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paper

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Using Short-Term Scenarios to Assess the Macroeconomic Impacts of Climate Transition

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ABSTRACT

This paper proposes a set of short-term scenarios that reflect the diversity of climate transition shocks : increase in carbon and energy prices, increase in public or private investment in the low-carbon transition, increase in the cost of capital due to uncertainty, deterioration of confidence, accelerated obsolescence of part of the installed capital, etc. Using a suite-of-model approach, we assess the implications of these scenarios for the dynamics of activity and inflation. By considering multiple scenarios, we therefore account for the uncertainty around future political decisions regarding climate change mitigation. The results show that the magnitude and duration of the macroeconomic effects of the transition to carbon neutrality will depend on the transition strategy chosen. While a number of short-term scenarios being inflationary or even stagflationary, there are also factors that could curb inflation and boost economic growth.

Keywords: Climate Transition, Scenario Analysis, Macroeconomic Modelling.
JEL classification: C60, E44, E50, G32, Q40, Q54.

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NON-TECHNICAL SUMMARY

As the world shifts towards a low-carbon economy, economic agents need to understand the risks and opportunities associated with this major change. Existing empirical evidence - mainly based on carbon taxation - shows relatively limited impacts of transition policies on the macroeconomy. However, these empirical assessments are based on past observations of periods in which the transition was only modest and carbon price increases were limited. They may thus ignore transmission mechanisms that will emerge in the future when transition risks are much more material.

The present research builds upon this existing work and brings three main novelties. First, instead of considering emission-pricing policies only, we develop eight different short-term scenarios, which cover representative cases of a wider spectrum of transition shocks. Second, it considers extremely adverse, though probable, narratives in order to assess credibly the largest impacts that can be expected from transition shocks. Third, by exploring shocks of different natures (positive/negative supply and demand drivers), it accounts for the uncertainty around the transition paths, providing a quantification of the range of likely effects over short-term horizons.

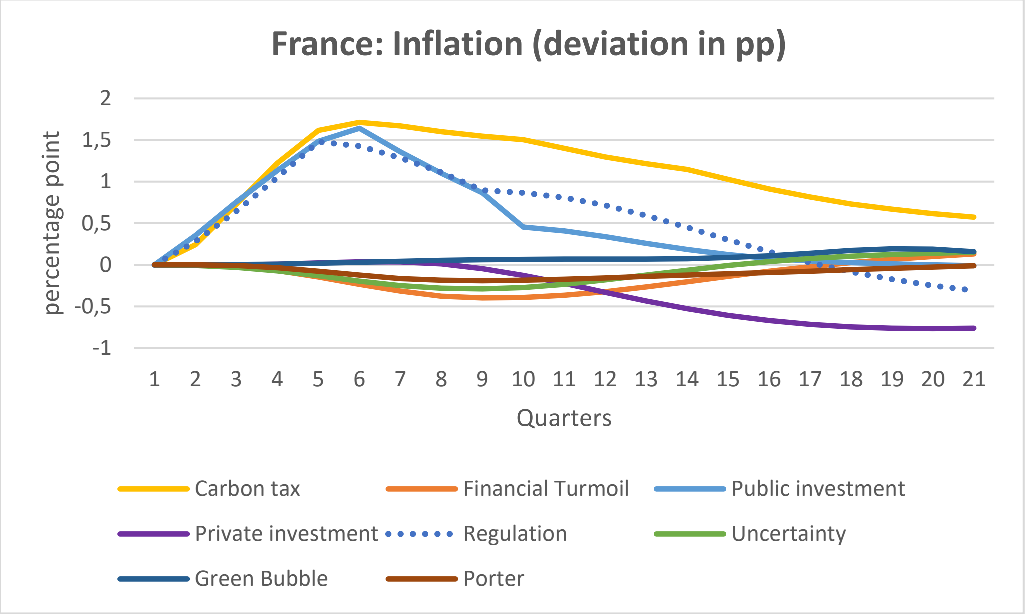
We start with detailed narratives that provide a story line behind each scenario: we first assess the consequences of negative supply shocks, such as a disorderly carbon taxation or a sudden tightening of environmental regulations. We also analyze negative demand shocks, like uncertainty on transition policies, or a scenario of financial market turmoil, which accounts for stranded assets due to environmental regulation. In addition, we consider positive demand shocks, such as a boom in green public investment or a green bubble, spurred by investors' exuberance for transition-related assets. Lastly, we simulate the effects of positive supply shocks, like a boom in green private capital expenditures and a scenario of green innovation that spills over to aggregate productivity.

Contrary to long-term scenarios, whose dynamics are generally smooth and gradual, the short-term scenarios simulated in this paper show how the transition to a low-carbon economy can become critical for policy-makers to achieve their objective to stabilize growth and inflation and ensure financial stability.

Our results show that the magnitude and duration of the macroeconomic effects of the transition to carbon neutrality will depend on the transition strategy chosen. A positive demand shock - the one usually presented in the orderly/optimistic scenarios - could have a positive effect on economic activity but also inflationary implications. In contrast, negative demand shocks - triggered by uncertainty or financial market turbulence - could be disinflationary and recessionary. On the supply side, positive shocks such as private investment boom or a green innovation scenario could stimulate economic growth and reduce inflation if they foster technological progress and productivity. On the contrary, if they are negative, triggered for example by higher costs due to carbon taxation or regulation, stagflationary episodes could appear. Scenarios based on financial turmoil or mispricing could endanger both financial and price stability. These different scenarios also illustrate the importance of private and public investment and of the support for households in limiting the macroeconomic cost of the transition.

From a policy perspective, our results show that the earlier and more gradually the transition is implemented, the lower the risks to macroeconomic stability. By contrast, if not properly anticipated, the transition to carbon neutrality could also lead to a rapid succession of shocks, increasing macroeconomic volatility. This increased volatility could then disrupt the decisions of economic agents, weaken inflation expectations and therefore constitute a real challenge for the conduct of a monetary policy adapted to the challenges of transition.

Figure N1. Overview of the impacts on France's inflation for all scenarios (FR-BDF, deviation in percentage points)



Sources: authors' calculations

Évaluation des effets macroéconomiques de la transition bas-carbone par l'utilisation de scénarios de court-terme

RÉSUMÉ

Ce document propose un ensemble de scénarios de court terme qui reflètent la diversité des chocs liés à la transition bas-carbone : augmentation des prix du carbone et de l'énergie, augmentation des investissements publics ou privés verts, augmentation du coût du capital en raison de l'incertitude, détérioration de la confiance, obsolescence anticipée d'une partie du capital considéré comme « non-durable », etc. En mobilisant une "suite de modèles", qui interagissent entre eux, nous évaluons les conséquences de ces scénarios sur les trajectoires d'activité et d'inflation. En évaluant plusieurs scénarios, nous tenons compte de l'incertitude entourant les décisions politiques futures en matière d'atténuation du changement climatique. Les résultats montrent que l'ampleur et la durée des effets macroéconomiques de la transition vers la neutralité carbone dépendront de la stratégie de transition choisie. Alors qu'un certain nombre de scénarios de court terme pourrait avoir des conséquences inflationnistes, voire stagflationnistes, il existe également des facteurs susceptibles de freiner l'inflation et de stimuler la croissance économique.

Mots-clés : transition bas-carbone, analyse de scénarios, modélisation macroéconomique

1 Introduction

As the world shifts towards a low-carbon economy, economic agents need to understand the risks and opportunities associated with this transition. While such risks and opportunities apply to individual firms or households, these developments have also significant impacts on aggregate variables and policy-makers are urged to improve their understanding of the macroeconomics of climate transition (Villeroy de Galhau, 2023). For instance, in July 2022, the European Central Bank (ECB) published its work plan on climate change stating that "the transition to a greener economy affect[s] our primary objective of maintaining price stability due to [its] impact on our economy"[1]. The first strategic priority area of this ECB-wide climate agenda is to "assess the macroeconomic impact of climate change and mitigation policies on inflation and the real economy".

Existing empirical evidence - mainly based on carbon taxation - shows relatively limited impacts of transition policies on the macroeconomy (Konradt and Weder di Mauro, 2021 or Ciccarelli and Marotta, 2021). However, these empirical assessments are based on past observations of periods in which the transition was only modest and carbon price increases were limited. They may thus ignore transmission mechanisms that will emerge in the future when transition risks are much more material. Against this background, scenario analysis can help explore different possible paths into the future, such as the adoption of carbon taxes, changes in consumer behavior, and advancements in renewable energy technologies. The work of the Network for Greening the Financial System (NGFS) provides prominent examples of climate scenarios which give details on key macroeconomic variables. However, these scenarios feature transition paths over long periods of time (2050 or 2060)[2] and Allen et al. (2020) show that while the transition shocks trigger larger changes at sectoral level, the usual macroeconomic variables (unemployment and GDP in particular) do not vary much within different long-term scenarios.

