WORKING paper

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EUROSYSTÈME

Climate-Related Scenarios for Financial Stability Assessment: an Application to France

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Abstract

This paper proposes an analytical framework to quantify the impacts of climate policy and transition narratives on economic and financial variables necessary for financial risk assessment. Focusing on transition risks, the scenarios considered include unexpected increases in carbon prices and productivity shocks to reflect disorderly transition processes. The modelling framework relies on a suite of models, calibrated on the high-level reference scenarios of the Network for Greening the Financial System (NGFS). Relying on this approach, the ACPR has selected a number of quantitative scenarios to be submitted to a group of voluntary banks and insurance companies to conduct the first bottom-up pilot climate-related risk assessment.

Keywords: Climate Change, Scenario Analysis, Economic Modelling, Financial Stability

JEL classification: C60, E50, G32, O44, Q40, Q54

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NON-TECHNICAL SUMMARY

This paper proposes an analytical framework to quantify the impacts of climate policy and transition narratives on economic and financial variables necessary for financial risk assessment. Focusing on transition risks, the scenarios considered include unexpected increases in carbon prices and productivity shocks to reflect disorderly transition processes.

The modelling framework relies on a suite of models, calibrated on the high-level reference scenarios of the Network for Greening the Financial System (NGFS). The baseline scenario is aligned with the NGFS narrative and data of an orderly transition toward a low-carbon economy. The severely adverse scenarios feature two different cases of a disorderly transition. The first relates to a delayed transition, which would be implemented only from 2030 onwards and requires an abrupt revision of climate policies. The second scenario covers for the case of a sudden transition. It would start earlier, in 2025, but assume lower technological progresses and crowding-out effects on investments leading to lower productivity levels compared to baseline.

To quantify these scenarios at the appropriate level of sectoral and geographical granularity, we identify three main modelling bricks. First, the NiGEM model is used to assess the impacts of these scenarios, including the baseline case, on key macroeconomic and financial variables. It results from the simulation that the tightening of climate policies, with a sharp increase in the carbon price, generates negative supply shocks with effects on growth and inflation. At the macroeconomic level, each scenario ends up including 12 variables, such as GDP, inflation or unemployment and covers four blocks of countries (France, the Rest of the EU, the USA and the Rest of the World).

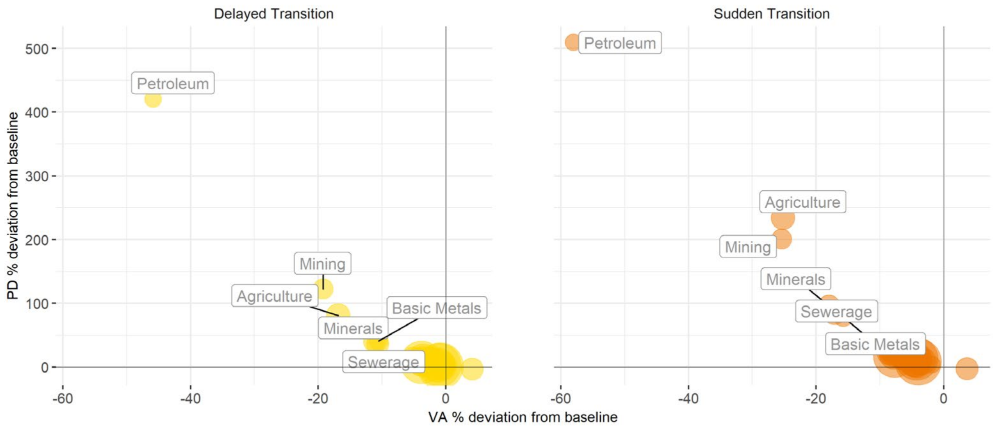
The second brick consists of a static multi-country, multi-sector model developed specifically for this exercise. It assesses the impacts of carbon price and productivity shocks across 55 sectors. Results provide an indication of the magnitude of the sectoral impacts of a disorderly transition, suggesting significative possible disruptions at the sectoral level.

Finally, a financial block is added to the modelling to estimate a number of financial variables. First, the Banque de France's rating model, providing financial information on firms, is used to generate probabilities of default (PD) at the infra-sectoral level. A number of macro-financial variables are further linked up to the modelling architecture. A dividend discount model is calibrated on the macroeconomic and sectoral results for each scenario to estimate the associated market stock price shocks at sector level. Simulations of the EIOPA risk-free interest rates and credit spreads complete the set of information.

The results show the materiality of the negative economic impacts of disorderly transitions toward a low-carbon economy. Although the effects at macroeconomic and financial market levels remain somewhat limited, the impacts on the sectors exposed to the transition policies simulated are substantial. This sectoral heterogeneity is also found at an infra-sectoral level, with companies within sectors affected differently by the transition. The magnitude of these sectoral and infra-sectoral impacts gives rise to financial stability risks that are potentially much more pronounced than macroeconomic and financial market overall levels would have suggested.

The modular approach adopted in this paper provides a flexible and efficient architecture, compartmenting the numerous modelling challenges. Based on this approach, the ACPR will develop and submit a number of climate-related scenarios to a representative group of banks and insurance companies in a bottom-up approach.

Estimated Probabilities of default and Value added by sector (in 2050)



Note: the figure shows firm-level probabilities of default and value added by sector change following two scenarios of disorderly climate transition: delayed (lhs) and accelerated (rhs).

Sources: WIOD, FIBEN, Authors' calculations.

Scénarios de transition climatique pour l'évaluation de la stabilité financière : Une application à la France

RÉSUMÉ

Ce document propose un cadre analytique pour quantifier les impacts de scenarios de transition et de politiques climatiques sur les variables économiques et financières nécessaires à l'évaluation des risques financiers. En se concentrant sur les risques de transition, les scénarios envisagés incluent des hausses non-anticipées du prix du carbone et des chocs de productivité reflétant des processus de transition climatique désordonnés. Le cadre de modélisation s'appuie sur une suite de modèles, calibrés sur les scénarios de référence de haut niveau du Réseau des banques centrales et des superviseurs pour le verdissement du système financier (NGFS). S'appuyant sur cette approche, l'ACPR a sélectionné un certain nombre de scénarios quantitatifs qui seront soumis à un groupe de banques et de compagnies d'assurance volontaires pour mener son premier exercice pilote d'évaluation du risque climatique.

Mots-clés : changement climatique, scénarios, modélisation économique, stabilité financière.

1. Introduction[1]

Climate change is likely to have severe effects on the economy and on financial institutions, possibly posing risks to the financial system as a whole and, therefore, to financial stability. As acknowledged by the Network for Greening the Financial System (NGFS), a group of central banks and supervisors established in 2018, climate change is one important source of structural change affecting the financial system. The group hence recommends "integrating climate-related risks into financial stability monitoring and micro-supervision" (NGFS, 2019a) and promotes joint work among central banks and supervisors on scenario-based financial risk assessment. To this purpose, central banks and supervisors have encouraged undertaking quantitative climate-related risk analysis using scenarios encompassing a range of different plausible future states of the world. In this context, the Banque de France and the ACPR[2] have engaged with banks and insurance companies since April 2019 to discuss the details and appropriate scenarios of a pilot bottom-up climate exercise aiming at assessing the vulnerabilities of the French financial sector to climate-related risks (see ACPR, 2020).

This paper presents the analytical framework developed by the Banque de France and the ACPR to build such scenarios, including a sufficient level of details to cover the needs of financial institutions to run bottom-up exercises. Following an initial exploratory assessment of climate-related risks in the French banking sector (DG Trésor, Banque de France and ACPR, 2017) and a stock take of current practices (ACPR, 2019a, 2019b), this paper focuses more specifically on methodological consistency. The modelling infrastructure builds on a suite of models, including a multi-country macroeconomic model, a sectoral model, various financial market modules and an infra-sectoral risk assessment framework. The paper then provides an application of the framework to two disorderly transition narratives: a "delayed" and a "sudden" transition. 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). While the scenarios developed by the ACPR encompass both types of risk, the framework presented here focuses only on transition risks.

Unlike usual quantitative risk assessments, the probability distribution of risks observed in historical data is a poor guide in the case of climate change-related risks, most of them being unobserved so far. Thus, instead of proposing the best predictions of future outcomes, scenario analyses rely on the comparison of different possible futures, typically testing at least two options such as a baseline and some a priori adverse scenarios (Chenet et al., 2019). The

[1] This paper benefited from detailed comments by Jean Château (OECD) and George Overton (ACPR), and helpful model assistance from Ian Hurst (NIESR). Remaining errors are the authors'.
The authors are also grateful to colleagues who provided useful comments and insights during internal seminars at Banque de France/ACPR, including David Adam, Emmanuelle Assouan, Antoine Boirard, Clément Bourgey, Régis Breton, Christophe Cahn, Gilbert Cette, Olivier de Bandt, Marie-Elisabeth de la Serve, Bertille Delaveau, Morgan Després, Olivier Gonzalez, Ivan Odonnat, Françoise Drumetz, Thomas Ferrière, Sophie Haincourt, Benoit Hallinger, Rémi Lecat, Jean-Stéphane Mesonnier, Sylvain Peyron, Loriane Py, Nathalie Rouillé and Lisa Schirmer.
Karine Craveiro, Julie Navarro, Florence Robert and Murza Tola provided excellent research assistance.
[2] The *Autorité de contrôle prudentiel et de résolution* (ACPR) is the French financial supervisor.

irreducible uncertainty about the future is then considered through the set of scenarios and assumptions, which are deliberately chosen to assess the variety of plausible outcomes.

In the context of climate change, scenario analyses have long been used by the Intergovernmental Panel on Climate Change (IPCC) to assess future vulnerabilities related to transition and physical risks, sketching out transition pathways. These scenarios have been useful in particular to policymakers to assess the effects of various mitigation and adaptation policies under specific assumptions about future economic, social, technological, and environmental conditions. However, they have shown limitations for assessing the implications of climate change at a local or industry sector level (TCFD, 2017). Regarding financial institutions, very few studies have used scenario analyses and most of them have concentrated on the implications of climate-related risks on financial institutions' portfolio or balance sheet levels over short-term horizons. Stress-test exercises have been performed using scenarios or shocks whose occurrence is plausible only 1 to 5 years ahead (e.g. Vermeulen et al., 2018; Battiston and Monasterolo, 2019).

While such stress tests over short time horizons are useful to check the resilience of financial institutions to risks that may materialize in the near future, scenario analysis needs to be developed over much longer horizons in order to identify key vulnerabilities and assess the ability of the financial system to cope sustainably with climate change-related risks. The theoretical framework we propose here therefore builds long-run scenarios, with a time horizon of 2050. To do so, we jointly rely on the multi-country model NiGEM and on the short set of reference scenarios developed at a *high-level* of aggregation by the NGFS, specifying the strength of the greenhouse gas mitigating policy response and how smoothly and foreseeably those actions are taken (NGFS, 2020b).

Although the NGFS high-level scenarios provide information about transition policies, emissions, temperature and GDP for major economic areas, the assessment of financial stability implications of climate change requires, in addition, more detailed information on key macro-financial variables and outlook at more granular levels (sectoral and infra-sectoral). Such details are necessary to provide financial institutions with the data required to run bottom-up exercises that will inform supervisors about their vulnerabilities and exposures to climate change-related risks as well as strategies to adapt. However, translating high-level scenarios into detailed and granular data poses a number of modelling challenges. It requires, in particular, accounting for the links between the economic impacts of climate-related risks at aggregate and granular levels and their implications to financial variables. By combining a number of macroeconomic, sectoral, financial and infra-sectoral models, our approach addresses some of these challenges, and provides disaggregated impacts consistent with the macroeconomic figures from the high-level NGFS scenarios.

The results show the materiality of the negative economic impacts of disorderly transitions toward a low-carbon economy. Although the effects at macroeconomic and financial market levels remain somewhat limited, the impacts on the sectors exposed to the transition policies simulated are substantial. This sectoral heterogeneity is also found at an infra-sectoral level, with companies within sectors affected differently by the transition shocks. The heterogeneity and magnitude of the sectoral and infra-sectoral impacts give rise to financial stability risks that are potentially much more pronounced than macroeconomic and financial market overall levels would have suggested.

The paper is organized as follows. Section 2 explains the specificities of climate-related scenario analyses for financial stability assessment. Section 3 presents the narratives of the scenarios used in the present analysis. Section 4 gives an overview of the modelling infrastructure and Section 5 presents the results at macroeconomic, sectoral and infra-sectoral levels as well as implications for financial market variables. Section 6 puts these results into perspective and provides a discussion of the limitations of the exercise. Section 7 concludes and provides areas for future developments.

2. Scenarios for financial stability assessment: a very specific exercise

As Danish wisdom has it, "it is difficult to make predictions, especially about the future." Several approaches exist, each with its own rationale. The most usual approach is forecasting: one seeks to make predictions of the future based on past and present data, most commonly by exploiting historical regularities. Forecasting could be a purely empirical exercise (i.e., predictions can be made through model-free statistical inference methods) or model-based (i.e., where data is used to estimate the key parameters of a model that is subsequently relied on to inform the prediction, which is deemed to be consistent with the model). Forecasting usually seeks to identify the most likely outcome and its performance will be assessed against what effectively happens (leading to the notion of a forecasting error that one would like to minimize). Scenarios belong to a rather distinct approach: rather than focusing on the identification of the most likely outcome, scenarios highlight the diversity of possible futures, helping explore less conventional pathways while maintaining internal consistency.

After highlighting key generic aspects of scenarios, this section will emphasize the specificities and differences between traditional financial stress test scenarios on one side, and climate scenarios on the other. Central banks and supervisors (alongside financial actors) need to develop a deeper understanding of climate scientists' approach to scenarios in order to develop consistent and relevant climate-related scenario-based financial risks assessments.

2.1. Understanding scenarios from the financial stability perspective

Scenario analysis has been part of the financial sector toolkit for a while. Financial institutions have long used scenarios to gauge the implied risks around their materialization in the future and relied on these assessments for planning and risk management purposes.

Central banks and supervisors have developed in particular stress tests as an exercise to assess the adequacy of capital at individual level or provide a system-wide perspective. The former (known as a microprudential stress test) focuses on the vulnerability of individual financial institutions' balance sheets for a number of years (Constâncio, 2016). The main objective of the latter (also referred to as macroprudential stress test) is to identify the structural vulnerabilities of the financial system that could lead to systemic failures and take preventive actions to mitigate them[3].

These financial stability stress tests are based on the design of scenarios consisting of a set of adverse yet plausible economic and financial events. These scenarios usually include assumptions as to the evolution of a set of key macroeconomic and financial variables (e.g. GDP, unemployment, asset prices, and bond yields) that are supposed to be internally consistent (i.e., conditionally to the trajectory of the other variables) and represent the tail events that could result in important financial losses and systemic risks. These scenario analyses focus on the "fat tail" or rare catastrophic events, such as deep recessions or severe financial crises. They explore lower probability but high impact developments.

In order to provide a relative assessment and/or given the modelling uncertainty, financial stress tests often contrast the outcome of these scenarios against the central case scenario of what is the most likely future outcomes, and focus on the difference between the adverse scenario and the baseline as much as on the consequences of the adverse scenario.

Scenarios also play a significant role in the analysis of climate change and climate change-related developments. 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, scenarios in a climate context represent probable representations of future evolution profiles of greenhouse gas concentrations and various adaptation/mitigation strategies associated with them (IPCC). The common use of the word 'scenario' should not obscure the differences in the practice of scenario analysis.

2.2. Main features of climate change scenarios and their use for financial purposes

The development and use of scenarios in climate science stems from a recognition of the limits of projections (especially when combining various models, e.g. probabilistic climate models and socio-economic models) and an acknowledgment of the deep uncertainty associated with climate change. Climate scenarios typically either describe the socio-economic and policy pathways compatible with a given greenhouse gas (GHG) concentration trajectory or illustrate the change in climate implied by such a trajectory.

In the former case (transition leg), socio-economic pathways correspond to various adaptation/mitigation strategies. These scenarios are meant to be optimal (i.e. cost effective) transitions given a set of policy and technology assumptions. In that sense, they are primarily

[3] These stress tests could 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).

normative scenarios intended for policy planning and evaluation. Scenario analysis is used in this context to inform decision-making under uncertainty, sketching out possible pathways to reach *desired outcomes* (e.g. identify optimal sets of policy instruments or technological mixes that align with a specific GHG emission reduction target).

In the latter case (physical leg), scenarios capture changes in the distribution of climate events (e.g. probability of a given climate related event, see Flato et al, 2013) and their possible outcomes, helping project *likely changes* in climate and their effects on resources. This type of climate scenarios are positive scenarios that help inform about the consequences (to be further translated into an economic impact – more likely, cost) of climate change. While rarely fully combined (see Stern, 2016, for a discussion of the need for and challenges in combining models), a comprehensive climate scenario should bring together both a transition leg and an associated physical leg.

The approach of financial stress tests and the approach of the climate science community both project scenarios that explore a range of plausible futures. However, they differ regarding the likelihood and desirability of these future states. On one hand, stress test scenarios are used to challenge risk management practices and push financial institutions to consider events that may only be remotely possible. On the other hand, climate scenarios revolve around the ideas of *likely changes* and *desired outcomes*. They tend to illustrate possible (and, in some case, aim to design optimal) pathways to achieve an overarching policy goal.

The choice of the baseline

Assessing climate-related financial risks requires specific adaptations to design climate scenarios suited to financial assessment. A key challenge is to identify which scenario serves as a baseline (or reference scenario).

Climate scenarios can first 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[4]. This approach might be informative but purely theoretical and largely inconsistent. It is increasingly difficult today not to recognize that the *status quo* (no transition) will come with change in climate and increased physical risks. This theoretical scenario would be hardly plausible if not outright impossible. An overwhelming majority of climate scientists recognizes today that a business-as-usual scenario will imply physical risks. The challenges in modelling climate outcomes – and therefore the sometimes low estimates of the materiality of physical risks in economics (if not simply absent from the analysis) – should not indulge us into thinking that a business-as-usual scenario would be less adverse than a transition.

A proper risk assessment should contrast a climate scenario incorporating some adverse features (i.e. some tail transition and/or physical risks) with the least adverse scenario as the

[4] An adverse scenario would then be either a transition scenario in line with an ambitious GHG emission trajectory (that would minimize physical risks) or a physical risk scenario consistent with the GHG emission associated with the business-as usual scenario.

baseline. The scenario narrative of a planned and smooth transition is precisely about sketching the least adverse option.

Against this background, climate-related scenarios developed by central banks and supervisors are used specifically for financial risk assessment purposes. Therefore, while informed by climate science, they should not be interpreted as alternative views or critiques of existing climate scenarios, such as those developed by national agencies. Following these principles, the scenarios developed in this paper aim only at assessing financial risks and sketch a future that is neither desirable nor the most likely to occur.

