:

$$\widetilde{A_1} = \underbrace{\text{VA} + \ldots - \ldots.}_{A_1} + \underbrace{\lambda\text{VA}}_{shock}$$

where λ represents the percentage change in value added. Therefore:

$$\boxed{\widetilde{A_1} = A_1 + \lambda\text{VA}}$$

We study whether firm's financial fundamentals are sufficient to absorb the underlying shock, and its potential impact on credit risk.

List of shocked financial aggregates

Hereinafter, i indexes firm, t denotes time in years and s is a sectoral index. $\xi_{s,t}$ and $\lambda_{s,t}$ are turnover and value added shocks for sector s at time t, and $\tau_{i,t}$ represents the corporate income implicit tax rate for firm i at time t:

1. Turnover (y), after shock:

$$\tilde{y}_{i,t} = \left(1 + \xi_{s,t}\right) y_{i,t}$$

2. Value added (va), after shock:

$$\widetilde{va}_{i,t} = \left(1 + \lambda_{s,t}\right) va_{i,t}$$

3. Internal financing capacity (ifc), after shock:

$$\widetilde{ifc}_{i,t} = ifc_{i,t} + \lambda_{s,t} va_{i,t}$$

4. Gross operating surplus (gos), after shock:

$$\widetilde{gos}_{i,t} = gos_{i,t} + \lambda_{s,t} va_{i,t}$$

5. Pre-tax profit on ordinary activities ($ptpoa$), after shock:

$$\widetilde{ptpoa}_{i,t} = ptpoa_{i,t} + \lambda_{s,t} va_{i,t}$$

6. Net profit on ordinary activities ($npoa$), after shock:

$$\widetilde{npoa}_{i,t} = npoa_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right) va_{i,t}$$

7. Cash assets (ca), after shock:

$$\widetilde{ca}_{i,t} = ca_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right) va_{i,t}$$

8. Operating cash surplus (ocs), after shock:

$$\widetilde{ocs}_{i,t} = ocs_{i,t} + \lambda_{s,t} va_{i,t}$$

9. Cash at bank and in hand, and convertible assets ($cbhca$), after shock:

$$\widetilde{cbhca}_{i,t} = cbhca_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right) va_{i,t}$$

10. Total Assets (ta), after shock:

$$\widetilde{ta}_{i,t} = ta_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right) va_{i,t}$$

11. Net cash (nc), after shock:

$$\widetilde{nc}_{i,t} = nc_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right) va_{i,t}$$

12. Shareholders' equity (se), after shock:

$$\widetilde{se}_{i,t} = se_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right)va_{i,t}$$

Redefining financial ratios after shocks

Financial ratios are grouped into four categories: financial autonomy, profitability, liquidity, and financial structure.

Financial autonomy Financial ratios in this category measure a company's level of dependence on its financial partners (especially banks). It also gauges a company's ability to meet payments coming due:

1. Internal financing capacity / value added, after shock:

$$\widetilde{R}^{fia}_{1,i,t} = \frac{\widetilde{ifc}_{i,t}}{\widetilde{va}_{i,t}} = \frac{ifc_{i,t} + \lambda_{s,t}va_{i,t}}{\left(1 + \lambda_{s,t}\right)va_{i,t}}$$

2. Stable financial debt / internal financing capacity, after shock:

$$\widetilde{R}^{fia}_{2,i,t} = \frac{sfd_{i,t}}{\widetilde{ifc}_{i,t}} = \frac{sfd_{i,t}}{ifc_{i,t} + \lambda_{s,t}va_{i,t}}$$

3. Financial expenses / gross operating surplus, after shock:

$$\widetilde{R}^{fia}_{3,i,t} = \frac{fe_{i,t}}{\widetilde{gos}_{i,t}} = \frac{fe_{i,t}}{gos_{i,t} + \lambda_{s,t}va_{i,t}}$$

Profitability Financial ratios in this category aim to assess a company's competitiveness, business performances, and ability to generate profits:

1. Gross operating surplus / turnover, after shock:

$$\widetilde{R}^{pro}_{1,i,t} = \frac{\widetilde{gos}_{i,t}}{\tilde{y}_{i,t}} = \frac{gos_{i,t} + \lambda_{s,t}va_{i,t}}{\left(1 + \xi_{s,t}\right)y_{i,t}}$$

2. Pre-tax profit on ordinary activities / turnover, after shock:

$$\widetilde{R}^{pro}_{2,i,t} = \frac{\widetilde{ptpoa}_{i,t}}{\tilde{y}_{i,t}} = \frac{ptpoa_{i,t} + \lambda_{s,t}va_{i,t}}{\left(1 + \xi_{s,t}\right)y_{i,t}}$$