While long-term scenario analysis is a useful tool for exploring the potential impacts of climate transition on a global scale, it may not provide an accurate picture of the effects of transition shocks in the shorter-term. Large-scale developments may occur over shorter periods of time, in the event of a rapid bifurcation or unexpected policy changes, technological advancements, and sudden shifts in consumer behavior. These factors can significantly influence macrofinancial variables in the short term, creating temporary movements in economic activity, inflation or financial prices that are usually ignored in long-term scenarios.

This paper proposes a set of short-term scenarios that reflect the diversity of transition shocks - increase in carbon and energy prices, increase in public or private investment in the low-carbon transition, increase in the cost of capital due to uncertainty, deterioration of confidence, accelerated obsolescence of part of the installed capital, etc. Using a suite-of-model approach,

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[1] See `https://www.ecb.europa.eu/press/pr/date/2022/html/ecb.pr220704_annex~cb39c2dcbb.en.pdf`

[2] The NGFS is currently developing a conceptual framework to also include short-term scenarios in its scenario database

we assess the implications of these scenarios for the dynamics of economic activity and inflation. As the transition implies a combination of supply and demand shocks, the total impact on macroeconomic variables is potentially important but its nature is above all uncertain. By considering multiple scenarios, we therefore account for such uncertainty primarily due to future political decisions regarding climate change mitigation. In particular, the evolution of carbon prices, or the amount of green investment and public subsidies prove to be particularly relevant. For policy-makers, such a diversity of possible futures can make them identify possible blind spots and biases in their policy assumptions, improve the accuracy and robustness of their narratives, and eventually make more informed decisions, while enhancing their ability to adapt to an ever-changing future.

The assessment of transition shocks over short-term horizons have been addressed by very few institutions so far. Most of them have been developed in the context of financial stability assessments (see Vermeulen et al., 2018, for seminal work on short-term transition risk scenarios). More specifically, short-term disorderly transition scenarios have been proposed in the context of the ECB climate risk stress test (ECB, 2022) or IMF Financial Stability Assessment Programmes (Adrian et al., 2022). In a macroeconomic context, the IMF (2022) assesses, using a macroeconomic model, the output-inflation trade-offs resulting from three different policy packages, all financed by greenhouse gas (GHG) taxation, and shows that policy design has a major influence on climate policy's final impact on output, inflation, and income distribution. However, it is shown that climate policies have a limited impact on output and inflation and thus do not present a significant challenge for central banks. Another paper by McKibbin et al. (2021) analyses the macroeconomic outcomes of the interaction between monetary policy and climate change, to assess how emissions mitigation policy and climatic disruption can affect central banks' ability to forecast and manage inflation. However, this work only considers the event of negative supply shocks (due to carbon price, environmental regulations or climate disruptions), which leaves room for further studies. The present research builds upon this existing work and brings three main novelties. First, instead of considering emission pricing policy only, we develop eight different scenarios covering a wider spectrum of transition shocks, including carbon taxation, regulation, green investment and innovation and climate-related financial shocks. Each of them could be used, as such, as stress-test scenario[3]. Second, it considers extremely adverse, though probable, narratives in order to credibly assess the largest impacts that can be expected from transition shocks. Third, by exploring shocks of different natures (positive/negative supply and demand drivers), it accounts for the uncertainty around the transition paths, providing a quantification of the range of likely effects over short-term horizons.

The results show that the magnitude and duration of the macroeconomic effects of the transition to carbon neutrality will depend on the transition strategy chosen. While a number of short-term scenarios may be inflationary or even stagflationary, there are also factors that could curb

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[3] One scenario is being used by the French supervisor, the ACPR, in a stress-testing exercise for insurance companies; another one is currently used by the ECB/ESRB Project Team on climate risk monitoring.

inflation and boost economic growth. From a policy perspective, our results show that the earlier and more gradually the transition is implemented, the lower the risks to macroeconomic stability. By contrast, if not properly anticipated, the transition to carbon neutrality could also lead to a rapid succession of shocks, increasing macroeconomic volatility. This increased volatility could then disrupt the decisions of economic agents, weaken inflation expectations and therefore constitute a real challenge for the conduct of a monetary policy adapted to the challenges of transition.

Section 2 gives some general considerations about the design of short-term scenarios to study the macroeconomics of climate transition and the narratives of the eight scenarios used in this paper. Section 3 presents the methodological framework and Section 4 gives details about the calibration of the various short-term scenarios. Section 5 presents the results of our eight short-term scenarios and Section 6 gives some concluding remarks and areas for future research.

2 Designing short-term scenarios to study the macroeconomics of climate transition

Scenario analysis is a technique used to assess the potential outcome of a given situation by exploring various hypothetical paths into the future. It involves constructing different scenarios based on different assumptions or events that could occur, and analyzing the potential impact of each of them on a set of output variables. Such a description requires "a story with plausible cause and effect links that connects a future condition with the present, while illustrating key decisions, events, and consequences throughout the narrative" (Glenn, 2009). Scenarios are not predictions but reflect experts' knowledge about probable future outcome based on "internally consistent and challenging narrative descriptions of possible futures" (Van der Heijden, 2005).

Scenario analysis is a powerful tool to assess the potential impacts of climate transition given the diversity of transition-related events and shocks. When designing short-term scenarios, it is important to consider a variety of narratives to capture the complexity of the future and provide a comprehensive view of potential outcomes. Each individual narrative should therefore represent an alternative description of how the future may unfold, highlighting different sources of shocks or drivers, and uncertainties that could shape outcomes. In our case, each scenario is then characterized by a particular combination of socio-economic, policy, technological, and climate-change assumptions (Mallampalli et al., 2016) and their impact on the future state of key climate, macroeconomic and financial variables.

2.1 A family of scenarios to account for the diversity of transition-related developments

A typology of potential shocks – both supply and demand related – is needed to properly assess the implications of transition risks. The scenarios proposed in this exercise correspond to representative cases of a "family of shocks" linked to the transition (policy shock, market shock, technology shock, etc.), focusing on polar cases. Thus, the scenarios result from stylized shocks assumptions based on reduced sets of variables and may mobilize different macroeconomic transmission channels, with effects that may be amplifying or, on the contrary, offsetting the initial shock.

Transition-related developments can be classified as supply or demand shocks, which can be both positive and negative. A positive demand shock - the one usually presented in the orderly/optimistic scenarios - could have a positive effect on economic activity but also inflationary implications. In contrast, negative demand shocks - triggered by uncertainty or financial market turbulence - could be disinflationary and recessionary. On the supply side, positive shocks could stimulate economic growth and reduce inflation if they foster innovation and productivity. On the contrary, if they are negative, triggered for example by higher costs due to carbon taxation or regulation, stagflationary episodes could appear. Figure 1 gives an overview of the scenarios considered in this paper sorted out according to this classification.

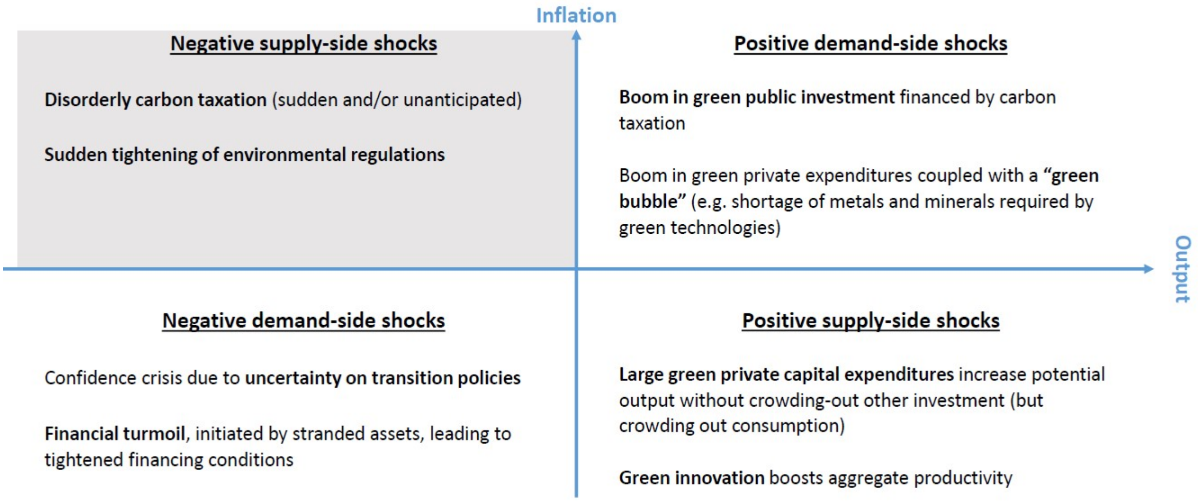

Figure 1: Climate transition: A wide diversity of shocks, which can coexist

The short-term scenarios can thus have a positive versus negative impact on supply, and a positive versus negative impact on demand respectively. They are not mutually exclusive, and may combine or succeed one another. Their stand-alone probability is hard to assess at this stage, but there are reasons to believe that the upper-left one (the negative supply shock) is slightly more probable than the others (grey area in Figure 1).