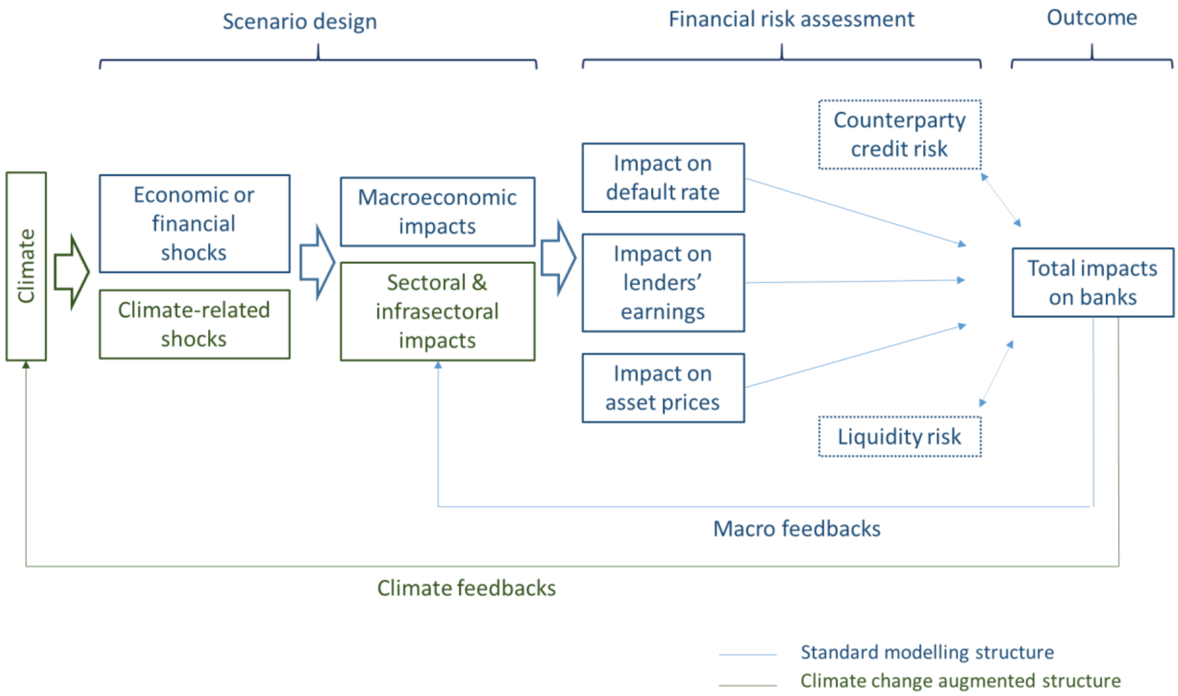
2.3. Climate scenarios fit for financial risk assessment

Central banks' macro-financial scenarios are generally defined for monetary policy or financial risk assessment. In stress test exercises for banks and financial institutions, scenarios are part of a process aiming to evaluate capital adequacy in case of adverse events. A stylized macro-financial stress test framework is presented in Figure 1. The forward-looking solvency analysis of the banking sector begins with the design of adverse macro-financial scenarios, which are then used by banks to simulate the impacts on their risk profiles (e.g., default rates, loss given default, credit ratings) as well as their profitability or loss-bearing capacity. The results are thereafter used to produce the total impact on banks' profits and solvency ratios. In macroprudential stress-testing exercises, a last step is conducted to model second-round effects, i.e., feedback effects on the economy and contagion effects through the financial markets.

Climate change-related stress test scenarios involve some changes compared to the standard stress test framework defined above. Patterns and potential shocks related to climate change need to be integrated upstream, at the scenario design stage; this implies a number of specific extensions all along the chain of models and modules to assess climate-related impacts on institutions' balance sheets and potential feedback to the economy. Figure 1 highlights some of the key changes to the standard stress test framework.

First, a new diverse set of climate-related scenario drivers need 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 central banks need to be prepared. These factors can relate to environmental conditions (e.g. whether events), longer-term physical impacts (e.g. impacts on infrastructure), climate policy (e.g. change in carbon pricing or regulation), or technology (the development of renewable sources of energy). Possible shocks are related to change in policy (e.g. different levels of carbon taxation or changes to the value of energy-related fixed capital/investment), change in energy and food prices, energy-related available technologies, energy demand, or market confidence.

Figure 1: Modelling structure of a climate-augmented macro stress test



Source: Adapted from Borio et al. (2014)

This new set of factors requires connecting the dots with the climate change-economy modelling literature, which has been developing approaches and models to inform policy makers of the interactions between economic and climate variables, and the potential trade-offs of different climate change scenarios. Transmission channels between climate change-related shocks and macro-financial risks need to be further identified to assess quantitatively their impacts on the financial system. The growing body of literature in climate economics can help model how climate-related shocks feed through the economic system.

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

Another key difference with standard stress-testing exercises relates to the horizon of risk materialisation. While stress-testing financial institutions requires a forward-looking analysis that typically does not expand beyond 3 to 5 years, climate change-related stress tests may require much further horizons. Analyses of physical risks might focus on multi-decade horizons given that some of the most (economically/financially) significant of these risks might not materialize in the short run. At the same time, not all climate change scenario analyses need to be long term. Although the horizon may be expanded compared to standard stress tests, climate change-related analyses should integrate short- to medium-term effects. First, 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. Likewise, some physical risks have also started to materialize with higher frequency of extreme weather events in many parts of the world. Short-term shifts in market sentiment induced by awareness of future climate risks could also lead to economic shocks.

2.4. The need for a carefully disaggregated approach

An important point that needs to be strongly emphasized is that climate change analyses need a much higher level of disaggregation than standard stress test scenarios. Usual stress tests have often focuses on macro-financial aggregates.

For transition risks, it is important to study effects at the sectoral level at least and in some cases, at the infra-sectoral level. For instance, as a general principle, industries that emit a high amount of CO_2 will be more severely hit if a price is imposed on carbon emissions (be it a direct price through a tax or an ETS-type scheme, or a shadow price through stricter norms). Yet, even within sectors, some actors might be more advanced than others and able to benefit earlier than others from induced changes. It might even prove highly erroneous to model, for example, the impact of a carbon tax proportionally with GHG emissions at an insufficient level of disaggregation.

Current approaches to climate change-related stress test have so far focused, at best, on cross-sector comparisons and neglected infra-sectoral dynamics. However, companies are increasingly challenged for action on climate change. Some have "turned the corner" and 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 exposure to climate change within a particular industry.

From a financial stress test perspective, this would be especially relevant when the low carbon transition implies an overall reduction of demand, as only the most advanced actors would efficiently operate in the sector while others would fail as the overall capacity of the sector adjusts downwards[5].

Firm size and business models, on top of climate/environmental related strategies and financial robustness, are also essential determinants of risk exposure and firms' capacity to leverage opportunities from changes in their business or policy environment. Although there might not be direct relationship between strong financial performance and an effective

[5] For instance, within the automobile industry, some car manufacturers have explicitly positioned themselves on possible alternative engine technologies (e.g. investments in electric vehicles). Similarly, car part suppliers might be involved in different segments of the supply chain, which might be differently exposed or able to cope and transform following a new environment policy.

strategic approach to climate change, both might impact the sensitivity of a firm to climate change-related risks.

A model based on a relatively aggregated sectoral classification may be unable to fully account for composition effects within a sector, for instance the entry of firms using green technology and the exit of firms relying on highly polluting technologies. This is especially true for the energy sector: while a coal power plant may be strongly hit by a carbon tax, green energy providers may flourish simultaneously. Modelling the energy sector as a single sector will achieve an average impact that may underestimate the within-sector heterogeneity in entry and exit. By considering a sectoral classification with 55 sectors (including two energy sectors), the modelling approach proposed in this paper tackles some of these issues, although incompletely because of remaining data limitations.

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).

3. The transition narratives

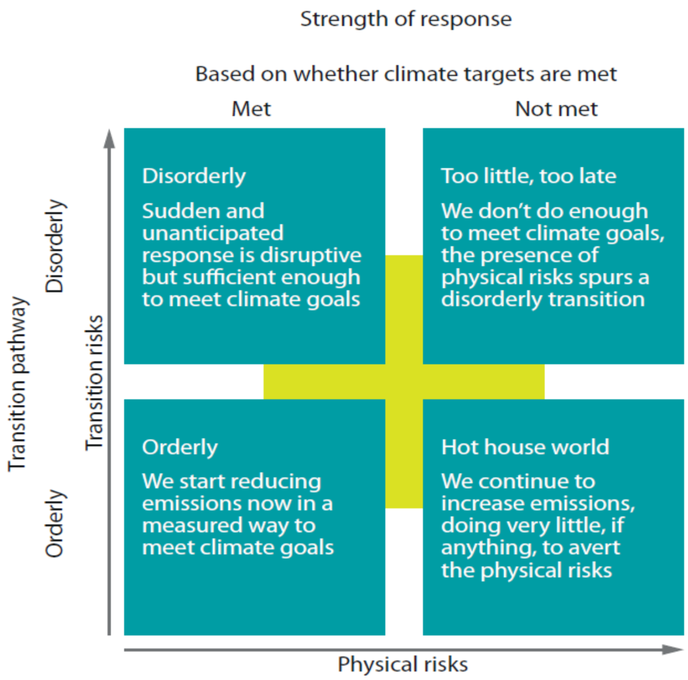
Scenarios are meant to provide a coherent and plausible story about possible futures. In this section, we present the qualitative storylines underlying the proposed quantitative scenarios. These narratives explore uncertain events. They provide consistent views on possible transition pathways, identifying plausible shocks on the economy. 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, for instance on physical and climate variables. The modelling approach presented in the following section focuses on macroeconomic, sectoral and financial information necessary for financial risk assessment purposes.

3.1. The NGFS reference scenarios

The NGFS classifies scenarios in four broad groups, which can be presented in a matrix (NGFS, 2019b). Figure 2 combines two important dimensions: the level of mitigation effort and the degree of uncertainty of the transition. In a first class of scenarios, the transition to a low-carbon economy occurs in an "orderly" way, i.e., smoothly and foreseeably while meeting the climate targets, which implies manageable transition risks and reduced physical risks. At the other end of the spectrum, the transition to a low-carbon economy might be insufficient and occur too late to meet climate objectives and prevent physical risks. As physical risks materialize, economies may need to take swift actions and shift towards a low-carbon economy, with transition risks occurring alongside physical risks. This "too little, too late" scenario is probably the most severe in the long-run. An intermediate situation relevant for stress testing would be a "disorderly scenario", where an abrupt transition occurs, implying a disruptive response with high transition risks but meeting climate goals. The "hot house world" would represent the final case, with severe long-term physical risks if we continue on our current business trend.

The NGFS has since been working on these key narratives with the academic community to select a set of data-driven reference scenarios that can be used by central banks and supervisors for macro-financial analysis. This includes a number of transition risks, physical risks and macroeconomic variables. These scenarios draw primarily on existing IPCC mitigation and adaptation pathways[6].

Figure 2. The NGFS matrix - Four categories of scenarios



Source: NGFS (2019b)

Three representative scenarios and a number of alternates

Building on these assumptions, the NGFS has proposed a representative scenario for three of the four categories of scenarios identified. The first scenario refers to an orderly transition. It assumes an immediate introduction of an optimal carbon price. That price increases by

[6] The IPCC collates and assesses a number of physical and transition scenarios. Building on Integrated Assessment Models (IAMs), these scenarios set out pathways for the atmospheric concentration of GHG and their consequences in terms of climate impacts. The IPCC reference scenarios combine different possible socioeconomic futures – the Shared Socioeconomic Pathways (SSPs), which provide the socioeconomic backdrop – with different climate outcomes – the Representative Concentration Pathways (RCPs), which describe different emissions trajectories. This matrix architecture draws a number of possible mitigation options that link SSPs future states with RCPs' climate outcomes (O'Neill, 2014; Riahi et al., 2017).

about \$10/ton of CO_2 per year until 2050[7]. Since the carbon price is introduced early and is increased steadily over time, physical as well as transitional risks remain low, with a climate target of 2°C attained by 2100.

The second scenario depicts a delayed policy response, with a sudden implementation of new regulations (e.g. ban on coal, imposition of carbon taxes). This scenario narrative dictates that until the year 2030, climate policy follows only nationally determined contributions (NDCs). In 2030, the carbon price is abruptly revised and increases by about \$40/ton of CO_2 per year afterwards to keep on track with climate commitments. The year in which net zero emissions will be reached is estimated to be around 2050. This scenario assumes that there is only limited Carbon Dioxide Removal (CDR) technologies available.

Finally, the third proposed scenario is a business-as-usual scenario to capture what would happen if no additional measures were taken. This scenario results in severe physical risks, with an estimated median temperature rise close to 4°C by 2100, but rather insignificant transition risks. Given the focus of this paper on transition risks only, this scenario has been discarded in this paper[8].

Other scenarios have been further identified as NGFS 'alternates' for each of these three families of scenarios. This has been done with the aim of simplifying communication and implementation, while also providing a rich database of scenarios for NGFS members to choose from depending on their needs. None of these scenarios has been proposed as a possible baseline; it is for each user to decide which scenario is appropriate as a reference scenario depending on the objective of the exercise. For more information, please refer to the NGFS reference scenario publication.[9]

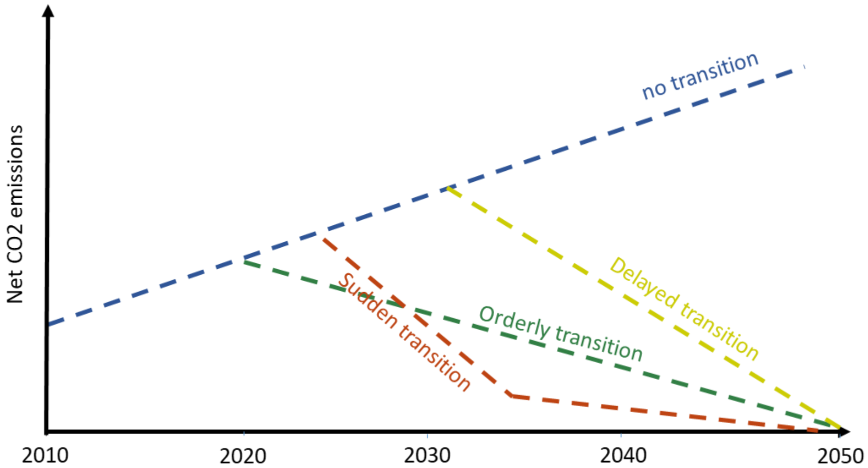
3.2. The three proposed scenarios

Building on the NGFS reference scenarios, three narratives focusing on transition risks have been developed to meet the Banque de France/ACPR specific purposes. The selected set of scenarios includes a baseline and two progressively more adverse alternative 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 spill-over effects on productivity. Each scenario combines 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

[7] The NGFS has used three IAM models to generate its reference scenarios, each providing slightly different results for each variables. One model has therefore been selected as a "marker" for each scenario, the other two models (when available) proving an indication of the validity range around the estimates.
[8] This scenario has however been included in the scenario-based framework developed for the ACPR 2020 climate pilot financial risk assessment exercise (ACPR, 2020).
[9] See https://www.ngfs.net/en/liste-chronologique/ngfs-publications

expected in the baseline). Figure 3 presents the three stylized scenarios in terms of their implied CO_2 emission profiles.

Figure 3: Proposed scenarios in terms of emission profiles



Baseline scenario: An orderly transition

As mentioned earlier, a first key question is to decide which scenario would best fit as a baseline. Baseline scenarios are frequently used in risk assessment such as stress testing in order to contrast the results under an adverse scenario with the results of a "business as usual" scenario. The baseline scenario usually reflects the most likely macroeconomic outlook. In the case of climate-related risk, however, the "business as usual" scenario indicates a scenario with limited mitigation efforts, which could in turn lead to severe physical risks. It might thus be more 'adverse' in this context than what would be expected from a baseline.

Given the nature of our exercise, it is assumed here that the most appropriate family of scenarios used for the 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 reach specific climate outcomes minimizing the trade-offs between climate and economic growth objectives, some even translating into more positive economic impacts than the forecasted trends.

The NGFS has proposed a representative high-level orderly scenario, informing a number of the key features of this transition including a global carbon price and growth trends for a set of country blocks. In terms of narrative, an orderly transition would correspond in France to the *Stratégie Nationale Bas Carbone*[10] (SNBC). The SNBC is the road map designed to sketch how France will fulfil its Paris agreement commitments, i.e., reaching zero net emission by

[10] In English, the French National Strategy towards a Low Carbon Economy. It has been first published in 2015 and is currently under revision.

2050. Currently under revision, it is assumed to reduce GHG emissions accordingly, while translating into positive impacts on growth and employment.[11]

Adverse scenario 1: A delayed policy action scenario

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, the government decides to revise the carbon price.

The NGFS proposes a representative high-level 'disorderly' transition that matches precisely this narrative. Our first adverse scenario has been precisely set according to this NGFS scenario features, reproducing its growth trends.

The revision of the carbon price implies a number of shocks over the period, jumping from $87 per ton of CO_2 in the baseline to $219 in 2035 (in the European Union), increasing steadily onwards. 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: An 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. It combines an early increase in the carbon price with a productivity shock. In this scenario, the carbon price is unexpectedly revised and assumed to reach $184 per ton of CO_2 in 2030, following the carbon trajectory set in the alternate NGFS reference scenarios for a disorderly transition. In parallel, it is assumed that, in 2025, low-carbon energy production technologies are not to be as mature as expected, and the required investments translate into lower productivity gains compared to the baseline scenario.

Alignment with the NGFS and calibration

The proposed scenarios are quantified using inputs from the NGFS reference scenarios. The NGFS database provides projections until 2100 for a set of variables for the main economic areas, including the price of carbon. The carbon price shocks simulated in this paper are

[11] Introduced by the Law on Energy transition and Green growth (LTECV), the SNBC defines the national, as well as sectoral, objectives over the medium to long term for France to reach its international commitment to achieve carbon neutrality by 2050. Currently under revision, the SNBC introduces new and ambitious objectives in terms of energy efficiency, GHG reductions and development of renewable energies:

- Reduction by 20% of final energy consumption in 2030 compared to 2012;
- Reduction by 50% of final energy consumption in 2050 compared to 2012;
- 23% of final energy consumption in 2020 out of renewable sources, and 32% in 2030;
- Reduction by 40% of its total emissions in 2030 compared to 1990;
- Reduction by 75% of its total emissions in 2050 compared to 1990 (Factor 4).

precisely set on the trajectories of the respective NGFS scenarios. Table 1 summarizes the source of inputs for the three selected scenarios.