3. Pre-tax profit on ordinary activities / turnover in $t - 1$, after shock:

$$\widetilde{R}^{pro}_{2,i,t-1} = \frac{\widetilde{ptpoa}_{i,t-1}}{\tilde{y}_{i,t-1}} = \frac{ptpoa_{i,t-1} + \lambda_{s,t}va_{i,t-1}}{\left(1 + \xi_{s,t}\right)y_{i,t-1}}$$

4. Pre-tax profit on ordinary activities / turnover in $t - 2$, after shock:

$$\widetilde{R}^{pro}_{2,i,t-2} = \frac{\widetilde{ptpoa}_{i,t-2}}{\tilde{y}_{i,t-2}} = \frac{ptpoa_{i,t-2} + \lambda_{s,t} va_{i,t-2}}{\left(1 + \xi_{s,t}\right) y_{i,t-2}}$$

5. Net profit on ordinary activities / turnover, after shock:

$$\widetilde{R}^{pro}_{5,i,t} = \frac{\widetilde{npoa}_{i,t}}{\tilde{y}_{i,t}} = \frac{npoa_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right) va_{i,t}}{\left(1 + \xi_{s,t}\right) y_{i,t}}$$

6. Net profit on ordinary activities / turnover in $t - 1$, after shock:

$$\widetilde{R}^{pro}_{5,i,t-1} = \frac{\widetilde{npoa}_{i,t-1}}{\tilde{y}_{i,t-1}} = \frac{npoa_{i,t-1} + \lambda_{s,t}\left(1 - \tau_{i,t-1}\right) va_{i,t-1}}{\left(1 + \xi_{s,t}\right) y_{i,t-1}}$$

7. Net profit on ordinary activities / turnover in $t - 2$, after shock:

$$\widetilde{R}^{pro}_{5,i,t-2} = \frac{\widetilde{npoa}_{i,t-2}}{\tilde{y}_{i,t-2}} = \frac{npoa_{i,t-2} + \lambda_{s,t}\left(1 - \tau_{i,t-2}\right) va_{i,t-2}}{\left(1 + \xi_{s,t}\right) y_{i,t-2}}$$

Liquidity Ratios in this category assess a company's ability to support its own development independently. More generally, liquidity ratios supply information about a company's ability to generate new funding sources and maintain a balance between sources of funds and expenses:

1. Cash assets / financial debt, after shock:

$$\widetilde{R}^{liq}_{1,i,t} = \frac{\widetilde{ca}_{i,t}}{fd_{i,t}} = \frac{ca_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right) va_{i,t}}{fd_{i,t}}$$

2. Cash at bank and in hand, convertible assets / short-term debt net of deferred income, after shock:

$$\widetilde{R}^{liq}_{2,i,t} = \frac{\widetilde{cbhca}_{i,t}}{std_{i,t}} = \frac{cbhca_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right) va_{i,t}}{std_{i,t}}$$

3. Sum of operating cash surplus in t and $t - 1$, after shock:

$$\widetilde{R}^{liq}_{3,i,t} = \widetilde{ocs}_{i,t} + \widetilde{ocs}_{i,t-1} = ocs_{i,t} + \lambda_{s,t} va_{i,t} + ocs_{i,t-1} + \lambda_{s,t} va_{i,t-1}$$

4. Net cash / shareholders' equity, after shock:

$$\widetilde{R}^{liq}_{4,i,t} = \frac{\widetilde{nc}_{i,t}}{\widetilde{se}_{i,t}} = \frac{nc_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right) va_{i,t}}{se_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right) va_{i,t}}$$

5. Net cash / turnover, after shock:

$$\widetilde{R}^{liq}_{5,i,t} = \frac{\widetilde{nc}_{i,t}}{\tilde{y}_{i,t}} = \frac{nc_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right)va_{i,t}}{\left(1 + \xi_{s,t}\right)y_{i,t}}$$

6. Net short-term debt / turnover, after shock:

$$\widetilde{R}^{liq}_{6,i,t} = \frac{nstd_{i,t}}{\tilde{y}_{i,t}} = \frac{nstd_{i,t}}{\left(1 + \xi_{s,t}\right)y_{i,t}}$$

7. Cash assets / turnover, after shock:

$$\widetilde{R}^{liq}_{7,i,t} = \frac{\widetilde{ca}_{i,t}}{\tilde{y}_{i,t}} = \frac{ca_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right)va_{i,t}}{\left(1 + \xi_{s,t}\right)y_{i,t}}$$