As the various possible transition paths partly depend on factors that are difficult to forecast (e.g. political decisions), we have chosen to consider a wide range of transition scenarios, representing polar cases. To better understand their mechanisms, we analyze eight standard scenarios which correspond to representative cases of transition-related shocks, starting with detailed narratives that provide a story-line behind each scenario:

- **Scenario 1: Disorderly carbon taxation**: This scenario features a public policy shock whereby the introduction of public measures, hypothetically sudden and abrupt, and unanticipated by economic agents, results in an increase in the implicit, and possibly also explicit, carbon price.[4] In terms of timing and magnitude of the shock, this scenario assumes that governments act hastily to implement ambitious mitigation actions in order to catch up for past delays in the transition policy.
- **Scenario 2: Sudden tightening of environmental regulations**: Transition risks here are the consequence of the implementation of stringent regulations to reduce drastically dependence on fossil fuels and transform the European energy mix. Ambitious targets are set for a number of energy sources, including renewables, nuclear and fossil fuel energies, corresponding to the ambitions of the European Union for 2030, which have been revisited following the war in Ukraine. The targets are brought forward in 2027 to make the scenario disruptive in the short run. In return, subsidies are provided to the renewable sector but the positive effect is only visible in the medium term.
- **Scenario 3: Uncertainty on transition policies**: This scenario envisages the macroeconomic consequences of policy uncertainty. As investment in energy infrastructure is capital-intensive and often irreversible, firms require a high level of certainty for planning purposes (Bernanke, 1983; Dixit and Pindyck, 1994). Using a firm-level data set for 12 OECD countries over the period 1990-2018, Berestycki et al. (2022) show that Climate Policy Uncertainty is associated with economically and statistically significant decreases in investment, particularly in pollution-intensive sectors that are most exposed to climate policies, and among capital-intensive companies. Similarly, households need clarity in transition policy to plan sufficiently ahead their investment in thermal renovation. The scenario therefore mainly affects private sector investment and consumption decisions.
- **Scenario 4: Financial market turmoil**: Following the hypothesis showed in the literature that the carbon transition risk may be significantly under-priced in European equity portfolios (Loyson et al., 2023), we build a scenario of sudden repricing of the transition risk

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[4] Whether these instruments directly charge for the costs of emissions, such as carbon taxation, reward their avoidance or constrain the use of carbon-based energy, they all result in the attribution of an explicit or implicit price to emissions. The implicit price – or shadow price – of carbon captures the marginal cost of abatement and can be interpreted as the willingness to pay for a given amount of emission reduction. It thus provides a good proxy for any mitigation policies, and not only carbon pricing policies. This shadow price of carbon can be estimated by models and is provided by the NGFS for a number of climate scenarios (and associated emission reduction pathways).

on financial markets. The shock here is triggered by a sudden announcement of stringent carbon regulation policies in EU and the US, both for domestic production and imports (e.g., ban on ICE vehicles and fossil fuel extraction, energy performance-based real estate regulation). The announcement of the implementation of carbon regulations in several major economies (EU, USA) affects both companies in these zones and those exporting to these countries (notably the UK, Japan). In the European Union, these regulations lead to a tightening of financing conditions for companies in the most carbon-intensive sectors and asset stranding (namely in the property market). Contagion mechanisms also cause an increase in interest rate spreads across all sectors (systemic shock due to a widespread climate of uncertainty). In line with these shocks to credit spreads, the main equity indices fall as a result of a general increase in market volatility across all sectors. Also, such transition policies destabilize the economies most dependent on fossil fuels (e.g. the United States, Norway, Saudi Arabia, Canada, Russia, etc.), causing a shock to the sovereign bonds of fossil fuel-producing countries.

- **Scenario 5: Boom in green public investment**: The public investment shock can take a variety of forms: investment measures to boost energy efficiency gains, interventions to address infrastructure bottlenecks, or increased support to renewable energy. The additional public investments are funded by a carbon tax, reducing the impact on public debt but shifting the burden on the private sector.

- **Scenario 6: A "green bubble"**: A green bubble, like the "Dot Com bubble" in 1998-2000, would be characterised by a rapid increase in the value of shares in companies developing sustainable technologies (e.g. clean mobility, carbon capture, renewable energies) in several countries at once (USA, China, India, Korea, Denmark, BRICS, etc.). The rising phase of the bubble would be fuelled by a situation of irrational exuberance (Shiller, 2016) temporarily generating large and rapid investments, encouraged by a sharp fall in credit spreads and risk premia. This major influx of funding would generate strong growth in the value of stock market indices specialising in green companies[5] (e.g. the Nasdaq index during the internet bubble rose from less than 1,000 to more than 5,000 between 1995 and 2000). The scenario includes a second phase where the bubble bursts, due to rising concerns on the limited availability and rising prices of transition-critical minerals (copper, lithium, cobalt, manganese, nickel, etc.). The dissemination of this information triggers a very pronounced adjustment on the markets (wake-up call). Investors realise that a majority of the investments made were non-productive, due to the disappointing profitability and effectiveness of the solutions promoted by the growing companies, and were brutally chilled, leading to the bankruptcy of many companies – due to a lack of financing and insufficient effectiveness of the technologies developed – and a major fall in the markets concerned (the Nasdaq index, which had increased five fold between 1995 and 2000, fell by 77% between 10 March 2000 and 4 October 2002).

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[5] such as the S&P Clean Energy or the NASDAQ OMX Green Economy (QGREEN)

- **Scenario 7: Large green private capital expenditures**: This scenario is based on a large increase in green private capital expenditures that does not crowd out the other types of investment. Governments give fiscal incentives to the private sector to invest in green production capacity through subsidies or lower taxes. At the same time, to avoid the negative impact on public finances, such incentives are financed by tax increases on households, leading to some crowding-out effects between consumption and investment. In other words, the increase in investment is fully financed by an increase in domestic private savings, being neutral for public finances and external accounts.

- **Scenario 8: Green innovation**: This last scenario assumes a number of game-changing energy-related innovations that, on the one hand, improve energy efficiency across all sectors of the economy and, on the other hand, reduce the cost of producing energy. It first assumes that the energy efficiency trends necessary to reach to carbon neutrality by 2050 materialise, but are concentrated in electricity generation. Furthermore, a series of innovations in clean technologies accelerate the fall in energy costs compared to the observed past trends. The gains in productivity in the renewable sectors drive structural transformations cascading differently across sectors, with positive impact on supply and activity but without translating in increased inflation.

2.2 Turning narratives into macro-financial shocks

Once the narrative, which remains essentially qualitative, is detailed, the scenario must be translated into a set of shocks that are sufficiently adverse to create risks to price and financial stability, while remaining quantitatively plausible. For example, a near-term scenario involving carbon taxation, while deviating from long-term trends, must remain consistent with expected policy trends in terms of the magnitude of carbon price increases. Similarly, a short-term scenario involving regulatory changes must be consistent with stated policies for the energy mix.

In all cases, the plausibility of the short-term scenario must be compatible with credible references, such as long-term climate scenarios that take into account the interaction between economic and climate systems. The specificity of the short-term scenario consists therefore in playing with the timing of plausible events, making them more sudden or taking into account likely additional effects that are ignored over longer time periods (e.g., short-term reactions of financial markets or temporary changes in agents' responses to policy changes).