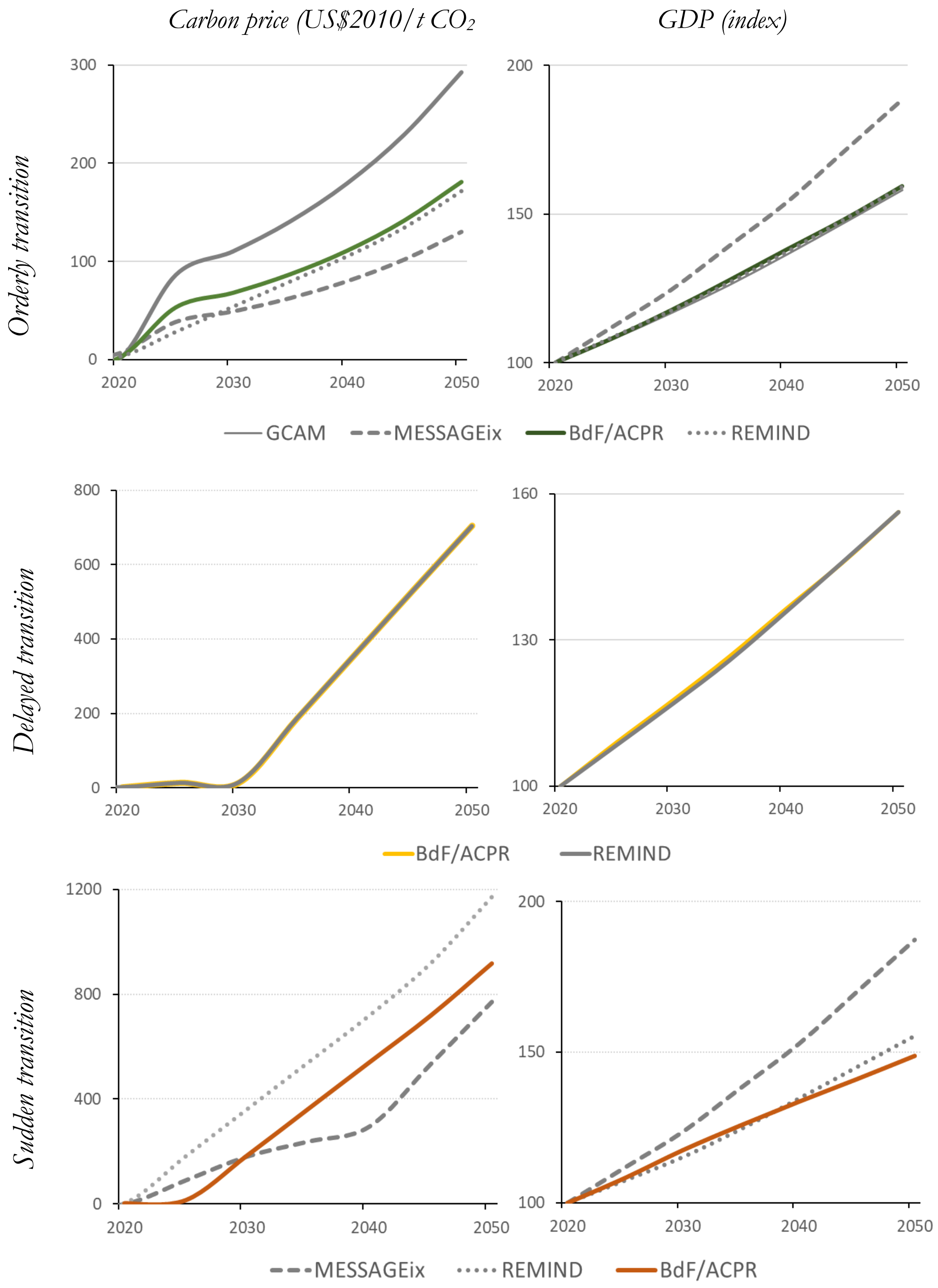
The GDP estimates generated by the models, which will be presented in the following section, are furthermore calibrated to replicate the NGFS aggregated growth rates for two of the selected scenarios, namely the orderly (baseline) and delayed transition scenarios. The productivity level is used as the 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 constant, generating therefore no productivity gain (contrary to the baseline). 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 across scenarios and held constant throughout the simulations. See Table 1 for a summary of the scenario assumptions.

Table 1 – 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

Figure 4: Alignment with the NGFS - Carbon prices and GDP growth[12]



Sources: NGFS and authors' calculations.

Note: The NGFS reference scenarios are constructed using three IAMs, namely GCAM 5.2, MESSAGE (with GLOBIOM) and REMIND (with MAgPIE). GCAM is the 'marker' model for the orderly transition scenario and REMIND the 'marker' model for the disorderly transition scenario.

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[12] Growth rates for the EU.

The NGFS high-level reference scenario data has thus been used as inputs for all scenarios. While productivity levels in the delayed transition scenario have been precisely calibrated to replicate the NGFS aggregated output, they have been set constant over the period in the sudden transition scenario. Figure 4 provides the details of the different carbon price trajectories used and an indication of the alignment of the three selected scenarios with the NGFS growth trajectories.

While a disorderly transition might be costly to the economy, the benefits of early action would still lead to significantly higher economic growth rates and returns over the long run compared to a worst-case 'no transition' scenario (or 'hot house world'), which would depicts future developments in a world without climate mitigation measures. Results from macroeconomic studies show that this scenario would trigger larger economic losses in the long run. For instance, Alestra et al. (2020) show that net GDP losses induced by climate policies in the medium term turn into favourable net impacts in the long term, thanks to the avoidance of greater climate damage. By contrast, in a 'no transition' or 'business-as-usual' scenario, global GDP would incur a loss of 12% at the 2100 horizon due to physical damages, which would be larger at such a horizon than any costs related to transition policies. Although not considered in this paper, this 'no transition' scenario including physical risks would deserve attention and has been included in the financial risk assessment conducted in 2020 (ACPR, 2020).

4. The modelling approach

A comprehensive scenario for stress-testing exercises usually extends several years into the future, which calls for the use of structural and time series models. In most cases, the construction of stress-test scenarios relies on suites of models, involving for instance reduced-form VAR-type models, multi-country structural models or non-parametric financial models. In all cases, the modelling apparatus aims at providing the macro-financial impacts of adverse shocks and how such shocks spill over across markets and countries[13]. Ultimately, the main objectives of the stress-test modelling infrastructure is to provide a set of risk factors that are relevant to obtain the sensitivities of financial institutions to such adverse scenarios.

As explained above, although climate-related scenarios require the same features as those built for standard stress-testing exercises, they are also more specific in two respects. First, they require the projections of a large number of macro-financial variables over very long time horizons and, second, they entail a more granular sectoral disaggregation of both economic and financial variables. As it would be a huge endeavor to build a single tool able to provide paths of variables at such a level of detail, the approach followed here relies on a

[13] See for instance Dees et al. (2017) for a description of a model suite for stress-testing purposes.

suite of models that translate transition scenarios obtained from climate models into macroeconomic, sectoral, financial and firm-level variables.

Figure 5 illustrates our modelling strategy, relying on a set of tools that are linked together in a modular approach. We combine climate models – the so-called Integrated Assessment Models (IAMs), a multi-country macroeconomic model – NiGEM, a sectoral model specifically developed in-house[14], the rating model of the Banque de France and a set of financial modules.

The initial input comes from the IAMs used to derive the NGFS high-level scenarios. These models provide GDP trajectories, carbon prices and GHG emissions for a number of country blocks (including EU, USA, rest of the World). The carbon prices trajectories are used as inputs to set the rates of carbon tax in NiGEM and the sectoral model, thus endogenously impacting GDP in both models. As explained earlier, for the baseline and the delayed transition scenario (Scenario 1), productivity shocks are calibrated in both NiGEM and the sectoral model so that the combined impact of carbon tax and productivity shocks matches the GDP trajectories given by the IAMs, ensuring consistency across the three models. For the sudden transition scenario (Scenario 2), we depart from the GDP trajectory implied by the IAMs: we assume no productivity gains in the sectoral model, and let GDP adjust endogenously to the carbon tax shocks[15].

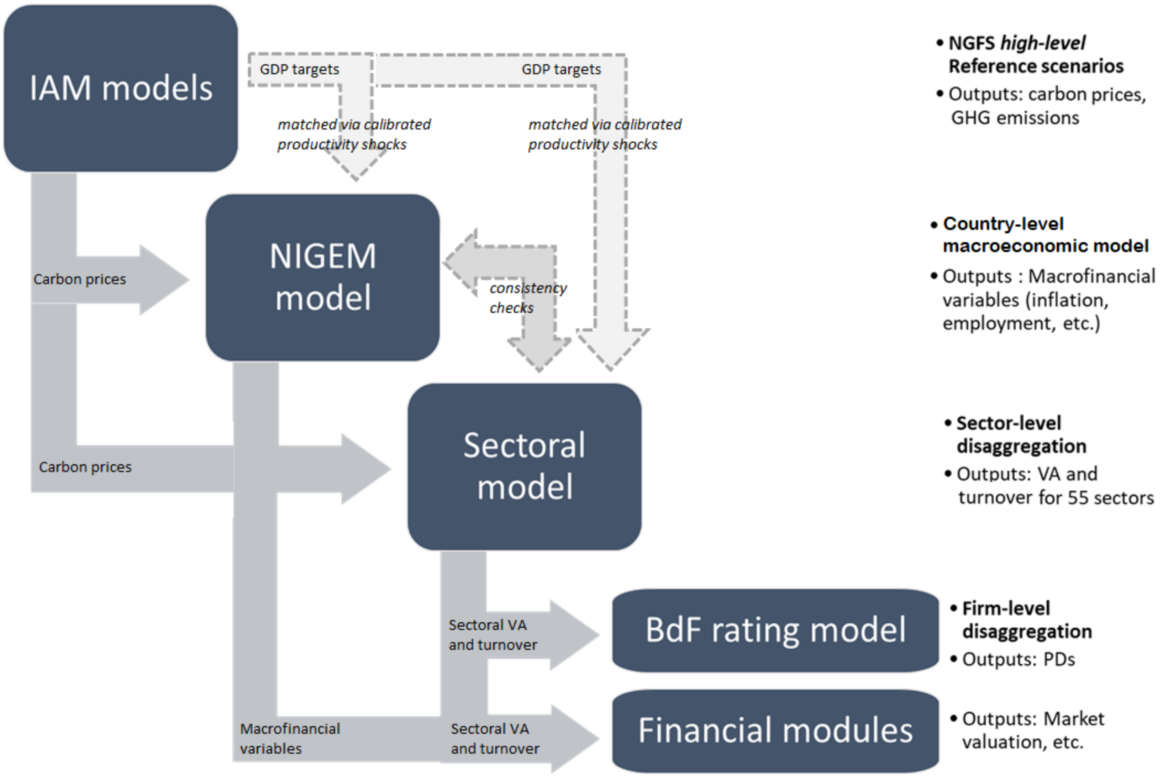
While NiGEM incorporates a number of nominal frictions that ensure a progressive diffusion of the shocks across the economy, the sectoral model is static, does not include any frictions and jumps directly to the new post-shock general equilibrium. To rebalance this across the two models, we therefore assume that the new, post-shock equilibrium described by the sectoral model is only attained five years after the shock occurs.

NiGEM provides a wide range of macroeconomic and financial variables across economies worldwide, while the sectoral model translates the transition scenario variables into impacts in terms of value-added and turnover at the sectoral level for France, the rest of the EU, the US and the rest of the World. Based on these sectoral results, the rating model of the Banque de France is used to assess financial outcomes at firm-level. Finally, a set of financial modules has been developed to translate the macroeconomic, sectoral and firm-level projections into financial variables, such as yield curves, asset prices and interest rate spreads of corporate bonds.

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

[15] Small, mostly negative productivity shocks are then added to the carbon tax shocks in NiGEM in order to match the GDP trajectories obtained from the sectoral model and ensure consistency.

Figure 5 - The modelling architecture



4.1. The macroeconomic model

Most of the macroeconomic variables used in the scenarios are simulated using NiGEM (*National institute Global Econometric Model*). NiGEM is a global macroeconomic model consisting of individual country models of New Keynesian structure. Each country/region is modelled through a dynamic set of equations where agents are generally assumed to have rational expectations[16] and there are nominal rigidities that slow the process of adjustment to external shocks (see Hantzsche et al., 2018, for a detailed introduction). Importantly, each country model has a well-specified supply side over the medium term. International linkages come from patterns of trade, the influence of trade prices on domestic prices, the impacts of exchange rates and patterns of asset holding and associated income flows. 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 (See Appendix 1 for details on NiGEM country coverage).

Although NiGEM is not a climate model, it has benefitted 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

[16] In general, the model can be solved under a number of different assumptions about behaviour: for example, whether expectations are rational or adaptive. In our simulations however, given the size and length of the shocks implemented, the model could not easily converge under rational expectations, so all simulations were carried out under adaptive expectations.

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. Moreover, the geographically-diverse characteristic of French banks' portfolio requires a detailed country coverage that NiGEM is able to provide, as well as a number of variables other than GDP (inflation, interest rates, public deficits…). As most macroeconomic models, NiGEM has however some limitations. In particular, it is not designed to simulate structural changes, such as those expected from the transition to a low carbon economy.

Below, we describe the features of the model most useful for understanding the transmission channels of the economic shocks implemented in the scenario simulations, as well as the additional subsets of equations that were integrated to the standard version of NiGEM to account for the specifics of the climate-related scenarios[17].

Carbon tax and prices of fossil fuels

Carbon emissions associated with the production process are not explicitly modelled but 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[18].

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.

A carbon tax can be introduced by increasing a country's price of fossil fuel. Prices of fossil fuels are determined at the international level and depend, among other variables, on world demand for each fossil fuel. Each individual country adjusts its short-term demand for oil, for example, on the evolution of international oil prices, and in the long term, oil demand will have a unitary elasticity to prices.

More specifically, in the model version used here, a country-specific *effective* price for each fossil fuel has been introduced in the equations including the international price and an extra element that represents the country tax levied on each fossil fuel.

$$Effective\ Price_{country\ X}^{Fossil\ fuel\ F} = International\ price^{Fossil\ fuel\ F} + Tax\ on\ usage_{country\ X}^{Fossil\ fuel\ F}$$

[17] We thank NIESR for working with us and communicating on a preliminary version of its "climate model extension" of NiGEM. This model extension has been presented in a slide deck available to users on the NiGEM website: *NiGEM Climate model extension,* NIESR, February 2020.

[18] See Appendix 1 and Hantzsche et al (2018) for details.

This effective price will then feed into each country's demand for oil, allowing its demand to respond to the tax as well as to changes in international prices. An interesting point is that, while international oil prices are exogenous at the country level, they adjust to changes in world demand for oil at the international level. This implies that a tax that is large enough and imposed in a large country (whose share is important in oil demand) will have a negative effect on world demand for oil and, assuming that supply is unchanged, international prices will decrease to reflect this reduced demand. The final impact of the tax on the effective price of oil will be lower due to the adjustments in international prices.

In practice, this tax on fossil energy is calibrated according to a predetermined path of carbon price and the carbon emissions associated with the CO_2 emissions for each type of fossil fuel; for instance, coal will have a much larger tax than oil or gas. This follows Vermeulen et al (2018), who use this approach to carry out DNB's energy risk transition stress tests[19].

$$\begin{aligned} &Tax\ on\ Fossil\ fuel\ usage \\ &\qquad = CO_2 emission\ per\ oil.equivalent\ barrel \\ &\qquad \times Unit\ conversion\ coefficient \times Carbon\ price\ per\ ton \end{aligned}$$

Price equations

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 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). In many countries like France, the carbon tax is often levied on consumers through a specific tax on gasoline prices, which depends on total sales of gasoline[20]. There are two ways of introducing a carbon tax on consumers in the NiGEM framework: either through a calibrated VAT increase, or through an *effective* import price of oil[21]. The latter has been chosen here in order to better exploit the pass-through mechanisms of the model (the increase in consumer prices will depend on each country's share of oil, for instance, in the consumption basket)[22].

[19] 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 kilograms for oil, 653 kilograms for coal and 316 kilograms for gas. A unit conversion coefficient is included to take into account the different unit measures of fossil fuels.

[20] *Taxe intérieure sur la consommation de produits énergétiques (TICPE)* in France.

[21] Most countries in NiGEM are considered net importers of oil.

[22] However, given the large oil price shocks implemented in the simulations and the generally dynamic trade equations in NiGEM (where the import volume of oil is not modelled separately), this *effective* import price of oil will not affect overall import volumes directly but only through second-round effects (overall increase in non-oil prices).

$$Effective\ import\ prices_{country\ X} = \alpha_X^{oil} \times Effective\ import\ price\ of\ oil_X + \sum_i \alpha_X^i \times Import\ price\ of\ good\ i$$

where α_X^{oil} is the share of imports of oil in country X's imports. This *effective* import price of oil will then feed into the consumer prices equations in place of regular import prices.

Redistribution of tax proceeds

As such, the carbon tax has been modelled through an increase in prices of fossil fuels, but 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 oil. Since oil 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 oil (following the increase in the effective price). Those tax proceeds are then, by default, added to the government's budget as an additional revenue source.

With no further action in NiGEM, the tax proceeds could be used as a means to finance the government's deficit. NiGEM however includes a "solvency rule" for government finances which ensures that in the medium term, the government's budget converges to a specific target. Short-term deviations from the target are compensated through corresponding increases or decreases in households' income tax rate. In our simulations, this solvency rule has been deactivated 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. We chose to redistribute the tax proceeds through a decrease in households' income tax rate, but in this framework another option could have easily been chosen instead.

Monetary policy assumptions

Finally, in our scenario simulations, monetary policy is endogenous and therefore reacts to changes in GDP and inflation according to a Taylor rule (see Appendix 1). However, it is worth highlighting that 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.

4.2. The sectoral model

The macroeconomic results from NiGEM are coupled with an in-house multi-country multi-sector framework that gives a disaggregated picture of the economy for four blocks of countries: France, Rest of EU (RoEU), USA and Rest of the world (RoW).

This 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). Moreover, 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 and 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 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. Concretely, 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 $N_E \leq j \leq N$, where N is the total number of sectors in the world), using the following CES technology with 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 $E_i = \left(\sum_{j=1}^{N_E} \left(\frac{\alpha_{ji}}{\alpha_{Ei}} \right)^{\frac{1}{\sigma}} Z_{ji}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}$ and $I_i = \left(\sum_{j=N_E+1}^{N} \left(\frac{\alpha_{ji}}{\alpha_{Ii}} \right)^{\frac{1}{\varepsilon}} Z_{ji}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}$

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).[23] The values of the substitution elasticities θ, σ and ε are obtained from the literature (see Appendix 2 and Devulder and Lisack (2020) for their calibration). We assume constant production technology. This will be discussed in section 6.

Within this framework, we impose sector-specific carbon taxes proportional to sectoral GHG emitted and declined into three types of taxes. First, there is a tax on a sector *i*'s

[23] World Input Output Database, see Timmer et al (2015).

production, proportional to 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 with 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 $\sum_{j=1}^{N} P_j \zeta_{ji} Z_{ji}$, but all ζ_{ji} corresponding to sectors *j* other than fossil fuels producers are zero. Last, each household pays a tax (at a rate κ) on her consumption of refined oil and coke that is proportional to the households' emissions of GHG (e.g., a tax paid by a household on gas used for their car). All tax proceeds are redistributed in a lump-sum fashion to the household of the country where they are levied. More details on the tax calibration strategy are available in Devulder and Lisack (2020).

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

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

subject to its production technology. In this expression, w is the wage rate in the country where firm *i* is located, and both taxes on production and fossil fuels inputs described above enter as expenditures.

The representative household maximizes a CES utility function subject to a budget constraint. The model assumes perfect international risk-sharing: households trade bonds internationally so that country specific shocks affect households' revenues abroad.

In the considered scenarios, taxes are applied in all countries. They are set building on the NGFS carbon price data. Since the sectoral model is a static set-up, we can compare the before- and after-tax situations and evaluate which sectors are most impacted by the tax, either positively or negatively.

In the delayed transition scenario (Scenario 1), we add to the above tax hikes country-wide TFP shocks (through changes in A_is that we impose to be identical for all sectors *i* located in the same country). As explained earlier, these shocks are calibrated so that the sectoral model matches the country-level impacts on real GDP provided by the NGFS for the baseline and delayed transition scenario. In the sudden transition scenario (Scenario 2), we assume that these productivity shocks, implicitly present in the baseline, do not occur. The simulation is hence performed without any productivity improvement compensating for the tax hikes, leading to more adverse impacts on real aggregate GDP and sectoral value added.