Financial structure Ratios in this category are used to analyze the resources employed by the company, its level of autonomy and the strength of its structure:

1. Financial debt / shareholders' equity, after shock:

$$\widetilde{R}^{fis}_{1,i,t} = \frac{fd_{i,t}}{\widetilde{se}_{i,t}} = \frac{fd_{i,t}}{se_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right)va_{i,t}}$$

2. Shareholders' equity / total assets, after shock:

$$\widetilde{R}^{fis}_{2,i,t} = \frac{\widetilde{se}_{i,t}}{\widetilde{ta}_{i,t}} = \frac{se_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right)va_{i,t}}{ta_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right)va_{i,t}}$$

3. Loss of more than half the share capital, after shock:

$$\widetilde{R}^{fis}_{3,i,t} = \begin{cases} 1 & \text{if} \qquad \widetilde{se}_{i,t} < \dfrac{sc_{i,t}}{2} \\ 0 & \text{otherwise} \end{cases}$$

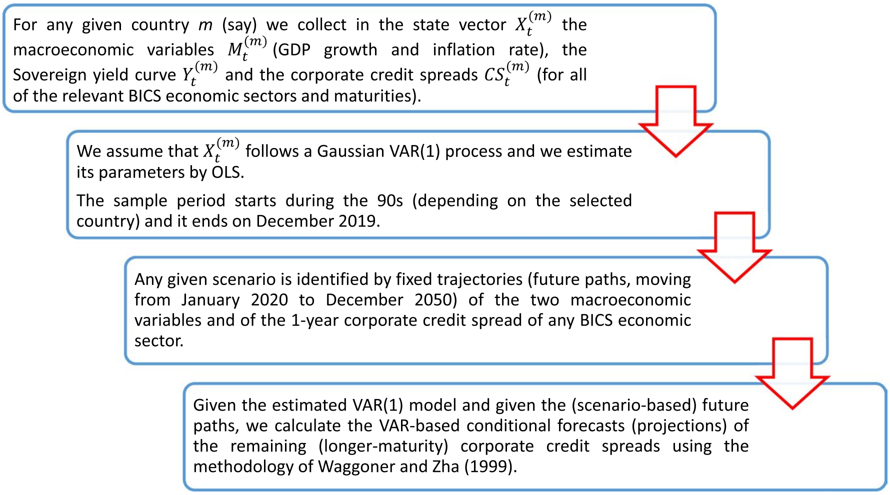
4. Shareholders' equity / share capital, after shock:

$$\widetilde{R}^{fis}_{4,i,t} = \frac{\widetilde{se}_{i,t}}{sc_{i,t}} = \frac{se_{i,t} + \lambda_{s,t}\left(1 - \tau_{i,t}\right)va_{i,t}}{sc_{i,t}}$$

Using these shocked financial ratios, we proceed to recalculate firms' probabilities of default using the aforementioned logistic regression.

Appendix H Scenario-based projections of longer-maturity corporate credit spreads

Figure 11 explains the estimation procedure adopted to obtain the scenario-based projections of longer-maturity corporate credit spreads.



For any given country m (say) we collect in the state vector $X_t^{(m)}$ the macroeconomic variables $M_t^{(m)}$ (GDP growth and inflation rate), the Sovereign yield curve $Y_t^{(m)}$ and the corporate credit spreads $CS_t^{(m)}$ (for all of the relevant BICS economic sectors and maturities).

We assume that $X_t^{(m)}$ follows a Gaussian VAR(1) process and we estimate its parameters by OLS.

The sample period starts during the 90s (depending on the selected country) and it ends on December 2019.

Any given scenario is identified by fixed trajectories (future paths, moving from January 2020 to December 2050) of the two macroeconomic variables and of the 1-year corporate credit spread of any BICS economic sector.

Given the estimated VAR(1) model and given the (scenario-based) future paths, we calculate the VAR-based conditional forecasts (projections) of the remaining (longer-maturity) corporate credit spreads using the methodology of Waggoner and Zha (1999).

Fig. 11 Flowchart of the estimation procedure of longer-maturity corporate credit spreads

Appendix I Alignment with the NGFS scenarios

The proposed narratives are fully aligned with the NGFS reference scenarios, allowing us to extract information from the NGFS database on features that are not embedded in the proposed modelling framework. Table 5 summarizes the source of inputs for the three selected scenarios.