Scenarios implying financial market reactions may also refer to past events that could share some similarities with future developments related to climate transition. For instance, the bursting of a "green bubble", linked to a temporary overvaluation of green assets, could be calibrated to previous bubbles in financial markets, such as the "Dot Com bubble" in the early 2000s with similar fluctuations in equity prices and possible contagion effects on other asset prices. Financial turbulence linked to stranded assets could in turn be calibrated using estimates of capital that could be at risk of becoming unprofitable in the event of a sudden change in transition policy.

Some transition shocks may also be related to expected needs that experts quantify for the future. For instance, several evaluations have been proposed in terms of additional investment necessary to realize the green transition. Such investment needs could be translated into both demand (additional expenditures) and supply shocks (additional production capacity), creating macroeconomic effects at business cycle frequency.

Finally, the theoretical and empirical literature may be used to obtain quantitative estimates of how a key driver reacts to a given transition policy. For instance, there is an abundant literature on the so-called Porter hypothesis (PH) which argues that well-designed and stringent environmental regulation can stimulate innovation, which in turn increases the productivity of firms (see Porter, 1991; Porter and van der Linde, 1995). Designing a positive supply-side scenario may rely on empirical estimates of the PH to calibrate shocks on innovation or productivity.

This paper aims to provide simulations of the macroeconomic transmission channels of transition-related shocks, through the analyses of aggregated effects on a set of relevant macroeconomic variables (including but not limited to inflation and GDP). Other relevant modelling approaches could lead to more granular financial analyses, as is the case in previous works, which for instance use a credit rating model to estimate the effects of various transition scenarios on corporate probabilities of default for France ((Allen et al., 2020)), or use general equilibrium sectoral estimates to assess U.S. banks' exposures to transition risks ((Jung et al., 2023)).

2.3 Modelling approaches to quantify short-term scenarios

Once the narratives have been translated into shocks to key drivers or assumptions, macroeconomic models are used to quantify how these shocks propagate to the economy and obtain general equilibrium effects. Several types of models exist, from a-theoretical time-series models to micro-funded computable general equilibrium models. Given the nature of the climate transition, the methodological framework needs to verify a series of criteria.

First, a comprehensive representation of the supply and demand sides of the economy is necessary to quantify how a transition policy could affect both firms – through changes in production costs, incentives to invest in green assets or decreased profitability of high-carbon assets – and households – through tax policy, changes in purchasing power or redistribution as a way to mitigate the social effects of transition policy. Second, given the global nature of climate change and climate transition, a multi-country approach seems necessary in order to account for the differentiation in transition policy across countries, which gives rise to changes in competitiveness and trade-related effects. Third, given the sensitivity of macroeconomic variables to economic policy assumptions (e.g. the way carbon tax proceeds are recycled or monetary policy reacts to inflation/output gap), the inclusion of a public finance and monetary policy block is warranted, including budgetary solvency rules and central bank reaction functions. The calibration of scenarios will therefore require the specification of policy reactions to the transition shocks. Fourth, to correctly assess the macrofinancial linkages, the modelling infrastructure should include a financial block that can account for spillovers, feedback loops and amplification mechanisms through the financing conditions of the different economic agents. Finally, because transition policy targets sectors – industries that emit a large amount of CO_2 will be more severely affected by policy measures – it is important to study the effects at the sectoral level or to have a sectoral tool when the transition shock comes from a particular sector (e.g. in a scenario with sector-specific regulations or when innovation efforts are applied only to green activities).

Overall, given that there is no “one-size-fits-all” model, the modelling infrastructure either relies on a single tool that provides only a partial account of the macrofinancial impact of the transition or on a suite-of-model approach for a more detailed description of the transition’s impacts (see Allen et al., 2020; ECB/ESRB, 2021; ECB/ESRB, 2022 ; Adrian et al., 2022).

3 Methodological framework

3.1 A suite-of-model approach

Our modeling framework is based on a suite-of-model approach. Three main models are used: a multi-country model, NiGEM, used to implement shocks in various countries and derive implications on trade volumes and prices, financial market valuations, and monetary policy conditions; a semi-structural model of the French economy, FR-BDF, which gives detailed impacts on France; and a multi-country sectoral model, used to simulate shocks specific to sectors and obtain their propagation through the supply chains. Figure 2 gives a representation of the interactions between these different models, their inputs and outputs.

According to the scenario narratives, a series of shocks is calibrated using various sources: IAM models for carbon prices, announced policies from regulatory bodies when available, past experience of financial shocks, estimates of impacts based on academic literature, etc. (see Section 4 for a detailed calibration of shocks). For the macro-financial scenarios, those shocks are generally implemented in NiGEM first in order to get their global impact, both on the financial side and on economic activity of France’s trading partners. The calibration of these financial stress narratives involves some changes compared to the standard stress test scenario framework. In order to simulate the financial consequences of low-carbon transition pathways, patterns and potential shocks need to be integrated exogenously, at the scenario design stage. For instance, some financial variables are designed as inputs into the suite of models, based on empirical evidence, rather than as model outputs (e.g. credit spread risks, etc.). This ensures a better assessment of transition-related impacts on financial markets and potential feedback to the economy.

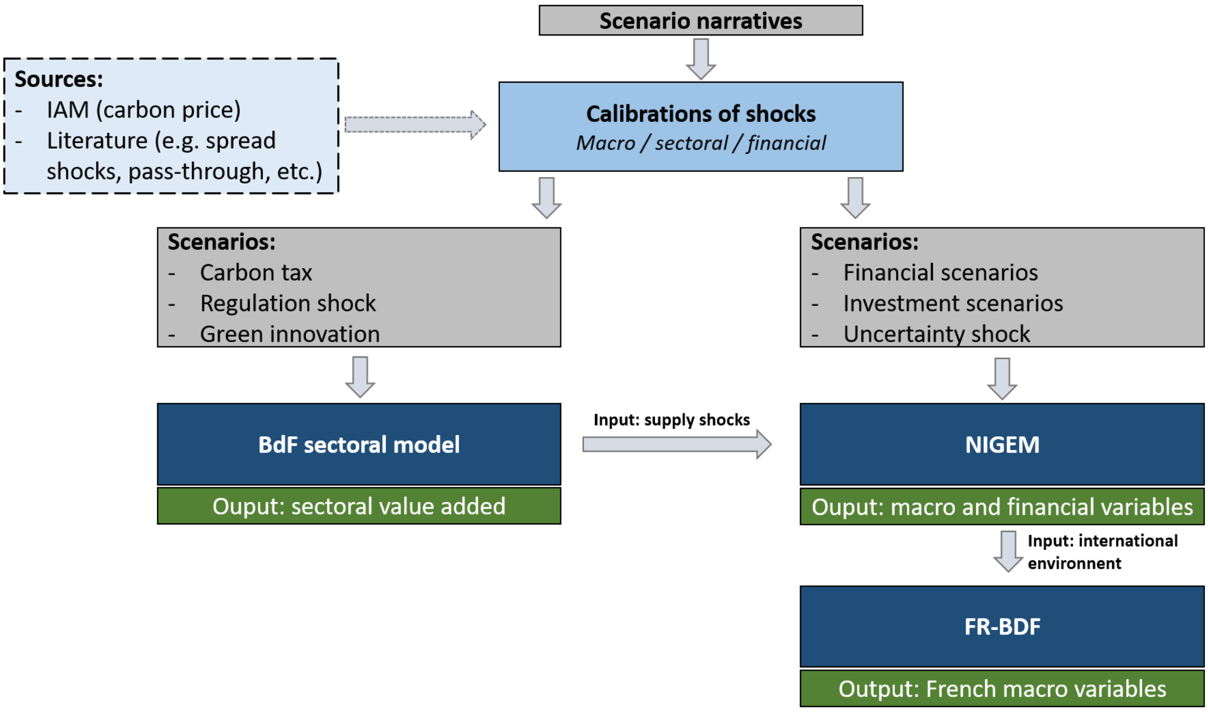

Figure 2: A suite-of-model approach

Scenarios requiring more sectoral details in the narrative are simulated first using the sectoral model in order to derive impacts on the supply side (except for the carbon tax scenario where the input comes from an IAM and which is simulated simultaneously by both models). Those impacts are then used as inputs in NiGEM, generally by calibrating energy price shocks or productivity shocks, in order to reach the aggregate targets given by the sectoral model. All scenarios are simulated by NiGEM in order to provide the necessary input on the international environment to the model for France of the Banque de France (FR-BDF), and in turn FR-BDF simulates all the scenarios to give the detailed impacts on France. The exogenous shocks implemented in both macro models are the same, for consistency, and since NiGEM also includes France in its country coverage, a special attention is given to the comparison of results for France in order to understand the sources of differences when they are significant. A manual iteration is then carried out by adapting certain specifics of the model (budget solvency rule desactivation in NiGEM for instance, or implementation of a less aggressive monetary policy reaction function) in order to produce macroeconomic impacts consistent across models. In the end, FR-BDF provides detailed macroeconomic impacts for France, NiGEM gives macroeconomic and financial impacts for the rest of the World and the sectoral model gives sectoral value added for France and regional aggregates (Rest of EU, US and Rest of the World). This suite-of-model approach also illustrates how climate scenarios can be integrated into workhorse models used in central banks for regular purposes, like forecasting or policy analyses (i.e. the main uses of FR-BDF).