4.3. The financial models

The coupled macroeconomic and sectoral models described above are augmented with a set of four specific models or modules designed to capture the financial implications of the scenarios. First, the Banque de France's rating model is added to our modelling infrastructure to assess credit risk at the firm level (for France only). Second, asset prices are estimated for each sector and geographical zones, via the discounting of scenario-based dividend streams (Dividend Discount Model). Projections of the EIOPA risk-free interest rate (RFR) term structures are further simulated conditional on each scenario to evaluate the liability side of insurers' balance sheets. Finally, corporate credit spreads for several economic areas and sectors are projected using the *Risk Management Institute* (RMI) dataset and, for France, the simulations of credit risk intensities derived from the Banque de France's data and rating model.

4.3.1. Addressing infra-sectoral heterogeneity

Results from the sectoral models described above are plugged in the Banque de France's rating model to further disaggregate impacts at firm level. Using the output of the sectoral model, the chain of models helps to disentangle, within sectors, between winners and losers by identifying the set of firms that exhibit the biggest decreases and increases in credit risk.

As part of its monetary policy strategy, the Banque de France is one of a few central banks to have developed an in-house rating model, which assesses the risk that a company cannot meet its financial commitments. In the assessment of credit standards of non-financial companies, the Banque has been recognized as an external credit assessment institution (ECAI)[24], and within the Eurozone as an In-house Credit Assessment System (ICAS).[25,26,27] The Banque de France ratings can then be used to evaluate the credit quality of loans used as collateral in Eurosystem monetary policy operations (granted by the Eurosystem Credit Assessment Framework – ECAF), and to calculate credit institutions' capital requirements with respect to solvency rules, in line with the standardised approach and securitization framework of prudential regulation. Each year, more than 260,000 groups and standalone companies are rated all over France by the Banque de France's large network of financial

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[24] This recognition means that the Banque de France's rating system meets the international requirements of reliable credit risk assessment systems, that is: objectivity, independence, regular review, transparency, and acceptance by the market.

[25] See Guideline (EU) 2015/510 of the ECB of 19 December 2014 on the implementation of the Eurosystem monetary policy framework (ECB/2014/60), Title V - Eurosystem Credit Assessment Framework For Eligible Assets, Articles 119 and 121.

[26] List of others ICAS include: Deutsche Bundesbank, Oesterreichische Nationalbank, Banco de España, Banca d'Italia, Banco de Portugal, Banka Slovenije and Národná Banka Slovenska.

[27] In accordance with the Eurosystem's general principles on credit assessment, an ICAS model is based on a preliminary statistical assessment (hereinafter ICAS Statistical Financial Rating) followed by a qualitative assessment by financial analysts (Expert System Final Rating).

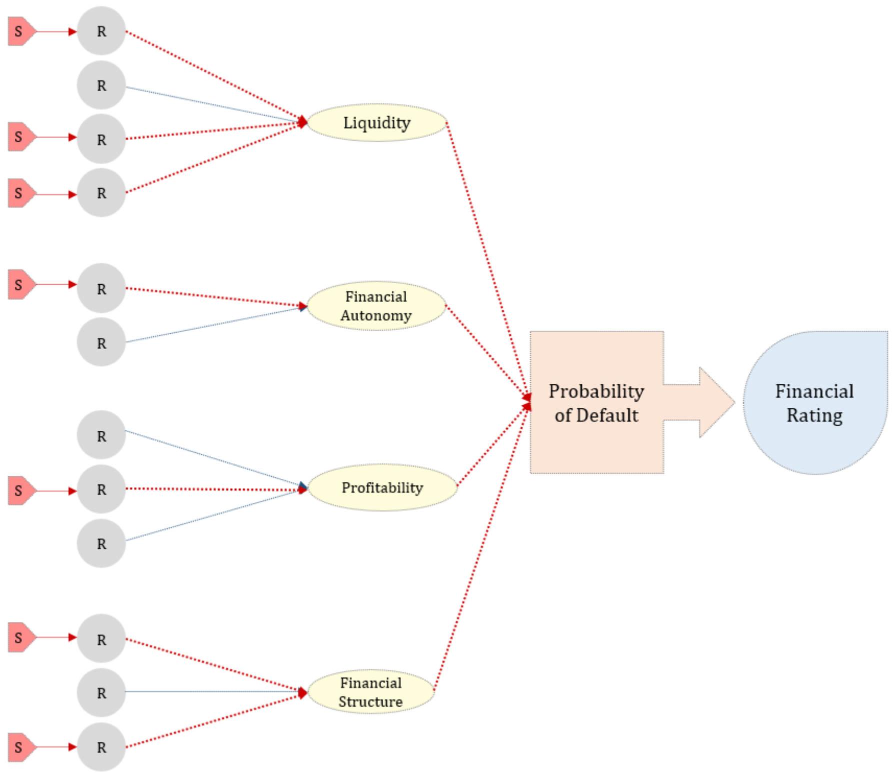
experts. The rating model was profoundly revised in recent years[28] to strengthen the robustness of its ICAS statistical financial rating and to adapt the methodology to include more rating classes. The aforementioned is the new rating model and more specifically its financial part (without the expert and qualitative analysis part) that is used for the estimation.

The overall financial rating procedure is based on the analysis of financial ratios. Financial ratios are initially selected based on a scoring procedure that measures their discriminatory power, while secondary importance is given according to the feedback of Senior Financial Experts. The thus selected ratios, which vary according to the sector concerned, are the rating model's core explanatory variables. Each selected ratio is assigned to a single financial theme[29], according to their structure and financial interpretation. Within each financial theme, ratios are discretized and summarized into a theme-based categorical variable[30], with an algorithm that uses a similar approach as decision trees[31].

The transmission of the underlying shocks of the sectoral model to financial ratios is done via the financial aggregates that compound these ratios. Examples of impacted aggregates include active treasury, net income, gross operating surplus and internal financing capacity. In Figure 6, *R* represents the financial ratios impacted by the sectoral-shock *S*. As each ratio is assigned to a single financial theme, the sectoral shock will be transmitted to the theme-based categorical variables. The latter are used in a logistic regression to estimate the impacts on the probabilities of default, which in turn could modify the assigned *Statistical Financial Rating*.

[28] The revised ICAS model validation approval by the Governing Council of the ECB should occur in 2020.
[29] We define four financial themes: profitability, solvency & financial structure, liquidity and financial autonomy.
[30] The implied discretization improves the explicability of the model, with explicit interactions and comparisons between categories. In addition, this technique allows us to deal with correlation between explanatory variables, flatten distributions, discontinuous default rate responses and missing values.
[31] See Delen et al. (2013) or Gepp et al. (2010).

Figure 6 – Overview of the transmission mechanism through the financial rating model



The model uses yearly firm accounting data directly from FIBEN, a Banque de France database that is mainly based on firms' accounting statements, supplier and customer trade bill payment incidents, bank loans reported by credit institutions and firm legal information. Our final sample includes companies with a minimum turnover of €0.75 million and that fulfilled their obligation to provide accounting statements to the Banque de France. Payment default data come from the French National Central Credit Register (CCR) operated by the Banque de France[32]. 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 (see Appendix 3 for details on the default definition). The binary default is defined as:

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

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

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:

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

We estimate the default probability π conditionally on a vector of observed covariates $\boldsymbol{X}_i$:

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

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[33]:

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

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

Adjustments are made to the main model in line with the literature, namely in order to adapt the estimation to low-frequency observations, with default rates that barely attain 1% in some sectors[34]. Regarding the final rating scale and the empirical delimitation of Credit Quality Steps, Annex 4 describes in detail the Smoothing Cubic Spline methodology that allows to obtain the underlying probability cut-offs.

4.3.2.Projecting dividend streams and the elasticities of asset prices

Shares evaluation, via the discounting of scenario-based dividend streams (Dividend Discount Model), for each sector and economic area (France, RoEU, USA and RoW), are obtained by combining results coming from NiGEM model, the sectoral model and a dividend discount model (DDM). More precisely, we proceed as follows: a) NiGEM and sectoral models presented above provide for each scenario, economic area and sector projections of turn-over and value added between 2025 and 2050; b) we assume that distributed dividends are 50% of return of capital, the latter being the 33% of value-added; c) thanks to the DDM, the associated dividend stream is discounted 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) plus a projection of a sector-specific risk-correction component mimicking the behavior of the corporate credit spread of the same sector.

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

[34] See Appendix 4 for further details.

In other words, for a given scenario α, we have a country-m and sector-j dividend stream $(D_{j,m}^{\alpha}(2025), \dots, D_{j,m}^{\alpha}(2050))$, where $D_{j,m}^{\alpha}(t) = 0{,}5 * (0{,}33 * VA_{j,m}^{\alpha}(t))$, with $VA_{j,m}^{\alpha}(t)$ being the projection at date *t* of the value added of the country-m and sector *j* for the scenario α. The associated discount factor over the period (*s, t*) is denoted by $(R_{j,m}^{\alpha}(s,t))^{-1}$, where $R_{j,m}^{\alpha}(s,t) = 1 + \bar{r}_m + rp_{j,m}^{\alpha}(s,t)$, where $\bar{r}_m$ is the average index stock return, while $rp_{j,m}^{\alpha}(s,t)$ denotes the relevant risk-premium component. The value of the stock at date s=2020 (the evaluation date), for a scenario α, is therefore given by:

$$P_{j,m}^{\alpha}(2020) = D_{j,m}^{\alpha}(2025) * \left(R_{j,m}^{\alpha}(2020, 2025)\right)^{-1} + \dots + D_{j,m}^{\alpha}(2050) * \left(R_{j,m}^{\alpha}(2020, 2050)\right)^{-1}$$

4.3.3. Projecting EIOPA risk-free interest rate

The estimation and projections of the EIOPA risk-free interest rate (RFR) term structures is based on a no-arbitrage Gaussian Affine Macro-Finance Term Structure Model (GMTSM) with unspanned macroeconomic variables *à la* Joslin et al. (2014) and estimated following the methodology of Adrian et al. (2013)[35].

The data set adopted to estimate the model is given by EIOPA risk-free interest rates with maturities from 1 year to 20 years observed monthly between January 1999 to December 2019.[36] The pricing factors are given by the first three principal components extracted from the panel of yields, while the unspanned macro variables are given by year-on-year economic activity HICP inflation rate.

The projections of the RFR term structures at date *t* (December 2019), for any given climate-risk-like scenario provided by NiGEM model, are obtained as conditional forecasts of the yield curve $(R_t^{(n)})$, conditionally to the future path (the scenario) of the macroeconomic variables X_t^u between 2020 and 2050 (denoted $\underline{X_{t+1y,t+30y}^u}$). More formally, we calculate for any forecast horizon $k = (1y, \dots, 30y)$:

$$E\left(R_{t+k}^{(n)} \,\middle|\, \underline{X_{t+1y,t+30y}^u}\right) = -\frac{1}{n}\left(A_n + B_n' E\left(X_{t+k} \,|\, \underline{X_{t+1y,t+30y}^u}\right)\right)$$

where $E\left(X_{t+k} \,|\, \underline{X_{t+1y,t+30y}^u}\right)$ is the conditional forecast (under the historical probability) of a Gaussian VAR process (Waggoner and Zha, 1999).

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[35] See Appendix 5 for further details.
[36] It is important to highlight that the monthly risk-free yield curves provided by the EIOPA span the period December 2015 – December 2019 only, while observations from January 1999 to November 2015 are obtained from the term structure of interest rate swaps corrected by a credit risk component following the same methodology of the EIOPA. In other words, we work with a (newly introduced) extended EIOPA database of RFR term structures able to provide the model with observations of interest rates at levels others than the very low levels we have recently observed.

The projections of the RFR term structures at date *t* (December 2019), for any given climate-risk-like scenario provided by NiGEM model, are obtained as conditional forecasts of the yield curve $(R_t^{(n)})$, conditionally to the future path (the scenario) of the macroeconomic variables X_t^u between 2020 and 2050 (denoted $\underline{X_{t+1y,t+30y}^u}$). More formally, we calculate for any forecast horizon $k = (1y, \dots, 30y)$:

$$E\left(R_{t+k}^{(n)} \,\middle|\, \underline{X_{t+1y,t+30y}^u}\right) = -\frac{1}{n}\left(A_n + B_n' E\left(X_{t+k} \,|\underline{X_{t+1y,t+30y}^u}\right)\right)$$

where $E\left(X_{t+k} \mid \underline{X_{t+1y,t+30y}^u}\right)$ is the conditional forecast (under the historical probability) of a Gaussian VAR process (Waggoner and Zha, 1999).

4.3.4. Projecting corporate credit spreads

The construction and projection of corporate credit spreads, for each of the scenarios, is obtained exploiting the simulation of credit risk intensities for France, using the Banque de France data and rating model, and the *Risk Management Institute* (RMI) dataset for the other countries. The considered countries are France, Germany, Italy, Spain, UK, US and Japan, while the economic sectors are the main GICS sectors. The RMI provides monthly data of default probabilities (with horizon from 1 month to 5 years) for several economic areas, countries and economic sectors, and they are calculated following the methodology of Duan et al. (2012), generalizing the approach of Duffie et al. (2007). The associated credit spreads of country *m* and sector *j* at maturity τ, denoted $CS(\tau)$, are calculated using the following Merton (1973) and Black and Cox (1976) formula:

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

where $PD(\tau)$ is the historical default probability at the same horizon, N is the cumulative distribution function of a centered and normalized Gaussian distribution, θ is the asset Sharpe ratio and RR is the recovery rate assumed constant at 40%. Focusing on maturities 1 year, 2 years, 3 years and 5 years, for any given country and economic sector, the Sharpe ratio parameter is calibrated in order to match the order of magnitude of the CDS spreads for the same horizon and sector.[37] The projections, for each scenario, of one-year-maturity credit spreads are calculated using and mimicking the projections of the one-year default probabilities of the infra-sectoral 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: i) for any given country, economic sector and scenario, we estimate a Bayesian VAR(1) model (with Minnesota priors) on the credit spread vector

[37] Under the absence of arbitrage opportunities, in a frictionless market, the corporate bond spread and the CDS spread on the same entity and horizon coincide. In reality, we empirically observe a difference (named CDS – bond basis) which is on average of a negligible amount of bps.

$(CS_{j,m}(1y), CS_{j,m}(2y), CS_{j,m}(3y), CS_{j,m}(5y))$ over the sample 1991y – 2019y; ii) given the future path from 2020 to 2050 of $CS_{j,m}(1y)$, function of the relevant scenario, we calculate the conditional forecast (projections) of the credit spreads for the remaining horizons and over the same period.

5. Results

This section presents the application of this analytical framework to the two adverse scenarios for disorderly transitions as developed in Section 3, including a 'delayed' (Scenario 1) and a 'sudden' transition (Scenario 2). The simulations are conducted across the four blocks of countries (France, Rest of the EU, USA and Rest of the World) and 55 sectors, and presented in deviation from the baseline case of an orderly transition. This reference scenario represents the necessary pathway that mitigates climate change while optimizing economic returns. The objective of this section is to test the consistency of the framework and generate the full quantitative set of information for each scenario at the macroeconomic and sectoral level.

It should be emphasized that this empirical exercise is not making any predictions about the economic structural change 30 years ahead, but rather simulating the impacts on different sectors of a set of plausible policy and productivity scenarios.

5.1. Macroeconomic impacts

The NiGEM model described above is used to derive the full set of macroeconomic impacts of the two adverse scenarios relative to the baseline. As explained earlier, the NGFS database does not provide the whole set of macroeconomic variables necessary for a financial risk assessment exercise and does not include data specific to France[38].

The two adverse scenarios are simulated assuming different carbon price trajectories (see Figure 4) set according to the NGFS disorderly transition scenarios. In these two adverse scenarios, the stronger increase in the carbon price leads to higher production costs for firms and losses in purchasing power for households, as the redistribution of the proceeds of the carbon tax is not sufficient to offset the effect of the increase in consumer prices on real income over the entire horizon.

Several adjustments have been introduced in the model for the baseline and the delayed transition scenario (Scenario 1). As explained above, productivity developments have been set to be compatible with the technological advances assumed in the NGFS scenarios (such as assumptions about energy efficiency or carbon capture technologies). In the case of the

[38] France is included within the EU block of countries, and cannot be isolated within the data.

sudden scenario (Scenario 2), while the carbon price trajectory is aligned with an NGFS alternative scenario (with a five year delay), there are no productivity gains[39]. The results in terms of GDP for this scenario therefore depart from the NGFS data, generating a more adverse scenario.

Figure 7 – Impacts on real GDP level of adverse transition (% deviation from baseline)

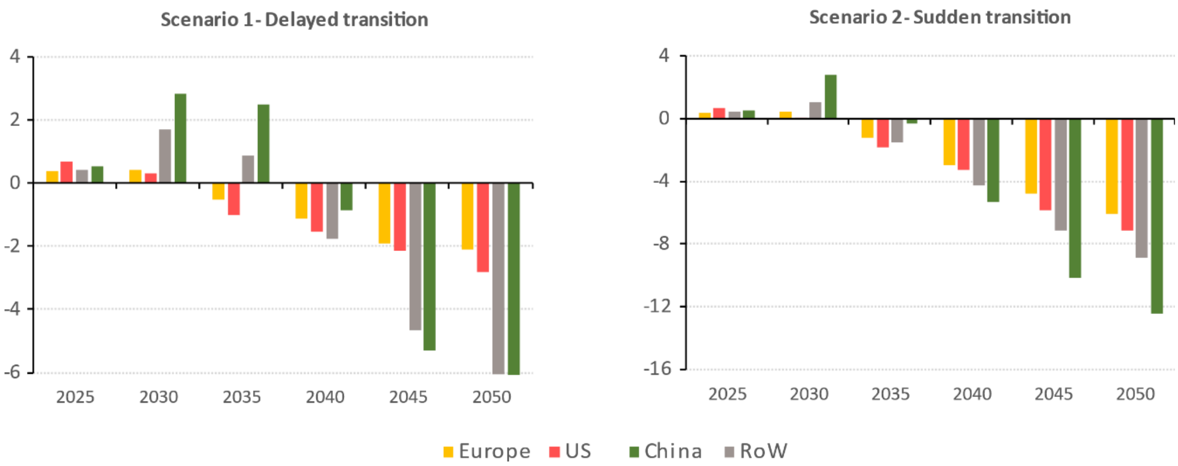
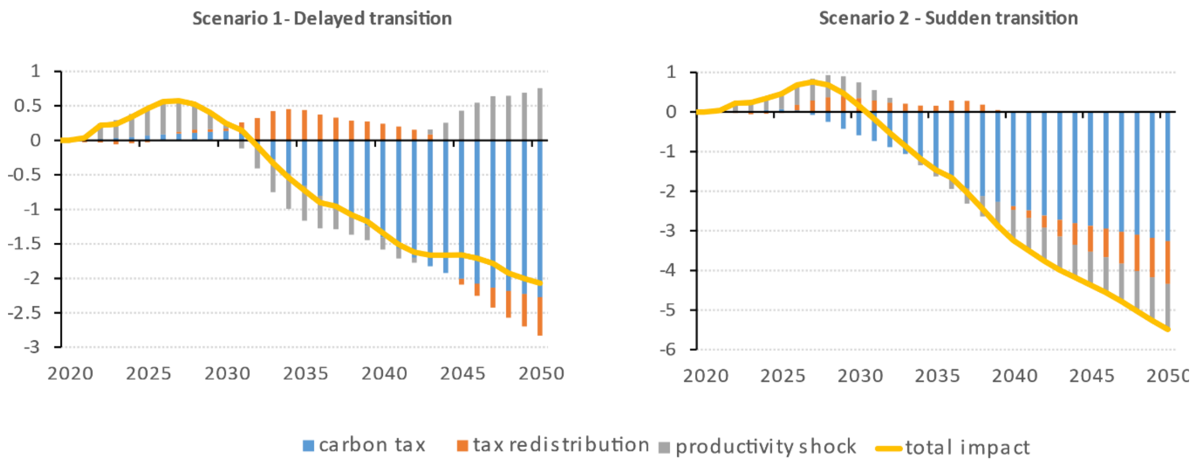


Figure 8 shows the impacts on GDP levels relative to baseline for the main economic areas. Whichever the scenario considered, the impacts are negative on real GDP by the end of the simulation horizon. In Europe and the US, results indicate that under the delayed transition scenario (Scenario 1), the longer-term impacts would be between 2% and 3% below what it otherwise would have been with an orderly transition, and between 6 and 7% in the sudden transition scenario (Scenario 2).