For instance, the carbon price shocks simulated in this paper are precisely set on the trajectories of the respective NGFS scenarios. The GDP estimates, which are generated endogenously by the models, are however calibrated to replicate the NGFS aggregated growth rates for two of the selected scenarios, namely the orderly (baseline) and delayed transition scenarios. The productivity level is used as the adjustment variable to calibrate the model in these two cases. The calibration implies positive productivity gains, which are interpreted as capturing the assumptions embedded in the NGFS scenarios related to technological innovations, changing behaviours, etc.

In the third case of a sudden transition, the simulation uses the carbon price trajectory of an NGFS alternative scenario, with a five-year delay to start in 2025 (instead of 2020). Productivity levels are assumed more adverse compared to the baseline, with no productivity gains assumed over the period. The proposed modelling suite is thereafter used to endogenously generate the GDP levels corresponding to this third more adverse scenario. This adjustment aims to reflect discussions with banks on the likely timeline of policy measures and capture delays in technological progress and their crowding-out effects. All other parameters are identical.

Table 5 Summary of the scenario assumptions

	Orderly transition	Delayed transition	Sudden transition
Carbon price	Input from the NGFS representative scenario for an orderly transition	Input from the NGFS representative scenario for a disorderly transition	Input from the NGFS alternative scenario for a disorderly transition with a 5-year delay to start in 2025
Productivity	Adjustment variable calibrated to match the NGFS GDP figures - translate into productivity gains	Adjustment variable calibrated to match the NGFS GDP figures - translate into productivity gains	No productivity gain assumed - Negative shock compared to baseline
GDP	Matched to GDP targets of the NGFS representative scenario for an orderly transition	Matched to GDP targets of the NGFS representative scenario for an disorderly transition	Generated endogenously by the models

Appendix J Sectors

NACE code	NACE sector name	Abbreviations
A01	Crop and animal production, hunting and related service activities	Agriculture
B	Mining and quarrying	Mining
C19	Manufacture of coke and refined petroleum products	Petroleum
C20	Manufacture of chemicals and chemical products	Chemicals
C23	Manufacture of other non-metallic mineral products	Minerals
C24	Manufacture of basic metals	Basic metals
D35	Electricity, gas, steam and air conditioning supply	Electricity
E37–E39	Sewerage; Waste collection, treatment and disposal activities; Materials recovery; remediation activities and other waste management services	Sewerage
H49	Land transport and transport via pipelines	Land transport
H51	Air transport	Air transport
H50	Water transport	Water transport

Appendix K Corporate credit spreads projections for Rest-of-Europe, USA and Japan

Table 6 here below presents the expected variations (w.r.t. the baseline scenario) of corporate credit spreads for the consumer non-cyclical and fossil energy sectors of Rest-of-Europe, USA and Japan. In the case of Rest-of-Europe, the corporate credit spreads are obtained as GDP-weighted average of corporate credit spreads of Germany, Italy, Spain and U.K.

Table 6 Expected variations (in bps) of corporate credit spreads in Rest-of-Europe, USA and Japan from January 2020 to December 2050 (average over 5-year intervals) for Consumer Non-Cyclical and Fossil Energy sectors. For each country (or economic area), period and sector, the cell $x \mid y$ shows the expected variation (with respect to the baseline scenario) under the delayed transition (x) and the sudden transition (y) scenarios

Years/maturity	Consumer non-cyclical				Fossil energy			
	1-year	2-year	3-year	5-year	1-year	2-year	3-year	5-year
Rest-of-Europe								
2020–2025	0 0	0 0	0 0	0 0	0 1	0 1	0 1	0 1
2026–2030	0 0	0 0	0 0	0 0	−1 −3	−1 −2	−1 −2	0 −2
2031–2035	1 0	1 0	1 −1	1 −2	−5 5	−5 4	−5 3	−5 1
2036–2040	1 1	1 −2	0 −5	0 −6	4 19	3 14	2 11	1 6
2041–2045	0 1	−2 −4	−4 −7	−6 −10	18 24	14 18	11 12	7 6
2046–2050	1 2	−3 −4	−6 −9	−8 −12	21 26	16 19	12 13	7 5
USA								
2020–2025	0 0	0 −1	0 −1	0 −2	0 1	−1 1	−1 0	−1 0
2026–2030	0 0	−2 −1	−2 −2	−3 −3	−3 −6	−7 −12	−9 −15	−9 −15
2031–2035	1 0	2 −1	2 −3	3 −5	−10 11	−18 15	−19 13	−16 8
2036–2040	1 1	4 −1	6 −6	7 −14	9 40	19 59	23 57	22 40
2041–2045	0 2	4 −2	5 −8	4 −19	38 51	71 74	81 71	72 50
2046–2050	1 2	6 −3	8 −12	8 −26	44 57	85 78	98 73	89 47
Japan								
2020–2025	0 0	0 0	0 0	0 0	0 0	0 0	0 1	0 1
2026–2030	0 0	0 0	0 0	0 0	0 −1	0 −2	0 −2	1 −2
2031–2035	0 0	0 0	0 0	0 −1	−2 2	−3 2	−3 1	−3 0
2036–2040	0 0	0 −1	0 −1	−1 −2	1 6	1 8	1 7	−1 4
2041–2045	0 0	0 −1	−1 −2	−2 −3	6 8	8 10	7 9	5 5
2046–2050	0 0	−1 −1	−2 −2	−3 −4	7 9	9 11	8 10	5 6