3.2 NiGEM

NiGEM (National institute Global Econometric Model) is a global macroeconomic model consisting of individual country models of New Keynesian structure (see Hantzsche et al., 2018 or Barrell et al., 2004 for a detailed introduction).[6] Each country/region is modelled through a dynamic set of equations where agents are generally assumed to have rational expectations.[7] There are also nominal rigidities that slow the process of adjustment to external shocks. Importantly, each country model has a well-specified supply side over the medium term. International linkages come from patterns of trade, asset holdings, and the impacts of trade prices and exchange rates on domestic prices. NiGEM's country coverage is quite extensive in that all OECD countries are modelled individually, as well as some large emerging countries, while the rest of the world is modelled through regional blocks. This detailed country coverage allows us to derive global impacts of our scenarios with a special focus on France's largest trading partners.

Although NiGEM is not a climate model, it has benefited from extensions to simulate macroeconomic scenarios for climate transition analysis, mostly associated with public policy action (e.g. carbon tax or border tax adjustment). It is thus particularly appropriate for the purpose of this exercise, complementing the FR-BDF model with an international dimension as well as endogenous monetary policy.[8]

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

Production function

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

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

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

In the standard version of the model, energy is proportionately decomposed into the three main types of fossil fuels: oil, coal and gas, 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

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

[7] The model can also be solved for adaptive expectations, which is used most of the time here for computational reasons.

[8] The model version used in this exercise is *v2.22-climate*.

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.

By increasing the price of fossil fuels, the carbon tax will affect firms' demand for fossil energy in the production process.

Prices of fossil fuels

Prices of fossil fuels are determined at the international level and depend, among other variables, on world demand for each fossil fuel. Carbon emissions associated with the production process can be introduced in this framework through each country's usage of fossil fuels. Moreover, a carbon tax can be introduced by increasing a country's cost of using fossil fuels so that the effective price of fossil fuel F in country X, P_{XF}, is equal to the international price of the fossil fuel, P_F, plus an extra element representing the country's carbon tax levied on the fossil fuel, CB_{XF}.

$$P_{XF} = P_F + \delta_F CB_{XF} \tag{2}$$

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

This effective price will then feed into each country's demand for fossil fuel, allowing it to respond to the tax as well as to changes in international prices, which depend on the world demand for fossil fuel. In the model, a tax on fossil energy based on a predetermined path of carbon price is calibrated according to the amount of CO_2 emissions released when burning one unit of fossil fuel. This follows Vermeulen et al. (2018), who use this approach to carry out the DNB's energy risk transition stress tests.[9]

Consumer price equations

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

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

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

Prices of imports are a weighted sum of commodity import prices and non-commodity import

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[9] The model uses 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.

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

A carbon tax would directly feed into consumer prices through the indirect tax rate (itr) which is replaced by an indirect energy tax rate (etr), calibrated on the country CO_2 emissions.

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

Monetary policy

Monetary policy in NiGEM mainly operates through the setting of the short-term nominal interest rate, using a simple feedback rule depending on inflation, the output gap, the price level, and nominal output. Different monetary policy rules are defined, but depending on the scenario simulated, we alternatively use two rules: the default one which is a *Two-pillar rule*, and a *Price-level targeting rule.*

In the *Two-pillar rule*, the policy rate is function of the ratio of the nominal GDP target to nominal GDP, the difference between inflation expectations and the inflation target and lagged policy rate:

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

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

In the *Price-level targeting rule*, the policy rate is function of the ratio of the level of the consumption deflator to its target, the difference between inflation expectations and the inflation target and lagged policy rate:

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

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

By default, in both equations, the γ coefficient, representing the inertia in the reaction function, is set at 0.5 and the β coefficient, representing sensitivity to inflation, is set at 0.7.

3.3 FR-BDF

FR-BDF is a semi-structural, large-scale model for France, which is used both for medium-run projection exercises and for policy analyses. The long-run equilibrium of the model is based on theoretical foundations, while short-run dynamics are based on empirical relationships that allow for temporary deviations from this long-run equilibrium. Furthermore, agents' expectations drive short-term dynamics, and FR-BDF allows for different assumptions regarding the expectation formation process ("VAR-based" or "model-consistent" expectations). This model thus combines an explicit role for expectations (both for financial and non-financial variables), estimates that are similar to observed data, a variety of financial channels and a balanced growth path towards which it converges in the long run in simulations (see Lemoine et al. (2019), for a detailed description and Figure 3 for a schematic representation).

FR-BDF offers a comprehensive, flexible modeling framework that allows to estimate the impact of a large number of transition shocks, which can affect relative prices, productive investment, monetary or budgetary policy reaction, international spillovers or financial variables. In particular, FR-BDF allows for several financial channels, operating for instance through a large set of interest rates yielding an endogenous term structure, a household financial block modeling the interactions between household debt and real estate prices, or a financial accelerator mechanism linking corporate leverage and financing costs.

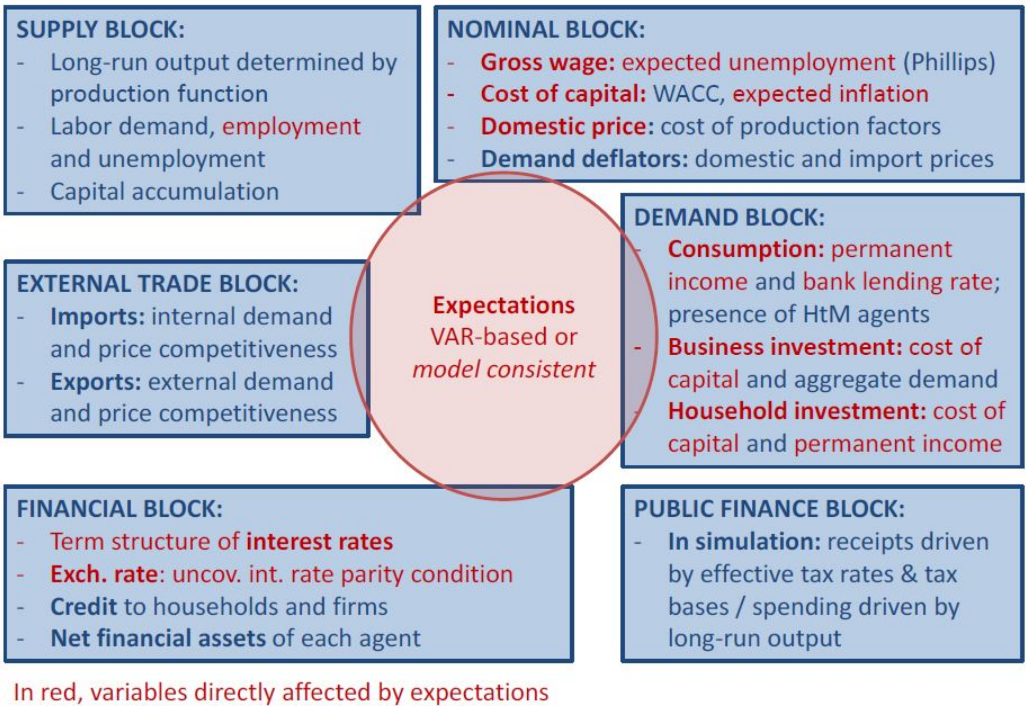

Figure 3: Simplified scheme of FR-BDF

3.4 Banque de France's sectoral model

Banque de France's sectoral model is an adjusted version of the model developed 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. (2019). As detailed below, the model accounts for carbon taxation in a more detailed fashion than NiGEM or FR-BDF, since it features carbon taxes not only on fossil fuel consumption, but also on GHG emissions inherent to the production process (e.g. methane for agriculture).