In the Rest of the World, economic activity is expected to be more harshly impacted by the structural changes embedded into the transition narratives, with a high heterogeneity across countries. This is in line with previous research highlighting that developing countries in particular might be the worst affected by an increase in the cost of energy (Cao, 2003; Kaygusuz, 2012). The potential long-term impact of a disorderly transition can thus be severe. In particular, countries like China experience the largest losses to GDP (around 6% in the delayed transition scenario and 12% in the sudden transition scenario by 2050). These effects are notably explained by larger energy consumption and lower energy efficiency compared with advanced economies like the US or the European countries. In all cases, however, the GDP losses are rather slow to materialize and GDP remains broadly unaffected until 2035-40.

[39] Introduced to ensure consistency with the sectoral model, see section 4 on the modelling approach.

Figure 8 – Contribution of various factors to GDP impacts in France (% deviation from baseline)



As explained above, the difference between the two adverse scenarios concerns not only the carbon price trajectory but also assumptions relative to productivity developments. Moreover, the assumption relative to the redistribution of tax revenues to the economic agents also shape the responses to economic activity. Figure 9 shows the contribution of the various factors in the case of France. In the scenario of a delayed transition (Scenario 1), the increase in carbon price explains most of the decline in economic activity. The redistribution of tax receipts absorbs part of the losses until 2045. Over time though, the restructuring in economic activity lowers the tax benefits, making the recessionary effect predominate towards the end of the scenario horizon. As this scenario also corresponds to a NGFS scenario of disorderly transition, we have mimicked the behaviour of macroeconomic variables with NiGEM by including productivity shocks, which contribute positively on average in this scenario. Overall, this productivity shock helps to reduce the GDP loss by close to 1 percentage point by 2050, limiting the total loss to 2%. In the second scenario of a sudden transition (Scenario 2), the positive contribution of the tax redistribution vanishes over time and all factors contribute negatively from 2040 onwards. At the end of the scenario horizon, in 2050, three-fifths of the GDP loss is explained by the increase in the carbon tax, a fifth is due to the deterioration in public finances and the negative productivity shock explains the remaining part.

In terms of final GDP impact in France, the delayed transition scenario (Scenario 1) is characterized by a drop in activity of around 2% compared to the level of GDP in the baseline by 2050. The decline however only occurs from 2035—the date of the carbon price increase. Prior to this date, due to a lower carbon price than in the baseline scenario, the effects on activity are slightly positive. The sudden transition scenario (Scenario 2) on the other hand implies an even sharper fall in activity. France's GDP level in 2050 is 5.5% lower than in the reference scenario. In this scenario, activity is penalized both by the rise in fossil energy prices and by the lower productivity gains (compared to baseline).

Figure 9 – Further macroeconomic impacts for France: impact on prices and fiscal balance

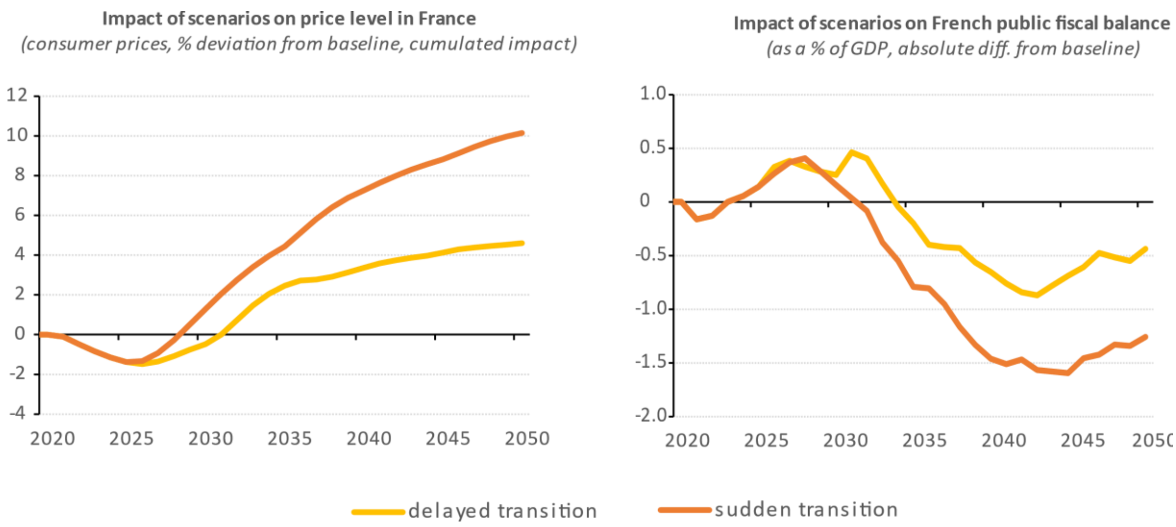


Figure 10 shows some further macroeconomic impacts for France, namely the impact on consumer prices and government budget. The introduction of a carbon tax leads first to a direct increase in energy prices. Other costs are also indirectly affected by this increase and, as a result, there is a general increase in consumer price levels. This can be seen as from 2030 in the sudden transition and a few years later in the delayed transition, consistently with the steep rise in the carbon price. Beforehand, since carbon taxation is delayed compared to the baseline, the effect is slightly disinflationary. After 2030, the inflation response becomes positive due to the rapid rise in the carbon price relative to the (more gradual and lower trajectory assumed in the) the baseline. The cumulated impact on consumer prices at the end of the horizon is around 4.5% in the delayed transition (Scenario 1) and 10% in the sudden transition (Scenario 1)[40]. In terms of dynamics, this increase in prices is relatively rapid in the years following the shock on carbon prices and tends to slow down afterwards as higher energy prices are offset by disinflationary pressures from lower activity. The impact on the annual inflation rate compared to the baseline thus reaches a maximum of 0.7 percentage points after 2030 in the delayed transition (Scenario 1) but averages 0.2 percentage points after 2035. In the sudden transition (Scenario 2), the increase in prices is more dynamic and persistent since the average impact on the annual inflation rate is 0.6 percentage points between 2030 and 2040 and then around 0.3 percentage points in 2040-2050.

The negative impact of inflation on households' purchasing power offsets the positive impact of the tax redistribution after 2040 in the delayed transition and after 2035 in the sudden transition. Real disposable income therefore decreases, leading to a reduction in private consumption and investment and implying lower labour demand, with knock-on effects on the unemployment rate. Lower employment leads to a further decline in personal income and consumption, in turn impacting output. The fall in output and employment also reduces government revenues, while the increase in the unemployment rate increases government

[40] Monetary policy is endogenous in the simulations and therefore reacts according to a Taylor rule. The final inflationary effect is therefore to some extent curtailed.

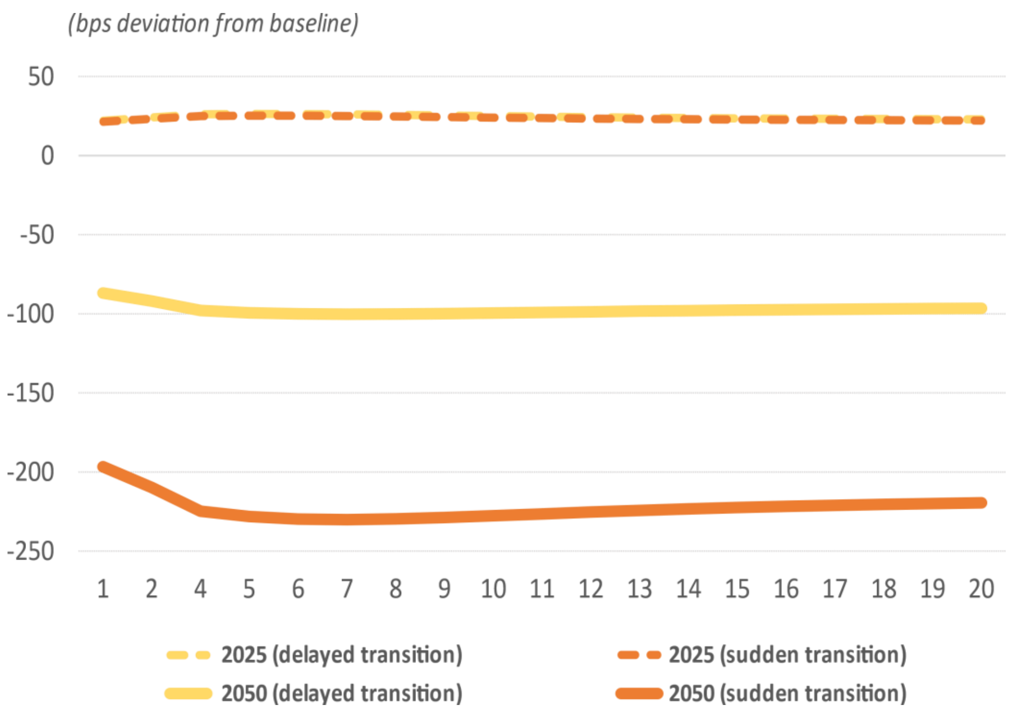
spending related to households' benefits. Ex ante, although the carbon tax should bring in additional receipts for the government, they are entirely redistributed to households. The net effect is a worsening of the general government balance over the long term, which deteriorates in the case of France by 0.7 percentage points on average between 2040 and 2050 in the delayed transition (Scenario 1) and by 1.5 percentage points in the sudden transition (Scenario 2).

5.2. Macrofinancial impacts

Projections of EIOPA RFR term structures

The purpose of this section is to present and to discuss the projections of the EIOPA RFR term structures in 2025 and 2050, for any given climate-related scenario, obtained using the methodology described in section 4. Figure 10 shows that the expected variation in 2025 of the RFR term structures for both the delayed and sudden transition scenarios (compared to the orderly transition) is slightly positive (around 20 bps) probably because of the strong rise in economic activity at the beginning of the period.

Figure 10: Expected variations of the EIOPA RFR term structures in 2025 and 2050.



Note: Maturities in years and interest rate variations in bps (annual basis).

As far as the longer forecast horizons are concerned, the expected variations become negative because of a downward trend in economic activity that offsets the effects from inflation. Moreover, the stronger reduction in economic activity for the sudden transition scenario (compared to the delayed transition) translates into even more negative variations (in absolute value) of the EIOPA RFR term structures.

Projections of corporate credit spreads

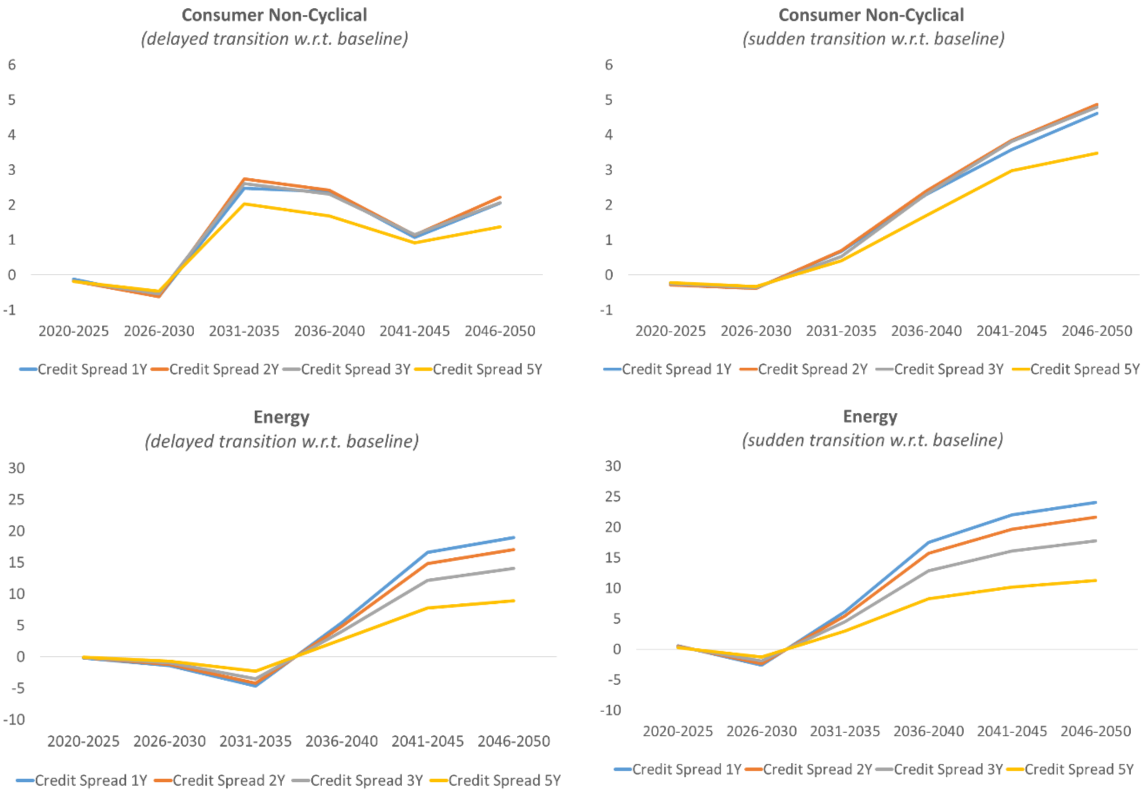
The methodology presented in Section 4 to estimate the corporate credit spread projections (scenario-based conditional forecasts) is applied here to determine their expected variations for the delayed and sudden transition scenarios over the period 2020-2050. For ease of presentation, we focus on two climate-relevant sectors: "Consumer non-cyclical" and "Energy"[41]. The results are presented in Figure 11 for France[42]. See Appendix 6 for the details about the RoEU, the USA and Japan (Figures 11B, 11C and 11D).

It results that the energy sector shows larger expected variations than the consumer non-cyclical one for all countries, regardless of the transition scenario. However, the sudden transition scenario (Scenario 2) triggers stronger expected variations than the delayed one (Scenario 1) for both sectors, with the latter showing negligible or negative expected credit spreads variations up to 2030.

Those results are in line with the expected deviations (from the baseline) of the projected 1- year default probabilities over those two scenarios. They feature a larger increase for the sudden transition scenario than for the delayed one and, compared to the baseline, default probabilities are more favourable until 2030 in the delayed transition scenario, with carbon price shocks starting only in 2030 onwards (see sub-section 5.4 for further details).

[41] The first one contains the (NACE-based) agriculture sector, while the second one contains mining and petroleum sectors.
[42] The expected variations are averages over 5-year intervals.

Figure 11: Expected variations (bps) of corporate credit spreads in France, from 2020 to 2050 (average over 5-year intervals) for consumer non-cyclical and energy sectors



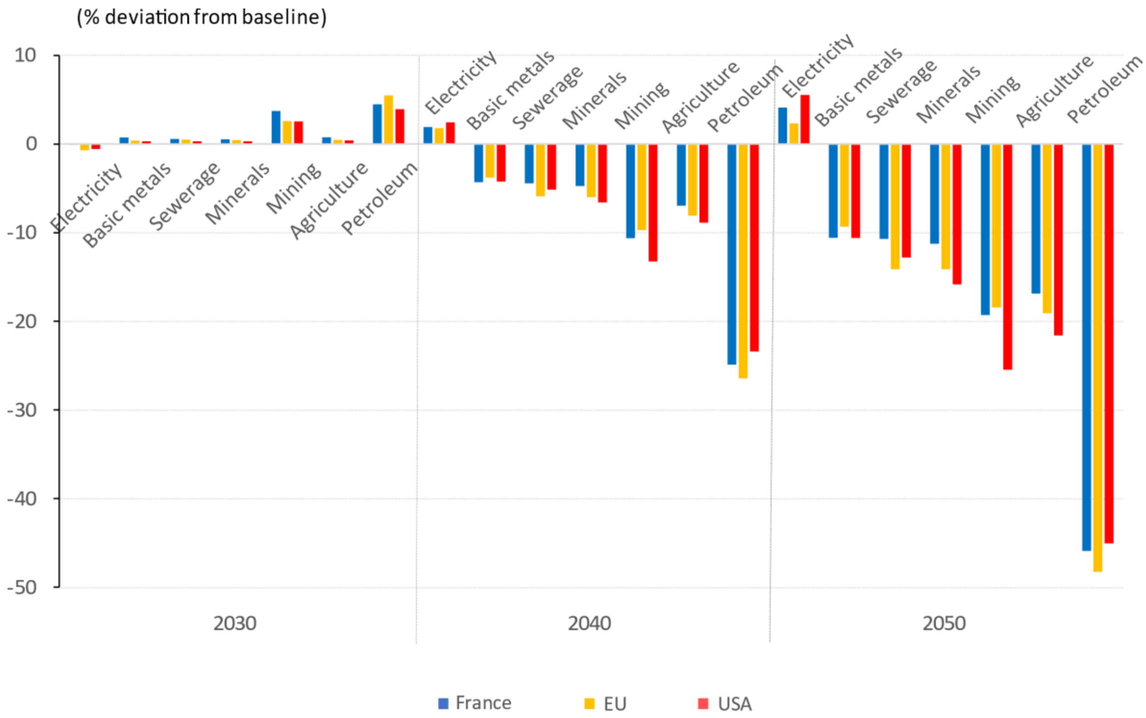
5.3. Sectoral impacts

Although the macroeconomic costs of the simulated shocks are rather mild, the impacts by sector can vary significantly and be more substantial. Figures 12 and 13 show the numerical results of the sectoral impacts across the two adverse scenarios. A country-wide carbon price may have 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).

Overall, the extracting and industry sectors are more affected than the service sectors, with the largest losses in the Refined Petroleum and Coke (thereafter 'Petroleum'), Agriculture and Mining sectors. Petroleum output in France in 2050 falls by 47% from the baseline in the delayed transition scenario (Scenario 1), and by close to 60% in the sudden transition scenario (Scenario 2).[43] Since producers have the possibility to substitute Electricity & Gas (thereafter 'Electricity') for Petroleum, they adjust their energy mix and the Electricity sector's output increases by 5.7% in 2050 in the delayed transition scenario, and by 5.6% in the sudden transition scenario.

[43] This fall is generally stronger in other countries, up to 53% in the rest of the World in the 'delayed' scenario and to 63% in the rest of EU in the 'sudden' scenario in 2050.