Appendix L Equity price variations for Rest of Europe, USA and Rest of the World

Figures 12, 13 and 14 here below present relative stock price variation (with respect to the baseline) of climate relevant economic sectors in the Rest of Europe, USA and Rest of the World.

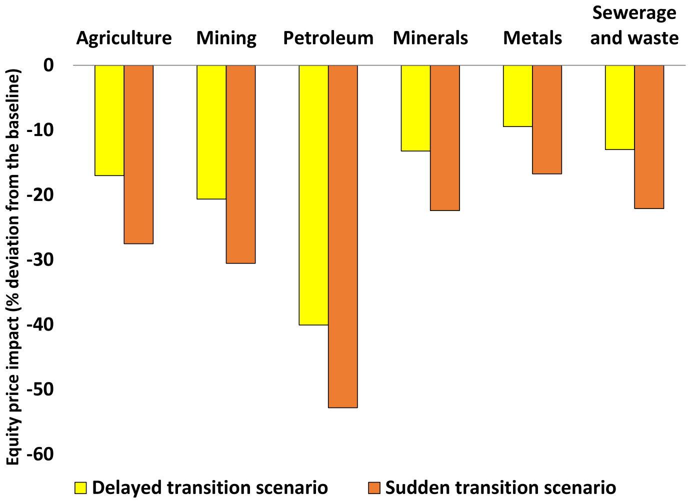


Fig. 12 Equity price impacts across economic sectors - Rest of Europe

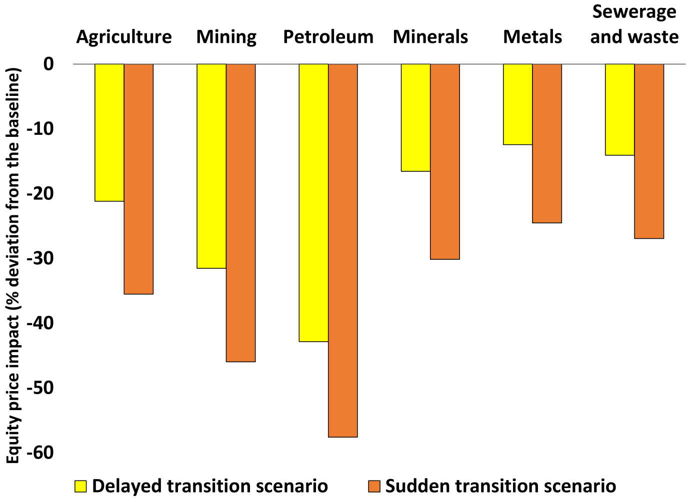


Fig. 13 Equity price impacts across economic sectors - USA

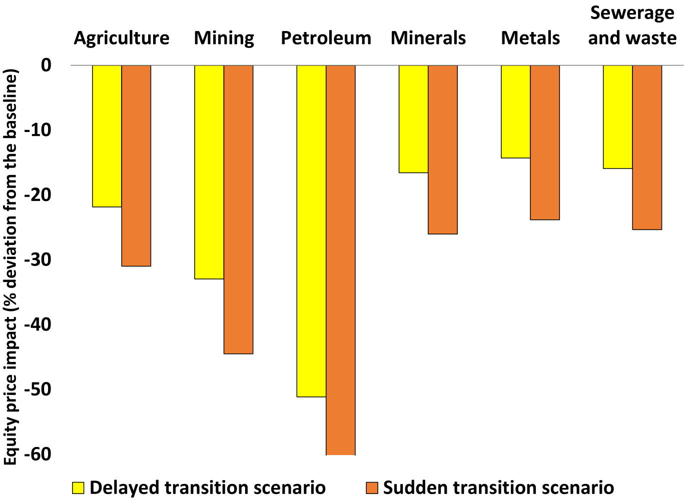


Fig. 14 Equity price impacts across economic sectors - Rest of the World

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