Our framework features a production network model calibrated using a global input-output matrix to represent the production in each sector in each country as a process involving non-energy and energy intermediate inputs from all countries and domestic labour. All these inputs are substitutable to various degrees. In each sector, a representative firm chooses its inputs mix given the prices in a perfectly competitive environment. On the final demand side, there is a representative household in each country who inelastically supplies labour in a frictionless domestic labour market and consumes goods from all countries.[10]

More specifically, in each country $A \in \mathcal{C}$ and sector $i \in \{1, ..., N\}$, a representative firm produces a quantity Q_{Ai} of good i using labour L_{Ai} and intermediate goods Z_{Aji}, corresponding to energy inputs for $j \leq N_E$ and to other intermediate inputs for $N_E < j \leq N$, where N is the number of sectors per country.[11] Intermediate consumption of good j in country A by sector i, Z_{Aji}, is an aggregate of locally-produced good j, Z_{AAji}, as well as good j produced in all other countries and imported in country A, Z_{ABji}, $B \neq A$ (imports of intermediate good j are aggregated into Z_{AMji}). Each sector i produces using the following CES technology with country-sector-specific input shares, exogenous country-sector-specific total factor productivity (TFP), A_{Ai},

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[10] Labor is perfectly mobile across sectors in given country, but fully immobile across countries.

[11] The produced good is homogeneous within sector across countries of production, meaning that good i is produced by all countries $A \in \mathcal{C}$.

and exogenous country-sector-energy-specific energy efficiency j, A_{AEji}:

$$\forall A \in \mathcal{C}, \forall i \in \{1, \ldots, N\}, \quad Q_{Ai} = A_{Ai}\left(\mu_{Ai}^{\frac{1}{\theta}} L_{Ai}^{\frac{\theta-1}{\theta}} + \alpha_{EAi}^{\frac{1}{\theta}} E_{Ai}^{\frac{\theta-1}{\theta}} + \alpha_{IAi}^{\frac{1}{\theta}} I_{Ai}^{\frac{\theta-1}{\theta}}\right)^{\frac{\theta}{\theta-1}}$$

where:

$$E_{Ai} = \left(\sum_{j=1}^{N_E}\left(\frac{\alpha_{Aji}}{\alpha_{AEi}}\right)^{\frac{1}{\sigma}}\left(A_{AEij} Z_{Aji}\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$$

$$I_{Ai} = \left(\sum_{j=N_E+1}^{N}\left(\frac{\alpha_{Aji}}{\alpha_{AIi}}\right)^{\frac{1}{\epsilon}} Z_{Aji}^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}}$$

$$\forall j \in \{1, \ldots, N\}, \quad Z_{Aji} = \left(\left(\frac{\alpha_{AAji}}{\alpha_{Aji}}\right)^{\frac{1}{\eta_X}} Z_{AAji}^{\frac{\eta_X-1}{\eta_X}} + \left(\frac{\alpha_{AMji}}{\alpha_{Aji}}\right)^{\frac{1}{\eta_X}} Z_{AMji}^{\frac{\eta_X-1}{\eta_X})}\right)^{(\frac{\eta_X}{\eta_X-1})}$$

$$\forall j \in \{1, \ldots, N\}, \quad Z_{AMji} = \left(\sum_{B\in\mathcal{C}, B\neq A}\left(\frac{\alpha_{ABji}}{\alpha_{AMji}}\right)^{\frac{1}{\xi_X}} Z_{ABji}^{\frac{\xi_X-1}{\xi_X}}\right)^{\frac{\xi_X}{\xi_X-1}}$$

$$\text{where} : X = E \text{ if } j \leq N_E \text{ and } X = I \text{ if } j > N_E$$

Firm i in country A takes all prices as given and maximises its profit subject to its production technology:

$$\max_{L_{Ai}, \{Z_{ABji}\}} \pi_{Ai} = P_{Ai}(1-\tau_{Ai})Q_{Ai} - w_A L_{Ai} - \sum_{B\in\mathcal{C}}\sum_{j=1}^{N} P_{Bj}(1+\zeta_{ABji})Z_{ABji}$$

Here, w_A is the wage rate in country A where firm i is located, τ_{Ai} and ζ_{ABji} are taxes on production and fossil fuel inputs described below.

The model allows for three types of taxes: on production, and intermediate and final consumption of fossil fuels. First, each sector i's production tax amounts to $\tau_{Ai}P_{Ai}Q_{Ai}$, where P_{Ai} is its selling price. Second, each producer pays a tax on its intermediate consumption of fossil fuels: ζ_{ABji} is the tax rate on intermediate inputs from sector j in country B entering in the production of sector i in country A. Firm i pays $\sum_{B\in\mathcal{C}}\sum_{j=1}^{N} P_{Bj}\zeta_{ABji}Z_{ABji}$ as taxes on its consumption of intermediate inputs, where all ζ_{ABji} corresponding to sectors j other than fossil fuels producers are zero. Last, the representative household maximizes a CES utility function subject to its budget constraint. Each household pays a tax at a rate κ_{Aj} on her consumption of fossil fuels.

The carbon tax of Scenario 1 applies only to European firms' GHG emissions (the final consumption tax is set to zero): the production tax is proportional to GHG emissions inherent to the production process (for instance, methane emitted by cows in the agricultural sector), whereas the intermediate fossil fuel consumption tax is proportional to the firm's CO_2 emissions (using again the example of the agricultural sector, this is a tax on the gas needed to operate tractors); more details are provided in Appendix C.1. In Scenario 2, the sudden reduction in energy consumption caused by a tightening of environmental regulations is modeled as the introduction of intermediate and final consumption taxes in Europe (production taxes are set to zero) ; the tax rates in Scenario 2 are calibrated so as to hit given consumption targets (see Appendix C.2 for specific values).

The model assumes perfect international risk-sharing: households trade bonds on international financial markets so that country-specific shocks affect households' revenues abroad. In order to be consistent with fiscal policy in NiGEM, tax proceeds are redistributed in a lump-sum fashion to the household of the country where they are levied. Appendix A describes in more details the maximisation programs and first-order conditions of the agents.

The shares of the inputs used for production in each sector (parameters αs and μs), the sectors' relative sizes and the shares of the various goods in final consumption are calibrated to match 2014 sectoral input-output and final consumption data from Exiobase 3 (Stadler et al., 2018). The values of the substitution elasticities θ, σ, ϵ, ηs, ζs are obtained from the literature (see Appendix B for their calibration and Devulder and Lisack, 2020 for a sensitivity analysis).

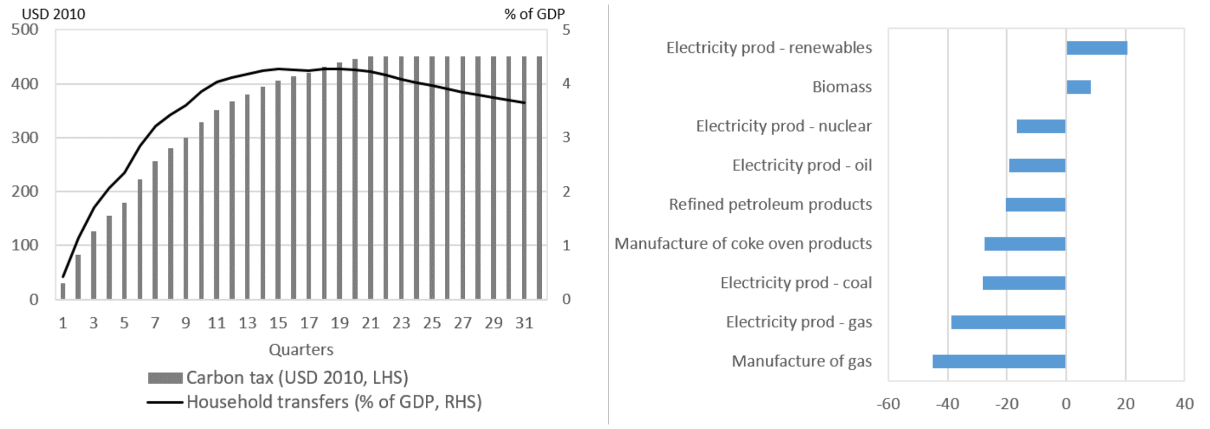
The sectoral model is used to simulate scenarios 1, 2 and 8. As scenarios 2 and 8 involve sectoral energy shocks (respectively on energy consumption and TFP of energy-producing sectors/energy-efficiency of all sectors), the macroeconomic impact is directly determined by the sectoral model and other models follow. Instead, in Scenario 1, in addition to the carbon tax, country-specific TFP shocks (identical across all sectors in a given country) are included so as to match NiGEM's macroeconomic impact by country.