Figure 12: Sectoral impacts on real value added – 'Delayed transition' (Scenario 1)



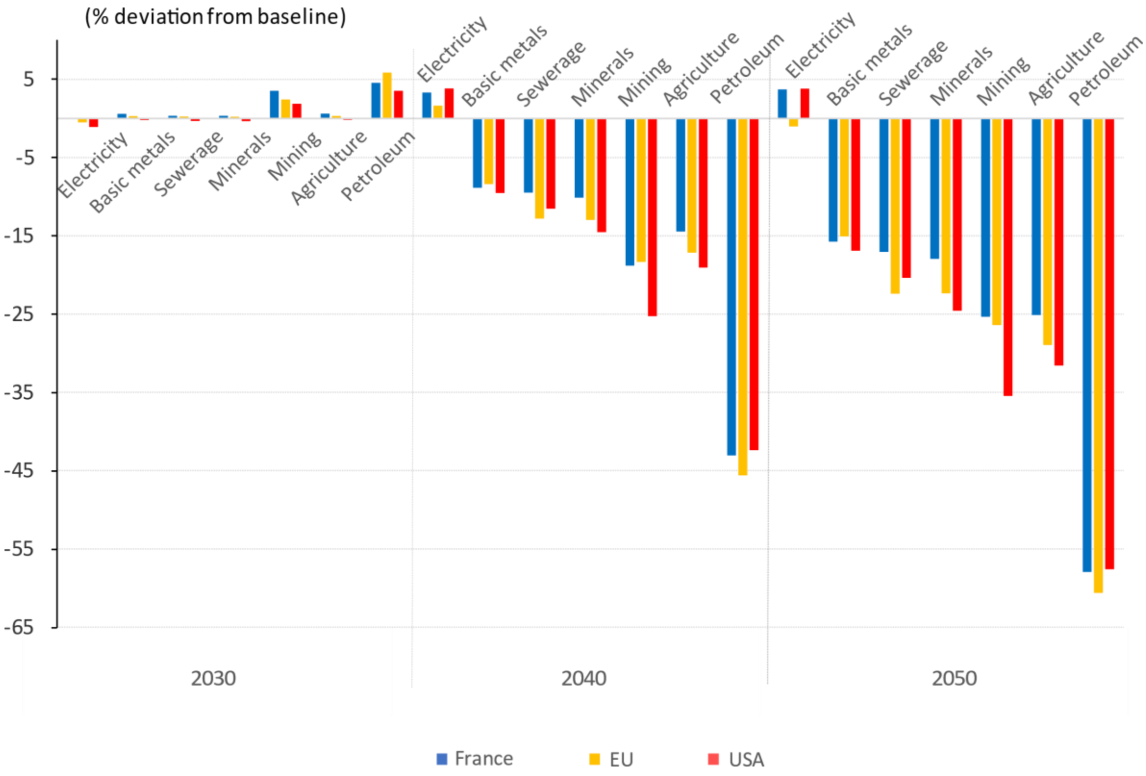
In the delayed transition scenario (Scenario 1), the Petroleum sector suffers a drop in real value added by more than 45% below baseline over the 2050 horizon in France, while the Electricity sector sees an increase by 4%. This drop amounts to 17% in the agriculture sector, 19% in Mining and Quarrying, 11% in Minerals, whereas trade and service sectors are generally less affected (e.g. the Retail Trade sector– excluding motor vehicles – bears only a 1% drop).

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. The impacts are mostly explained by the economic cost imposed by the carbon taxation. This cost is passed through into the prices of sectoral outputs after producers have optimally substituted their intermediate inputs towards cheaper (less polluting, hence less taxed) ones.

The introduction of a tax on fossil fuel intermediate consumption favours substitution towards greener energy. For instance, for 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 Transportation. Some sectors with a very high dependence on fossil fuels (Air and Water Transports for instance) face somewhat limited possibilities to shift towards greener energy and their energy mix remains more stable, while their total output significantly decreases.

Upstream sectors in the production network also tend to be more affected by spillovers across sectors. A striking example is the Mining sector, heavily affected due to its position upstream from the Petroleum sector: the latter is impacted by a demand drop, thus lowering its intermediate inputs demand and transmitting the shock to the former. The Agricultural and Sewerage sectors are impacted given their direct non-CO_2 GHG (methane among others) emissions, while the Minerals and Basic Metals sectors include the cement, iron and steel industries that are strong CO_2 emitters. 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.

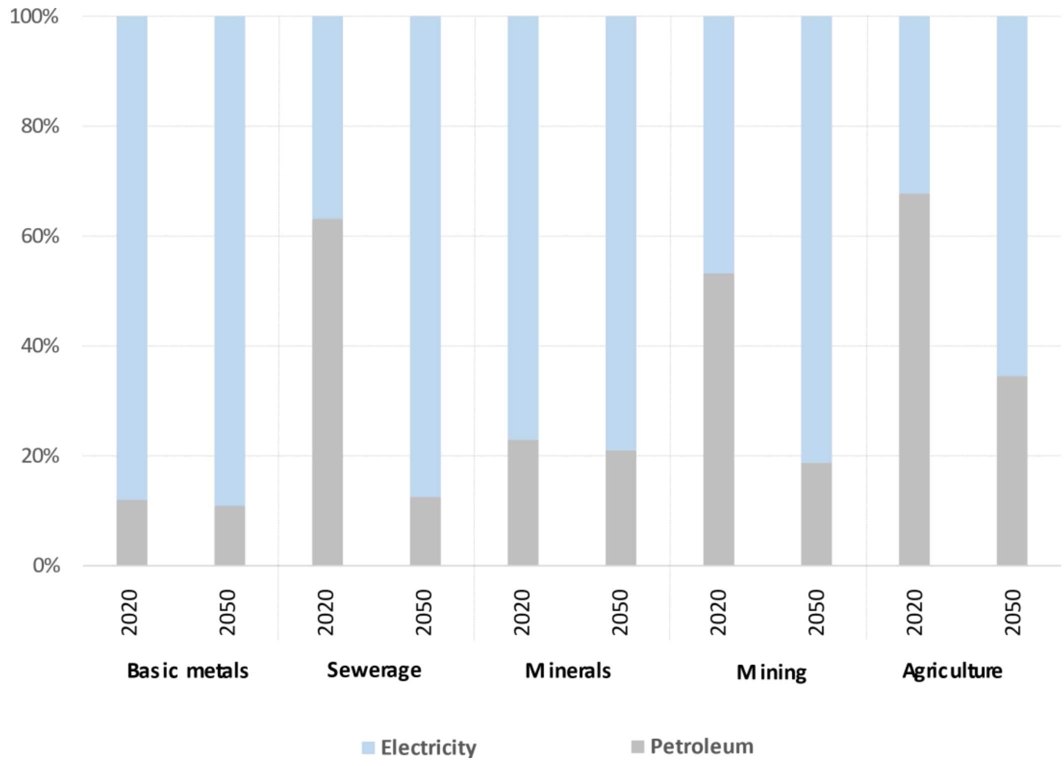
Figure 13: Sectoral impacts on real value added – 'Sudden transition' (Scenario 2)



In the sudden transition scenario (Scenario 2), the output impacts are even stronger reaching up to a 60% decline in Petroleum in 2050 relative to baseline for the US and the EU. The effects of the carbon price and productivity assumptions on the six most exposed sectors' real VA, as well as on Electricity's real VA, are presented in Figure 13. Unsurprisingly, Petroleum and Agriculture are the most harmed sectors, with Mining. In France, their sectoral value-added losses reach 58% and 25% respectively. The real value added of the Electricity sector increases by 3.7% relative to baseline in 2050 in France. This is less than in Scenario 1, due to the generally less favourable productivity assumptions.

Figure 14 shows the share of oil and coke intermediate inputs in the energy mix of the most impacted sectors. Clearly, the share of fossil fuels decreases with the implementation of the carbon tax, although not in the same proportions in all sectors. Producers do not have the same initial uses – their initial reliance on fossil fuels vary – and do not face the same tax rate on fossil fuels consumption, which depends on their CO_2 emissions, thus reflecting various energy mixes within fossil fuels (coke vs. oil). For instance, while 63% of the energy used by the Sewerage sector in France comes from the Petroleum sector in 2020, this share drops to 3% in 2050.

Figure 14: Evolution of the energy mix across key sectors – Sudden transition (%)

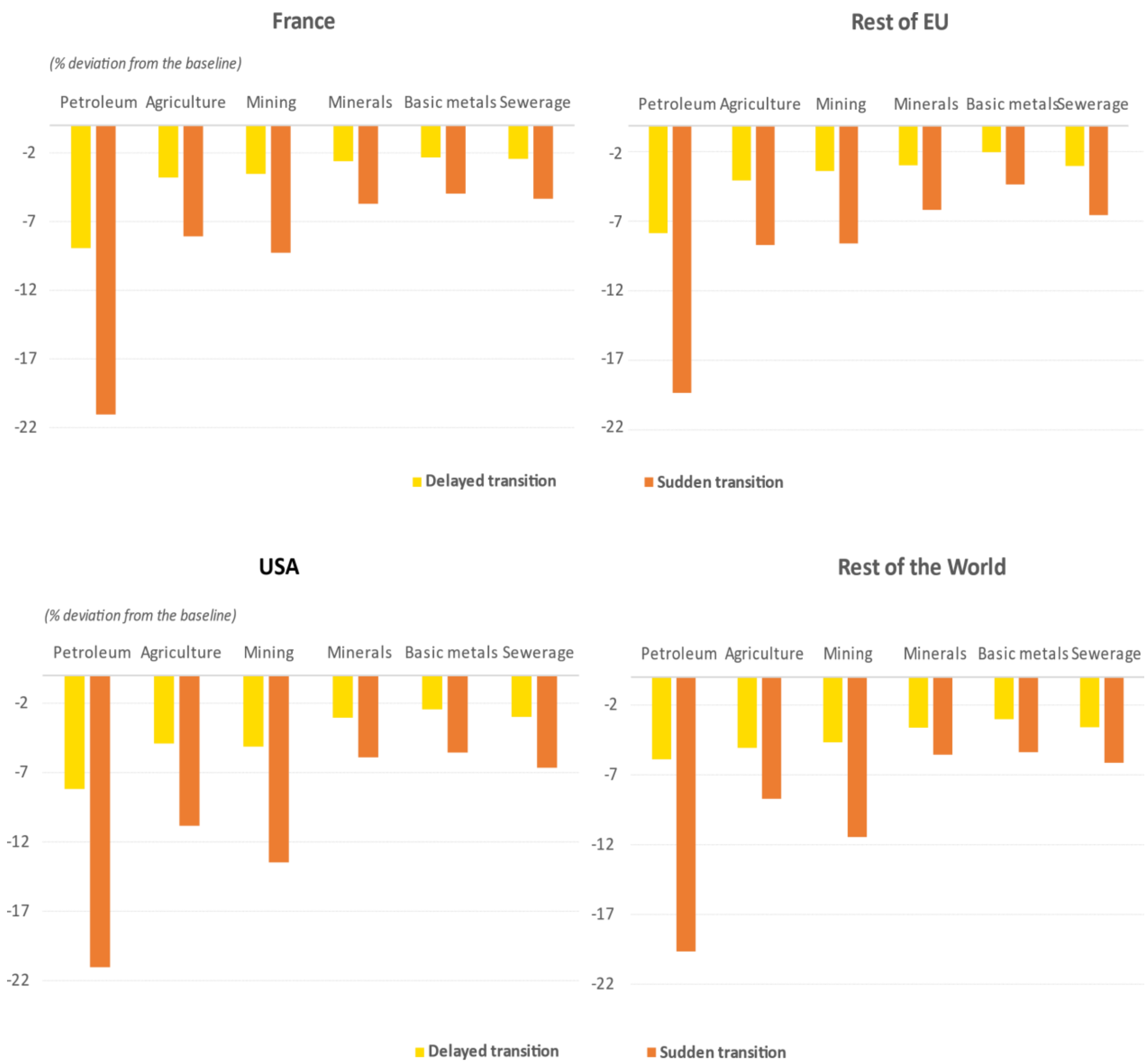


5.4. Market valuation and credit rating impacts

The elasticity of stock prices to climate-related scenarios

The pricing framework presented in Section 4 estimates the elasticity of market stock prices (of a given country and economic sector) to a shift in the (discounted) dividend stream resulting from the deviations of the delayed transition (Scenario 1) and sudden transition (Scenario 2) scenarios from the baseline (orderly transition). In other words, we assess the relative stock price variation as of 2020 if investors were reevaluating their anticipated dividend stream taking into account the new information associated with two adverse scenarios (compared to the baseline). Figures 15 shows the elasticities for climate relevant economic sectors of France, RoEU, USA and RoW. If we consider for instance the case of the Petroleum sector, we observe that a shift today in investors' expectations about the sudden transition scenario (Scenario 2) dividend stream would imply a negative price variation of 20% for the economic areas mentioned above.

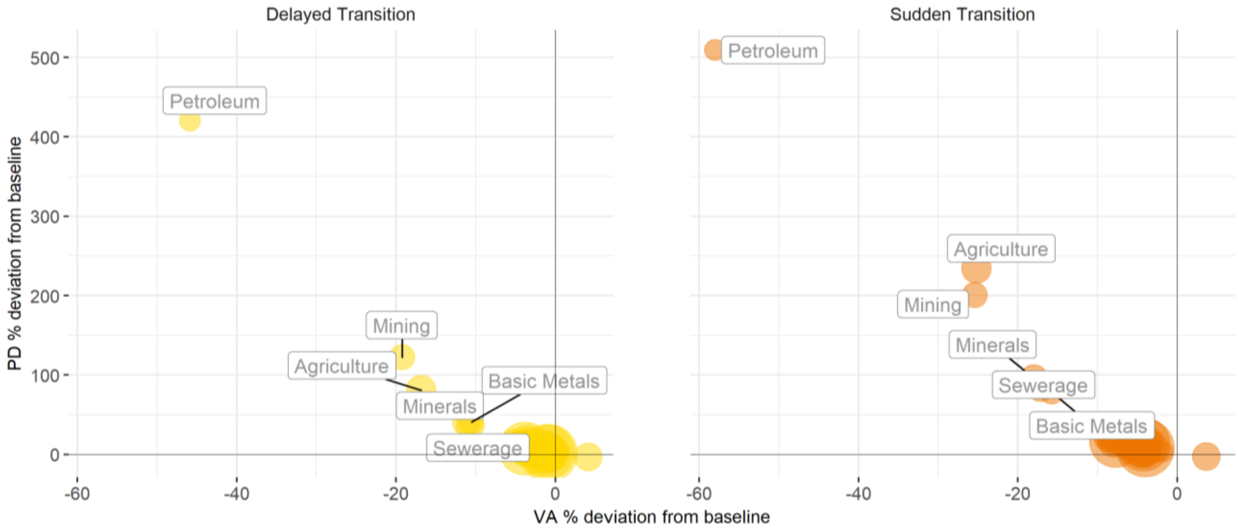
Figure 15: Stock price shocks by sector (% deviation from baseline)



Value added and turnover shocks have also been introduced as input in the Banque de France's rating model. Combined with financial information on firms, the model estimates probabilities of default (PD) at the firm level. Results underscore that the disorderly transition scenarios simulated in this paper imply series of disruptive structural changes across and among sectors, with differentiated impacts on firms' financial fundamentals that consequently impact PDs. Consistently with the underlying narratives, PDs degradations are more severe in the sudden transition scenario than in the case of a delayed transition.

Figure 16 suggests that there is a negative relationship between VA and PD variations for the two scenarios, with the sectors experiencing the highest recessionary pressures in VA (in deviation from the reference scenario) reporting structurally different and higher differentials in PDs in 2050. Relative to baseline, the sluggish and negative growth rate of sectoral value added in 2050 may weigh on firms' economic fundamentals, which without any further policy adjustment or supportive financial conditions, may reflect higher financial distress for the most impacted sectors. In the face of the overall developments and the ongoing risks in 2050, petroleum, agriculture and mining are expected to be among the most impacted sectors. On the contrary, the Electricity sector emerges as an overall winner, with slightly improved PDs in both scenarios. This is the logical consequence of the positive impacts on its real VA of the simulated shocks.

Figure 16: Estimated Probabilities of default and Value added by sector (in 2050)



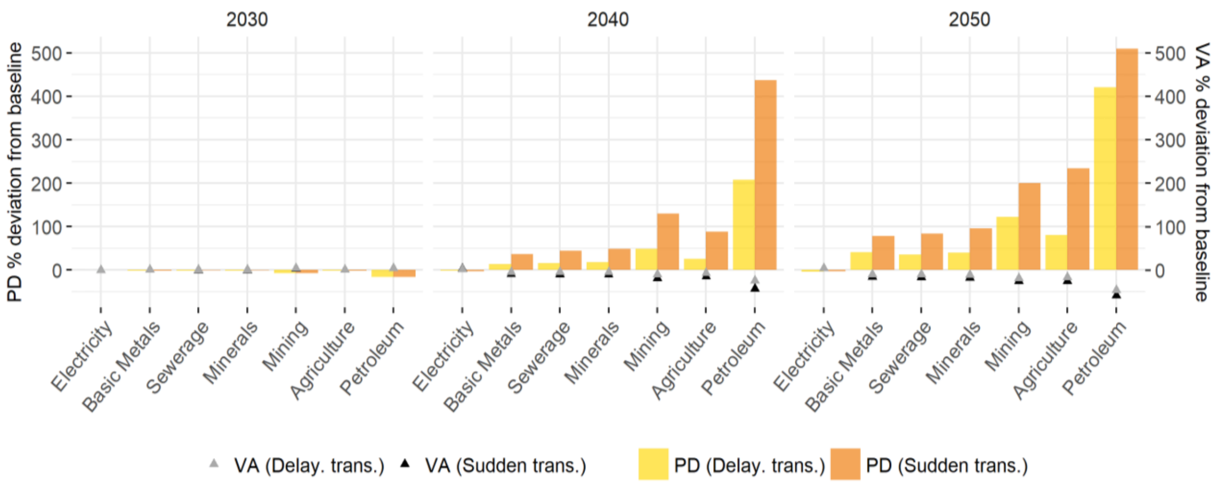
Note: The size of the dot is proportional to the size of the sample.

This relationship may however not be linear, and the results suggest that the transition to carbon neutrality implies a heterogeneous structural change for the underlying economic sectors. The differentiated impact on firms' fundamentals implies a differentiated impact on

PDs, and on their capacities to cope with sectoral stress. For instance, petroleum products see their PD more affected than agriculture from an equivalent shock in VA in the delayed transition scenario (Scenario 1). This indicates that this adverse scenario is more likely to lead to a weakened capacity of debtors in the Petroleum sector to meet their financial commitments relative to other sectors. Reversely, the Electricity sector's PDs improve less than the simulated increases in VA, suggesting weaker financial fundamentals.

Furthermore, Figure 17 highlights that, in deviation from baseline, the sudden transition (Scenario 2) has higher recessionary impact on PDs as of 2050, compared to a delayed transition (Scenario 1), for all sectors except Electricity. The increase in the expected PDs, in deviation from baseline, is gradual over time and counter-cyclical, with however a structural and larger increase for a sudden transition (Scenario 2) than for a delayed one (Scenario 1).

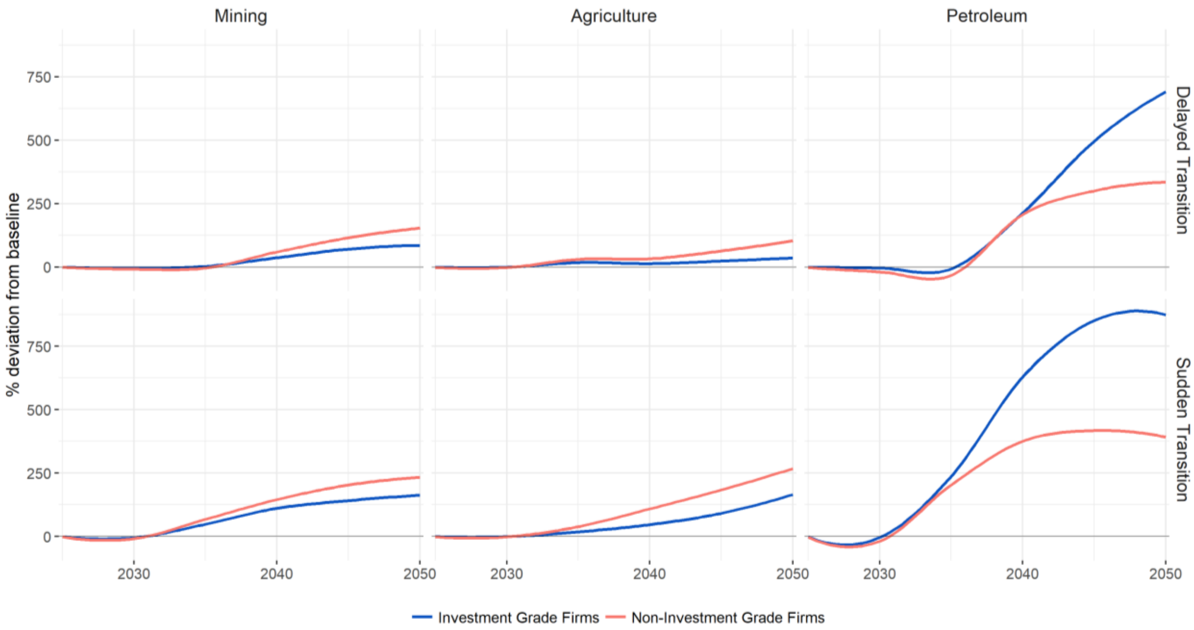
Figure 17: Probabilities of default and value added by sector



Similarly with VA impacts, PDs are more favourable until 2030 in the delayed transition (Scenario 1) compared to the baseline, assuming that recessionary shocks remain muted before the transition occurs. This is consistent with the scenario narrative, which introduces carbon price shocks from 2030 onwards. Broadly consistent with the economic outlook and the policy adjustments as the transition occurs, PDs increase at a steady path, resulting in less favourable expected probabilities in 2050, compared to an orderly transition. In the case of the sudden transition scenario (Scenario 2), regressive shocks start as of 2025 with adverse impacts as of 2030 which prove progressively more severe.

In deviation from baseline, sustained recessionary pressures on VA and turnover do not have the same impact on so-called *Investment* and *Non-Investment* grade firms, as stressed in Figure 18. Looking ahead as developments emerge, *Investment* grade firms, with stronger economic and financial fundamentals, will be able to better accommodate the idiosyncratic sector-specific shocks included in the rating model, compared to *Non-Investment* grade firms. The latter will experience higher PDs, as adverse business, financial and economic conditions may distress their capacity to meet their financial commitments, relative to the baseline scenario.

Figure 18: Probabilities of default by sector and credit rating (as of 2020)

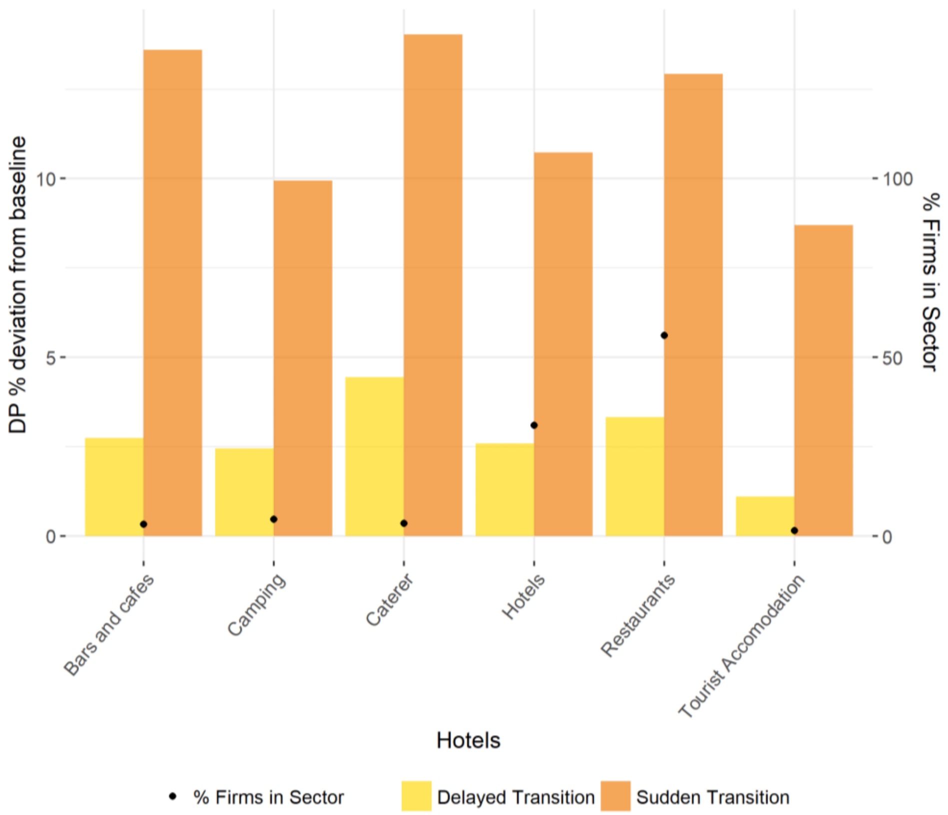


According to estimations, petroleum firms experience important PD degradations, with *Non-Investment grade* firms bearing most of the risk of this sector. Even if petroleum *Investment grade* firms benefit from strong financial fundamentals, the unprecedented shock has a recessionary impact on their underlying PDs. Accounting for firms' specific financial capacities is key for understanding the financial risks. These results further highlight the need to assess climate-related risks at the appropriate level of disaggregation. More needs to be done to additionally include firms' strategic plans, in particular investments undertaken towards emerging energy markets.

Projections of corporate default probabilities at the infra-sectoral level

Information at the infra-sectoral level might indeed reveal heterogeneity within sectors, and help to disentangle between losers and (relative) winners, with some firms performing better than the average. This heterogeneity is observable within a sector, impacted by the same value added and turnover shock. It is of particular interest for both the highly and weakly impacted sectors as their average could hide risks or opportunities.

Figure 19: Infra-sectoral default probabilities – Food service and accommodation



This is the case in particular of the tertiary sector, which is a low GHG emitter and can be a frugal energy consumer. The tertiary sector as a whole represents almost 80% of total GDP. Figure 19 presents the differentiated PDs' impacts for accommodation and food services sector. Overall, this sector is weakly impacted by the shocks introduced in both disorderly scenarios[44]. However, this sector is expected to exhibit quite strong infra-sectoral heterogeneity in terms of probabilities of default as of 2050.

Diving into more details at the sub-sectoral level suggests more disruptive shocks, with some sub-sectors better off than others. The bars and cafes sub-sector stands out in particular as a relative winner (relative to the sector average), with its PDs only marginally affected by a mere 1.6% in the worst case scenario (Scenario 2 - in comparison to the baseline). This highlights the importance of operating at a level of disaggregation that is sufficiently granular to capture the financial risks associated with the transition.

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[44] In deviation from baseline, VA shocks represent -2.50% for a delayed transition (Scenario 1) and -5.83% for a sudden transition (Scenario 2), for the whole sector.

6. Discussion

This section discusses some of the modelling choices and results presented in the previous sections. It proposes a critical analysis of scenario-based approaches, highlights the features and limits of integrating a suite of independent models, and suggests some avenues for future research.

It should be recalled first that the scenarios estimated in this paper are not forecasts. They describe a hypothetical set of events selected and modelled specifically for financial stability assessment. They are not predicting what will happen or giving any indication as to what future transition pathway is more likely. They are also not to be used for another purpose than the one for which they were designed, namely financial risks assessment, although they might be of interest to the wider community.

Scenario-based approaches and uncertainty

The selected assumptions and proposed methodology does not negate the fact that the low-carbon transition is filled with uncertainty (Bolton et al., 2020). This scenario-based approach has been precisely considered appropriate because of this context of high uncertainty on future transition pathways. Climate-related risks are, for example, likely to be correlated with and potentially aggravated by tipping points and non-linear impacts (NGFS, 2019a). Because of this level of uncertainty, traditional forecasting techniques are of little help and scenario-based approaches have been proposed as a way forward (NGFS, 2019b; Bolton et al., 2020). Scenario-based approaches would provide the creative and flexible framework to explore a variety of possible futures. See Colin et al. (2019) for more details on the different categories and approaches to scenario.

There are however at least two limitations to the insights provided by scenario-based approaches. First, since they need to be quantified in order to be relevant to the targeted community (i.e. central banks and financial institutions), they then often rely on the very same models that they were supposed to provide an alternative approach to. All the extensive literature on climate-economy modelling limitations and sensibility to parameterization and calibration (Pindyck, 2013) therefore applies as caveat to our results. Second, scenario-based approaches require selecting an actionable set of a handful of scenarios. The selection of the scenarios becomes the very first assumption that might have a strong bearing on the results. In our case, we built on the collective intelligence of the NGFS, which has engaged in a consensus-based process to identify a first set of reference scenarios.

Selecting the key drivers of change

As presented earlier, the approach of the NGFS has been to select a number of existing scenarios among the IPCC set of scenarios. These scenarios model the carbon prices as the key mitigation variable (given a socio-economic backdrop provided by the SSPs and a climate target associated with an RCP – see Section 3). The modelling approach in this paper is mainly based on accounting for changes in the carbon prices (with the productivity assumptions to cover for the wide range of other dynamics). As acknowledged by the IPCC (2014), this assumption overlooks many dynamics that will be essential to a low-carbon transition. For instance, historical evolutions of energy systems have responded to a variety of incentives including changes in relative energy prices (which can be captured through carbon prices) but also many other considerations including geopolitical and institutional ones, as well as unexpected technological breakthroughs.

A large stream of literature has emphasized the importance of institutional inertia and path dependency, making pricing mechanisms alone insufficient to switch toward a low-carbon economy (Pearson and Foxon, 2012; Smil, 2017). In this context, direct government expenditures will likely play an important role in the transition, at least for two reasons. First, to fund investments in R&D for early-stage technologies with uncertain and long-term returns (Mazzucato, 2013). For instance, the sharp decrease in the cost of many renewable energy technologies over the past few years (which outpaced most predictions) seems to have responded to massive investments in R&D and targeted subsidies rather than carbon pricing (Zenghelis, 2019). Second, public expenditure can be essential to invest in sustainable infrastructure (Aglietta and Espagne, 2016; Fay et al., 2015; Krogstrup and Oman, 2019). These public investments can notably lock in carbon emissions for the decades to come, and they can also pave the way for a smooth and efficient implementation of carbon prices (for instance, building an efficient public transportation system in semi-urban areas may be a precondition to an ensuing effective taxation of individual car use).

Such public expenditures, in turn, would bring methodological challenges when it comes to modelling them. In particular, it is unclear whether they would crowd out private investments (as would likely appear if one uses a supply-led equilibrium model) or crowd them in, for instance if we use a demand-led non-equilibrium model (Dafermos et al., 2017; Mercure et al., 2019). The choice of the model therefore becomes paramount to the outcomes of any low-carbon scenario analysis.

The role of technological innovations in the transition

Another dimension of the transition that is only partially captured by this exercise but is worth emphasizing has to do with technological innovation. Whereas the cost of many renewable energy technologies has sharply decreased and many technological breakthroughs may be on the way, technical limitations may also prevent a smooth transition from occurring (regardless of the level of carbon prices and public investments). For instance, the intermittency of renewable energy remains a considerable problem that tends to be overlooked (Moriarty and Honnery, 2016; Smil, 2017). Other sectors such as aviation or the cement industry may remain difficult to decarbonize in the medium term. Moreover, given the critical role of technological innovations, energy efficiency and sobriety for the transition, future transition scenarios could simulate such impacts through models that better account for the peculiar role of energy in economics (e.g., The Shift Project and IFPEN, 2019).

Such limitations are often avoided in climate-economic models by allocating a critical role to negative emissions and to carbon capture and storage technologies. However, the maturity of these solutions remains uncertain (IPCC, 2014) and could have negative impacts on biodiversity (Deprez et al., 2019). The technological dimensions of the transition are only partially addressed in our methodology through the simulated shocks on productivity. Innovations, either early or delayed, are assumed to eventually translate into improvements or decreases in productivity. However, by choosing homogeneous technology shocks across sectors, the proposed approach fails to recognize sector-specific technological change with potential sector-differentiated impacts. Integrating them would bring new methodological challenges (including the calibration of such sectoral technology shocks), which we will explore in future research. Regarding carbon capture and storage technologies, differentiated assumptions are embedded in the NGFS reference scenarios, and their impacts are accounted for in the modelling architecture at the aggregate level.

Model coupling, calibration and feedback loops

Another issue relates to the potential feedback effects between macroeconomic and financial variables, as well as between climate and economic variables. The incorporation of feedback loops between macroeconomic and financial variables is still a work in progress for standard scenario analyses. For physical risk, this could include the interaction between economic developments and climate change (e.g., a stronger economy may exacerbate GHG emissions, thereby accelerating climate change). For transition risk, this could include an interaction between economic policy and climate change (e.g., a slow build-up of physical risks could foster complacency among policymakers with respect to climate policy). Finally, there may be a link between banks' financial health and climate change, as banks are important actors in the financing of the energy transition. A negative feedback loop may therefore emerge if, for instance, stranded assets significantly affect the financial system, which in turn may impede the ability of banks to finance the transition.

However, the sequential nature of such modelling, with climate variables included upstream and sectoral and financial impacts downstream, limits the possibilities to include such features. The amplification of industry-specific shocks (i.e., the aggregate response following a sector specific shock) is however covered in the proposed modelling. The production network framework implies that a shock to a single industry will affect both output of downstream industries and demand for upstream industries, translating eventually in aggregate impacts.

Modelling sectoral and infra-sectoral economic impacts

As discussed in Section 2, it is important to appreciate transition risks at the sectoral and infra-sectoral levels. The approach taken in this paper assumes that each sector's vulnerability to climate change is depends on its emissions, its intermediate inputs use and the substitution elasticities (as observed in the literature). Since there is considerable uncertainty regarding the value of these elasticities, the calibration choices we made may impact the outcome of the scenarios considered. Moreover, technological break-through may greatly modify the sectoral landscape of the economy, with for instance new sectors emerging (e.g., it would have been impossible to assess the transition of the information and technology sector decades ago without accounting for the creation and diffusion of the Internet).

The results obtained should be assessed with great caution. For instance, the fact that the agricultural sector appears as a highly exposed sector does not suggest by any means that a financial institution should not be exposed to agricultural activities. The agricultural sector will continue to play an important role and its transition toward low-carbon outcomes will indeed require consistent financial support. Similarly, the mining sector generates a relatively high level of GHG emissions but may be necessary to extract the mineral resources needed for low-carbon technologies. Reversely, firms in sectors that appear as being not exposed (e.g., services in general) could actually be impacted by the transition (for instance, an advertising company that depends on sales generated by polluting sectors).

The estimates reported here nevertheless important information on structural determinants, which help understand the behaviour of the outputs. Going forward, next steps will include exploring new empirical transmissions channels, in particular two complementary research avenues. First, it is necessary to rely on existing methodologies that explore climate-related risks at the infra-sectoral level, by assessing the preparedness of each firm within a portfolio (see Hubert et al., 2018, for a summary of methodologies on physical risks, and UNEP-FI, 2019, for a summary of methodologies on transition risks). As mentioned in Section 2, companies within the same sector are not necessarily equally vulnerable to climate-related risks: some companies within a highly exposed sector may have already started to invest in new technologies and new products that make them particularly capable of reaping the benefits of the transition. In addition, two companies in the same sector may have little in common (e.g., a renewable energy company and a coal power plant both pertaining to the electricity sector).

The approach proposed in this paper includes firm-specific information on financial robustness. This represents a major improvement and provides a complement to existing studies. It however does not yet include any information on the firms' emissions or strategies regarding the transition. It will be essential that future scenarios rely on such a disaggregated information on firms' business plans and R&D capacities to leverage the opportunities associated with the transition. In this respect, the banking industry is well positioned to tailor existing scenarios and fine-tune sectoral analyses to their specific knowledge of companies in portfolio.

Second, additional work on potential contagion channels would be an interesting avenue for research. For instance, with regard to physical risks, Hildén et al. (2020) seek to explore the potential transboundary cascade effects that could result from a shock in one country/sector. Such methodologies seem particularly insightful in the context of Covid-19, which has shown how global supply chains can be disrupted in unpredictable ways.

The first climate change-related bottom-up financial risk assessment

The coupling with the macroeconomic model NiGEM allows us to alleviate some of the limitations of the sectoral model, such as the absence of capital or nominal frictions. Capital in particular is not accounted for but, under an adverse scenario, it could be impacted both through an increase in the capital depreciation rate (higher default probabilities, bankruptcies, accelerated capital scrapping, etc.) and through falling investment. This allows us to benchmark our aggregate effects on NiGEM results, while obtaining sectoral impacts via the production network.

Results indicate that the macroeconomic and financial impacts of a disorderly transition remain limited, in particular in the case of the delayed transition scenario (Scenario 1). This is primarily because of the calibration on the NGFS estimates. The analysis shows that a disorderly transition to a low-carbon economy implies economic costs in the short term, compared to an orderly transition. It has to be kept in mind that, according to many experts, the 'business-as-usual' scenario would have even larger negative impact on output in the long run because of the physical risks implied (NGFS, 2020c). The longer-term discounted benefits from the transition would then overtake the negative impacts in the first period, making the transition to a low carbon economy worthwhile. The results also show clearly that some sectors are significantly more exposed than others, and provide systematically quantified estimates of these impacts. This heterogeneity is even further enhanced within sectors when taking into account firms' initial financial situation.

This climate-related framework provides a functional and relatively easy-to-implement tool to develop scenarios for financial risk assessment. Thanks to the downstream financial modules, it represents a step forward in understanding the links between climate change and the financial system, which is the end point of interest for central banks and supervisors. These scenarios will be explored by the ACPR in its 2020 pilot financial risk assessment, which will be the first climate change-related bottom-up exercise to be conducted.

7. 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. It aims specifically to provide the French supervisor – the *Autorité de contrôle prudentiel et de résolution* (ACPR) – with an analytical framework for developing climate-related scenarios for risk analysis. Focusing on transition risks, and building on the NGFS reference scenarios, the framework is applied to three hypothetical scenarios: a baseline case and two severely adverse scenarios.

The newly released NGFS database provides high-level scenarios aggregated by key economic areas and for a reduced set of macroeconomic variables. These scenarios provide a consistent framework that offers guidance and helps normalize and compare supervisors' initiatives across jurisdictions. Estimated using IAMs modelling, these high-level data help articulate climate and physical variables with some key economic aggregates, easing the modelling requirements of the climate-economy interactions for central banks and supervisors.