4 Calibration of transition shocks

4.1 Carbon taxation

To calibrate **Scenario 1**, the carbon price trajectory from the NGFS delayed transition scenario is introduced as an explicit price, in this case a tax. This NGFS scenario (taken from the third vintage published in 2022) is based on the implementation of a sudden, delayed transition, which results in a carbon price increase of almost USD 400 per ton of CO_2 equivalent between 2030 and 2035 in European countries. To translate this narrative into our short-term scenario, we assume instead that most of the increase in the carbon tax is front-loaded in the first three years of our horizon. The tax is phased in using an exponential interpolation to put more weight on the first quarters/years of the horizon and reflect a more abrupt dynamic of the shock (see Figure 4 left panel). The proceeds of the tax are then redistributed to households in the form of lump-sum transfers. The succession of shocks being abrupt and unanticipated by agents, there is no adjustment of the production process nor any productivity gains linked to the change in energy mix.

Most EU countries, as well as the UK, Switzerland, the US and China, experience a similar increase in carbon price, such that there is no induced distortion in country competitiveness in this scenario. Moreover, monetary policy will react endogenously to the shocks, as will be the case in all other scenarios. In supply-led inflationary scenarios such as this one, the central bank is however assumed to be less reactive and a price-level targeting rule is used, where inertia is increased and sensitivity to inflation decreased.[12]



(a) Carbon tax and Household transfers in Sc. 1

(b) Consumption of energy in Sc. 2 (% deviations from baseline)

Figure 4: Calibration of Scenarios 1 and 2 (Carbon tax and Regulation)

4.2 Regulation

Scenario 2 is calibrated using the EU "Fit for 55" objectives adjusted for the Ukrainian crisis (RePower EU), brought to 2027. They include a target to reduce gas consumption by 40-60%, oil by 20-30%, coal by 30-40%, nuclear by 20% together with a target to reach 45% of renewables in the EU energy mix, i.e. an increase of 80%. This scenario is simulated using the Banque de France sectoral model (see Figure 4 right panel for total effective sectoral energy consumption).

The targeted changes in European energy consumption are reached by taxing European agents' (firms and households) fossil fuel consumption and subsidizing their renewable energy consumption. The tax rates applied on fossil fuels range from 35-40 % for oil and oil- or nuclear-generated electricity up to 55-80 % for gas, coal and gas- or coal-generated electricity ; the consumption of biomass and renewable energies in general (*e.g.* wind or solar electricity) are subsidized at around 30-40 %. These tax rates depend only on the energy type and the consuming country: all European sectors face the same tax rates and the tax rates are the same for domestically-produced versus imported energy (see Appendix C.2 for specific values).

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[12] The inertia coefficient is increased from 0.5 to 0.9, and the sensitivity to the inflation differential reduced from 0.7 to 0.2.

In the short run, substitution elasticities are assumed to be low and there are no subsidies (i.e. the tax rates on biomass and renewable energies are nil); in the medium run, subsidies kick in and elasticities of substitution are slightly increased (cf. Appendix B for the calibration of the elasticities of substitution).

In order to obtain the macroeconomic dynamics of the shock, this scenario is also simulated using NiGEM and the FR-BDF model. The shocks are implemented first by using the decreased quantity targets to obtain corresponding increases in fossil fuel prices. This is done using price elasticities taken from literature (see e.g., Caldara et al., 2019). The overall price shocks are then injected into the macro models. Then, in order to reflect the overall impact of the sectoral adjustments simulated by the sectoral model, productivity shocks are applied, calibrated using potential GDP targets given by the aggregate impact of the sectoral model.

4.3 Policy uncertainty

In **Scenario 3**, due to the uncertainty associated with the transition policies, corporate financing costs are subject to an increase in risk premia of 100 basis points for 4 years before gradually decreasing over the following two years. The magnitude of the shock corresponds to what has been assumed in NGFS disorderly scenarios. Uncertainty affects all sources of financing (bank, bond and equity). Equity prices, due to a rise in risk premia, fall by 15% immediately and remain around 5% below their baseline level for 5 years. On the household side, the rise in risk premia has a very limited effect. Nevertheless, to take into account the impacts of uncertainty on household consumption, we include a confidence shock calibrated using Dees (2017). This scenario of increased uncertainty in financial markets does not, however, take into account the risk that part of the instruments held on banks' balance sheets become "stranded assets" as a result of the transition policies implemented. This risk is accounted for in Scenario 4. The magnitude and timing of the shock is illustrated in Figure 6 (left panel).

4.4 Investment shocks

Scenario 5 and **Scenario 7** are both based on the IEA's estimates of net additional annual global investment needs in the key transition sectors (including the energy sector, transport, housing, infrastructure and industry) over the period 2020-30 (i.e. USD 2,690 billion). These net additional investment needs are broken down by regional block according to NGFS estimates of investment in the energy sector in the Net-Zero scenario over the period 2020-25. Specifically, we compute an average of the investment in each region in the three IAM models used by the NGFS (REMIND, GCAM and MESSAGE).[13] This spatial distribution allows us to account for the relative importance of the economies, their respective carbon intensities and the respective costs of decarbonization effort (non-linear with emission levels given increasing marginal

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[13] The NGFS Phase III estimates, released in September 2022, were used for this exercise.

abatement costs) included in the NGFS models. The investment shock within each region is then disaggregated by country according to each country's share of greenhouse gas emissions. A description of our procedure is summarized in Figure 5.

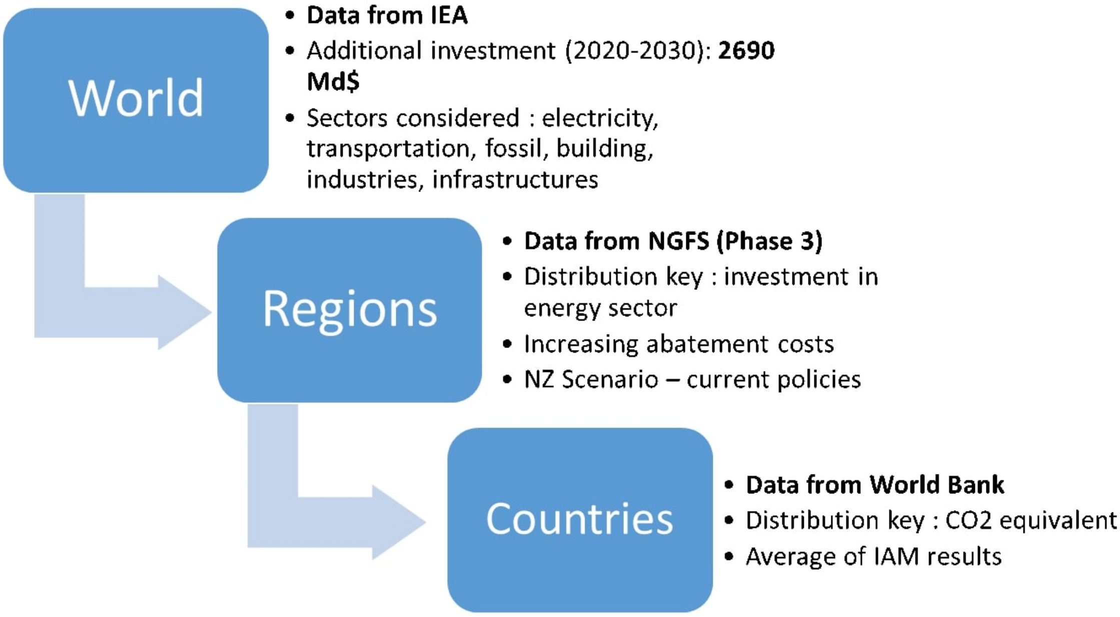

Figure 5: Calibration procedure for investment shocks

Regarding the source of investment, **Scenario 5** assumes that only the public sector is investing in green infrastructure while **Scenario 7** assumes that the capital formation comes from the private sector. These two scenarios are polar, as reality is likely to be a mix of the two sources. However, each scenario underlines the challenges in terms of financing. In **Scenario 5**, the additional investment by the public sector is considered to be financed by a carbon tax, which is not set according to the NGFS targets as in Scenario 1, but calculated to cover only the revenues needed to finance public investment levels.[14]

In **Scenario 7**, the additional private investment is induced in the model by a decrease in corporate taxes, financed by an increase in income taxes so that the financing is neutral for the public sector. Household consumption is reduced through the rise in income tax and by a negative shock to the marginal propensity to consume, allowing a crowding-out effect on consumption to be simulated or, in other words, allowing private investment to be financed by the surplus savings of households. The objective of this polar adverse scenario is to illustrate a situation that would generate disinflationary effects in the short term, and it therefore deliberately accentuates the adverse effect on household consumption. It does not take into account the fact

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[14] Under the same monetary policy assumption as Scenario 1, because this scenario also includes a carbon tax shock that is similar to a supply shock.

that, on top of the preference shock, there will be additional financing needs (renewal of goods that have become obsolete prematurely or unplanned investments). Moreover, the consumption crowding-out effect can only apply to households whose savings and propensity to consume can cover these additional investment needs, which is not explicitly taken into account in the model.