The proposed scenarios in this paper are not forecasts. They describe a hypothetical sets of events designed to assess the strength and vulnerabilities of the financial institutions. The baseline scenario is in line with the NGFS narrative and data of an orderly transition. The severely adverse scenarios feature two different cases of a disorderly transition toward a low-carbon economy. The first relates to a delayed transition, which would be implemented only from 2030 onwards and requires an abrupt revision of climate policies. It replicates the associated representative scenario of the NGFS. The second scenario covers for the case of a sudden transition. It would start earlier, in 2025, but assumes lower technological progresses and crowding-out effects on investments leading to lower productivity levels compared to baseline. It translates into an even more severe global recession in which French

GDP would fall by 5.5% compared to baseline at the end of the time horizon. All proposed scenarios start in 2020 and extend until 2050.

To process these narratives, we identify three main modelling bricks. We first examine the impacts of these scenarios, including the baseline case, on key macroeconomic and financial variables. The NiGEM model is used to provide more detailed macroeconomic information. It results from the simulation that the tightening of climate policies, with a sharp increase of the carbon price, generates negative supply shocks with effects on growth and inflation. At the macroeconomic level, each scenario ends up including 12 variables, such as gross domestic product, inflation rate, unemployment rate, interest rates or government spending and public debt, and covers both domestic and international economic activity for four blocks of countries (France, the Rest of the EU, the USA and the Rest of the World).

The second brick consists of the junction with a sectoral model. The Banque de France developed specifically for this exercise a static multi-country, multi-sector general equilibrium model including the key features to model the impacts of carbon price shocks and changes in productivity levels. The impacts from the transition can indeed be significantly more dramatic at the sectoral level, presenting both higher risks and opportunities for a number of sectors. This model coupling allows us to simultaneously assess the economy-wide implications and the cross-sectoral effects of the simulated scenarios.

Finally, a financial block is added to the modelling to estimate a number of financial variables at the appropriate level of granularity. Macroeconomic and sectoral results are processed as inputs in the Banque de France's rating model. Combined with financial information on firms, the model generates PDs at the infra-sectoral level. The disorderly transition scenarios result in a series of disruptive structural changes across and within sectors, with differentiated impacts on firms' financial stability and PDs. A number of macro-financial variables are further linked up to the modelling architecture. A dividend discount model is calibrated on the macroeconomic and sectoral results for each scenario to estimate the associated market stock price shocks at sector level. Simulations of the EIOPA risk-free interest rates and credit spreads complete the set of information.

The modular approach adopted in this paper provides a flexible and efficient architecture, compartmenting the numerous modelling challenges and allowing for further enhancement with fewer resources. Based on this approach, the ACPR will develop and submit a number of climate-related scenarios to a representative group of banks and insurance companies in a bottom-up approach.

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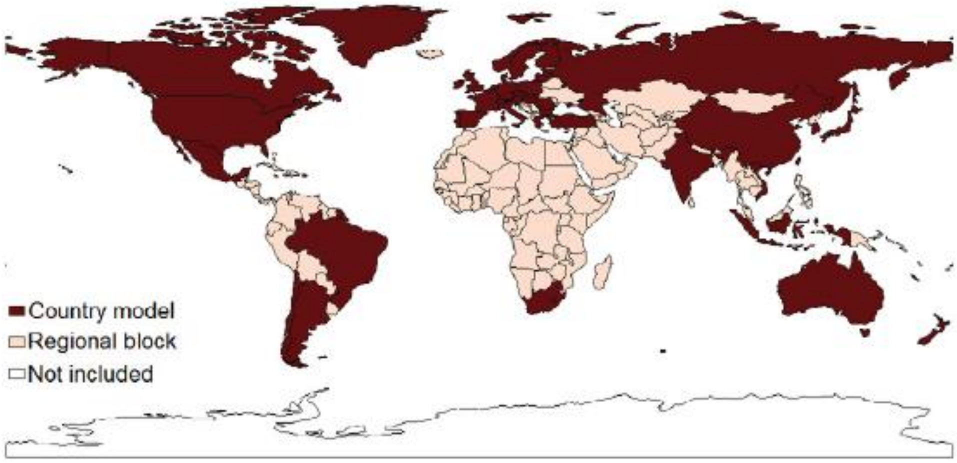
Appendices

Appendix 1: Further details on the NiGEM model

Figure 20: NiGEM country coverage



Source: Hantzsche, Lopresto and Young, Using NiGEM in uncertain times: Introduction and overview of NiGEM, NIESR Review, May 2018.

The production function

Aggregate supply in NiGEM's individual country models is based on an underlying constant-returns-to-scale CES production function with labour-augmenting technical progress. This is embedded within a Cobb-Douglas relationship to allow the factors of production (labour and capital) to interact with energy usage.

$$Q = \gamma^{Q}\left\{\left[s^{Q}(K)^{-\rho} + (1 - s^{Q})(Le^{\lambda t})^{-\rho}\right]^{-\frac{1}{\rho}}\right\}^{\alpha} M^{1-\alpha}$$

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

Monetary policy assumptions

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 Taylor 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:

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

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 2: Elasticities of substitution in the sectoral model

We calibrate the elasticity values as in Devulder and Lisack (2020), except for the substitution across energy type: 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).

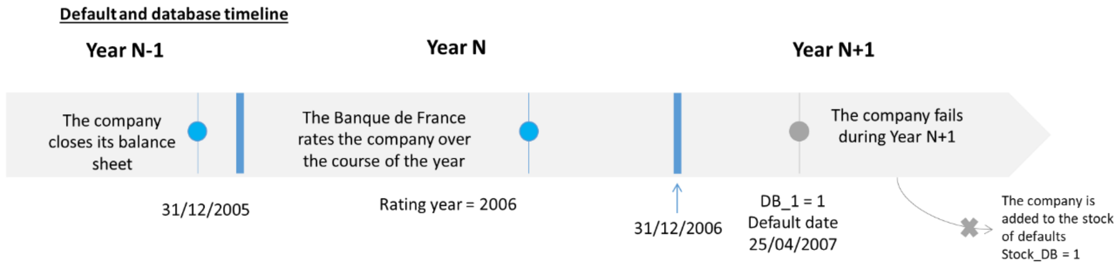
Sectoral model - Calibration of the elasticities of substitution:

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 3: 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.



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.

The notion of failure is also added to the previous definition of default. Failure indicates that legal proceedings have been opened against the company.

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

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

Appendix 4: 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[45]. Heinze & 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 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:

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

$$s.t.\gamma_1 = 1$$

Such that:

$$\mathbb{P}(D=1|\hat{\eta_i}) = \frac{1}{1+exp(\,\gamma_0+\hat{\eta_i})}$$

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[46]:

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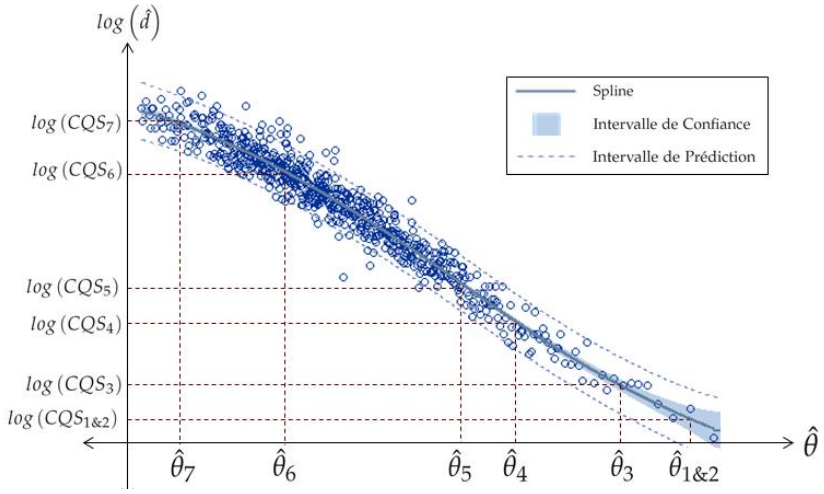
45 Firth's method consists on a systematic corrective procedure that is applied ex-ante to the same score function that is used to calculate the estimated parameters.

46 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.

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

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[47].

Figure 21: The Smoothing Cubic Spline and the Empirical delimitation of Credit Quality Steps



[47] 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 & Wahba (1979).

Appendix 5: Gaussian Macro-Finance Affine Term Structure Models

We consider a K-dimensional vector of state variables X_t made of a K_s-dimensional vector of spanned variables X_t^s with nonzero risk exposure and a K_u-dimensional vector of unspanned macroeconomic variables X_t^u with zero risk exposure. The vector of (so-called) pricing factor X_t^s is made of the principal components of the adopted panel of yields. The state vector $X_t = (X_t^s, X_t^u)$ follows under the historical probability a Gaussian VAR process:

$$\begin{bmatrix} X_t^s \\ X_t^u \end{bmatrix} = \mu + \Phi \begin{bmatrix} X_{t-1}^s \\ X_{t-1}^u \end{bmatrix} + \begin{bmatrix} \nu_t^s \\ \nu_t^u \end{bmatrix}$$

where $\nu_t = (\nu_t^s, \nu_t^u)$ is an iid Gaussian white noise with mean zero and variance-covariance matrix Σ. Under the no-arbitrage assumption there exists a (one-period) positive stochastic discount factor (SDF) $M_{t,t+1}$ such that the price at date *t* of a zero-coupon bond with residual maturity *n*, denoted $P_t^{(n)}$, is given by $P_t^{(n)} = E_t(M_{t,t+1} P_{t+1}^{(n-1)})$. We assume that the SDF takes the following exponential-affine specification:

$$M_{t,t+1} = \exp\left(-r_t - \frac{1}{2}\lambda_t'\lambda_t - \lambda_t' \Sigma^{-\frac{1}{2}}\nu_{t+1}\right)$$

where $r_t = -\ln\left(P_t^{(1)}\right) = \delta_0 + \delta_1' X_t$ is the (one-period) risk free rate (assumed to be affine in the state vector), and where the market prices of risk are of the following essentially affine form:

$$\lambda_t = \Sigma^{-1/2}(\lambda_0 + \lambda_1' X_t)$$

If we denote by $rx_{t+1}^{(n-1)}$ the one-period log excess holding returns of a bond maturing in *n* periods, namely:

$$rx_{t+1}^{(n-1)} = \ln\left(P_{t+1}^{(n-1)}\right) - \ln\left(P_t^{(n)}\right) - r_t$$

and by $\beta^{(n-1)\prime} = Cov\left(rx_{t+1}^{(n-1)}, \nu_{t+1}'\right)\Sigma^{-1}$, then it is possible to prove that:

$$rx_{t+1}^{(n-1)} = \beta^{(n-1)\prime}(\lambda_0 + \lambda_1' X_t) - \frac{1}{2}\left(\beta^{(n-1)\prime}\Sigma\beta^{(n-1)} + \sigma^2\right) + \beta^{(n-1)\prime}\nu_{t+1} + e_{t+1}^{(n-1)}$$

where $e_{t+1}^{(n-1)}$ denotes the return pricing error with variance σ^2. The affine yield-to-maturity formula is given by:

$$R_t^{(n)} = -\frac{1}{n}(A_n + B_n' X_t)$$

where (A_n, B_n) are described by the following recursive equations:

$$A_n = A_{n-1} + B'_{n-1}\mu^Q + \frac{1}{2}(B'_{n-1}\,\Sigma\,B_{n-1} + \sigma^2) - \delta_0$$
$$B'_n = B'_{n-1}\Phi^Q - \delta'_1$$

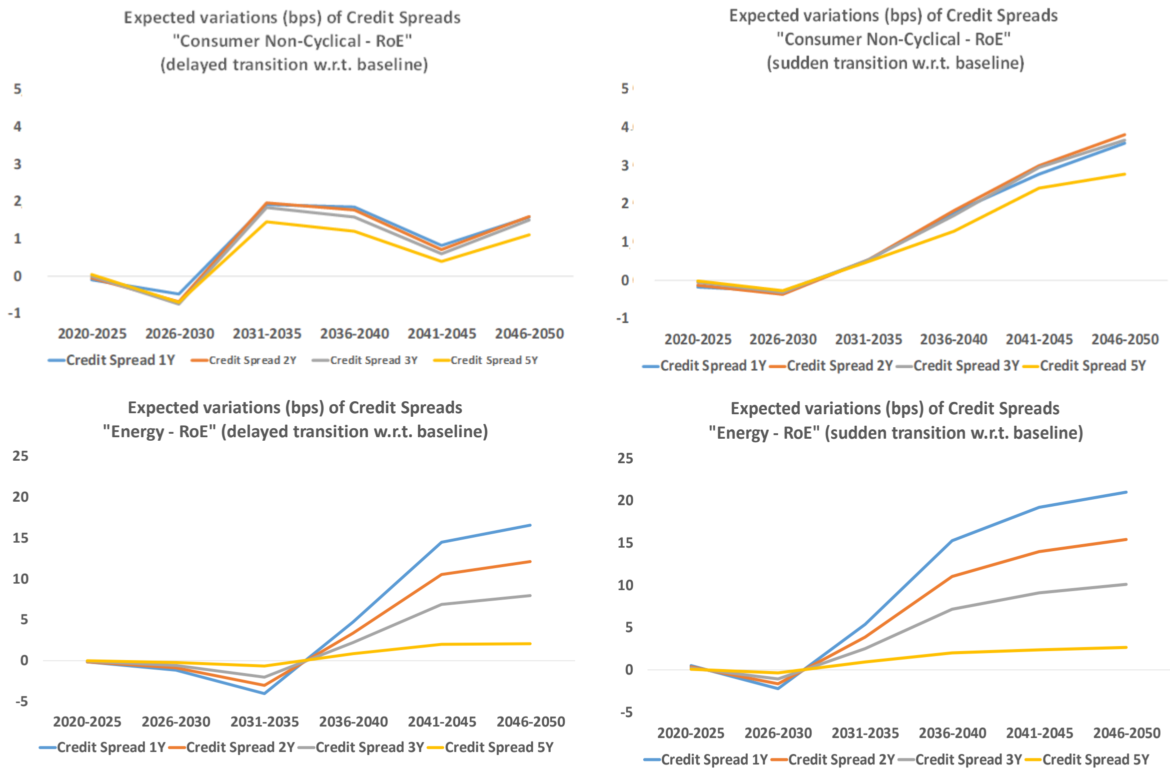
where $\beta^{(n)} = B'_n$, $A_0 = -\frac{1}{2}\,\sigma^2$ and $B_0 = 0$ are the starting conditions of the system, and where $\mu^Q = (\mu - \lambda_0)$ and $\Phi^Q = (\Phi - \lambda_1)$ are the constant term and autoregressive matrix of state vector under the risk-neutral probability.

The spanning restriction means that the risk exposures of the unspanned factors are equal to zero, i.e. $\beta^{(n)} = (\beta_s^{(n)'}\,, 0')'$. This restriction implies that $\delta'_1 = (\delta_1^{(s)'}\,, 0')'$ and that the upper right $(K_s\,, K_u)$ block of the risk-neutral autoregressive matrix is equal to zero. In other words, the yield-to-maturity formula is an affine function of the spanned (pricing) factors only, while spanned and unspanned (macro) factors maintain a joint Gaussian VAR dynamics under the historical probability. If this restriction was not imposed, the affine framework would imply that date-*t* macroeconomic variables would be perfectly correlated with the date-*t* yields (i.e., yields at date *t* can explain any set of macroeconomic variables at the same date). This theoretical property is empirically rejected.

Adrian et al. (2013) show that not only historical parameters (μ, Φ, Σ) but also risk-premia parameters $(\lambda_0\,, \lambda_1)$ can be instantaneously estimated (consistently) and by means of explicit formulas. A key ingredient behind this relevant result is the representation of one-period expected bond returns as affine function of $(\lambda_0\,, \lambda_1)$ (see Adrian et al. (2013) for a detailed derivation of the estimators).

Appendix 6: Details on corporate credit spreads for the RoEU, USA and Japan

Figure 11B: Expected variations (bps) of corporate credit spreads in RoEU[48], from 2020 to 2050 (average over 5-year intervals), for consumer non-cyclical and energy sectors.



[48] GDP-weighted average of credit spreads of Germany, Italy, Spain and UK.

Figure 11C: Expected variations (bps) of corporate credit spreads in the USA, from 2020 to 2050 (average over 5-year intervals), for consumer non-cyclical and energy sectors.

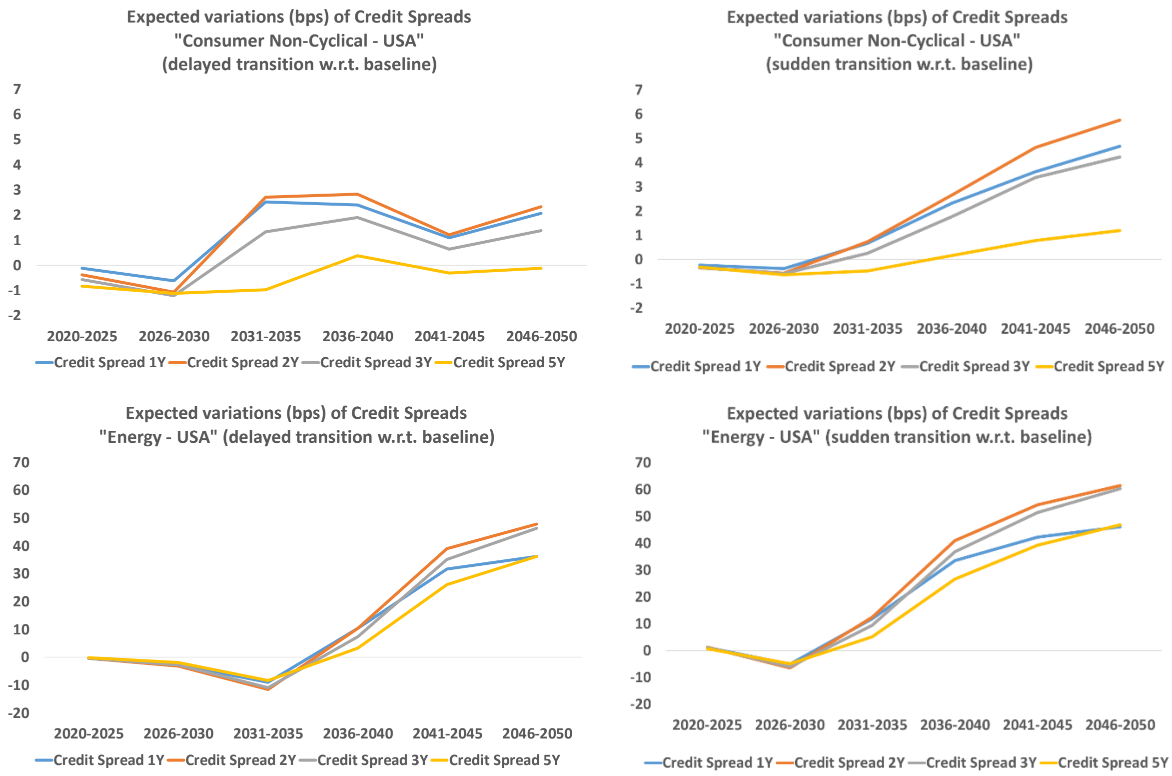


Figure 11D: Expected variations (bps) of corporate credit spreads in Japan, from 2020 to 2050 (average over 5-year intervals), for consumer non-cyclical and energy sectors.