Finally, in both scenarios, the additional capital generates positive productivity effects, calibrated using Bom and Ligthart (2014). More precisely, in Scenario 5, it is assumed an extra gain of 0.12 percent of GDP, related to productivity growth, for a one-percent increase in public investment in the long term. In the scenario, this translates into a productivity shock which is proportional to the public capital level. A similar approach is applied to the private investment shock in Scenario 7.

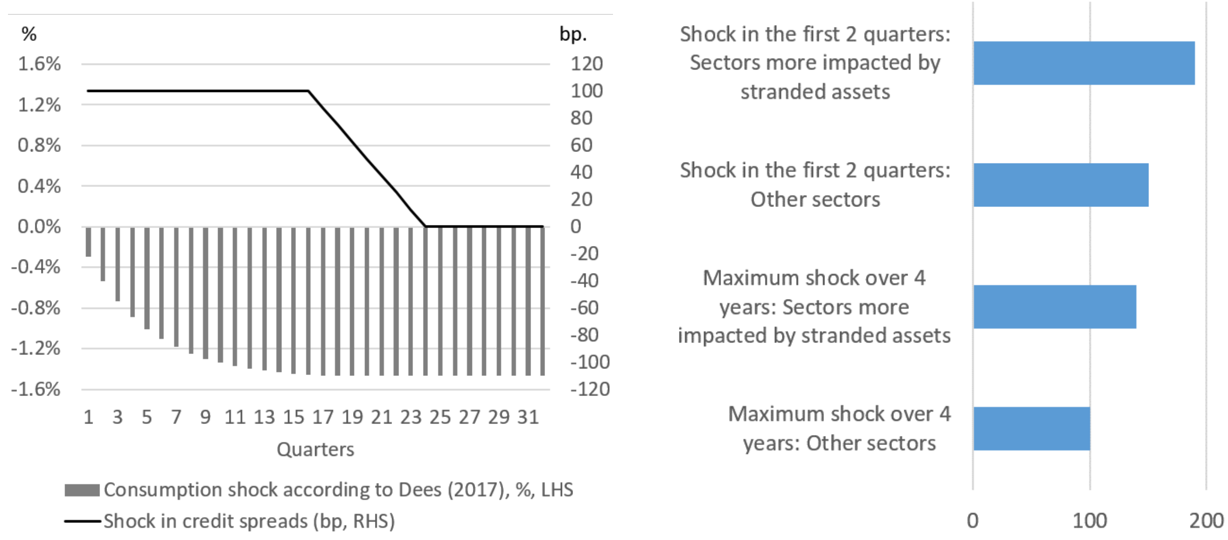
4.5 Financial market shocks

For **Scenario 4** (financial market turmoil), three types of shocks have been introduced: (i) an increase in credit spreads based on an initial confidence shock augmented by an additional shock in sectors more affected by stranded assets, (ii) an increase in the depreciation of capital linked to IRENA Delayed scenario on stranded assets by region/country and (iii) a shock on sovereign interest rates.

The initial uncertainty shock would be of the same order of magnitude as the one in Scenario 3 (100 basis points over four years), with a higher front-loaded initial rise in credit spreads (150 basis points) during the first two quarters reflecting the immediate tensions on the markets following the announcement of the more stringent carbon regulation policies. Such tensions would be exacerbated in the most carbon-intensive sectors whose cost of funding would rise by a further 40 basis points following Seltzer et al. (2022). The hierarchy of shocks (short term versus long term, carbon-intensive sectors versus others) is illustrated in Figure 6, right panel. In line with these shocks to credit spreads, the main equity indices would fall as a result of a general increase in market volatility across all sectors. The shock will gradually be absorbed and business financing conditions gradually improve over the following four years.

Second, we introduce an increase in the depreciation of capital. According to IRENA Delayed Action projection (IRENA, 2017), the stranded assets caused by a delayed transition scenario in Europe (which would therefore be sudden when finally implemented) would mainly concern the residential sector. The implementation of restrictive regulations in certain areas (e.g. the property market, restrictions on renting for properties with an Energy Performance Certificate of E, F or G, i.e. 39 percent of the housing stock in France) leads to a greater depreciation in the value of property assets with lower energy performance. We use IRENA's regional estimates and break them down by country according to their share of residential assets in total European assets. This affects the cost of capital in the model.

The third shock relates to an increase in sovereign interest rates, as international transition



(a) Sc. 3. Uncertainty shock: rise in credit spreads and fall in consumption

(b) Sc. 4. Shock in credit spreads (bp.)

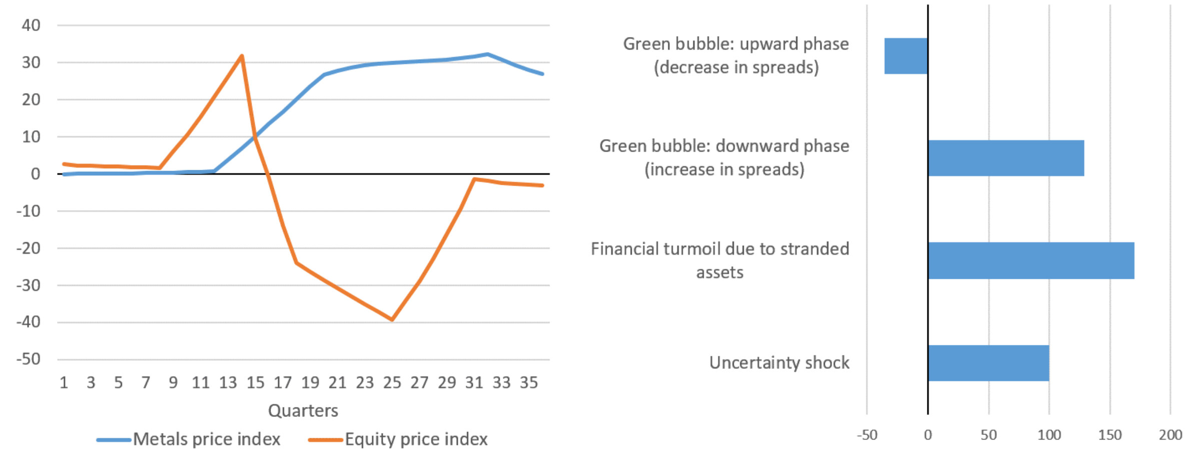
Figure 6: Calibration of Scenarios 3 and 4 (Uncertainty and Financial market turmoil)

policies destabilize the economies most dependent on fossil fuels (e.g. the United States, Norway, Saudi Arabia, Canada, Russia, etc.). The strict regulations announced to implement the climate transition raise fears about the capacity of fossil fuel-producing countries to absorb the large losses in revenue that will occur. At the same time, volatility on financial markets affects the financing costs of emerging countries, which are traditionally more vulnerable to portfolio reallocations by investors. To reflect this risk, we apply a shock of around 80 basis points to the sovereign risk premium of emerging countries and 200 basis points to that of fossil fuel-producing countries (shocks calibrated according to Battiston and Monasterolo, 2020).

The green bubble scenario (**Scenario 6**) has been calibrated in the form of several layers of shocks, which are modelled based on the Dot Com Bubble that took place in the United States between October 1998 and March 2000. The scenario is based on a succession of two periods:

- The rising phase of the bubble originates in an equity shock (around +30%) to which a credit spread shock in line with the shock on equity markets is added. The NiGEM model is used here in forward mode to reflect investors' anticipation of positive growth, which triggers investment a little before the shock and generates positive effects on GDP from the outset. The positive shock itself on financial markets lasts a bit less than 2 years (peak of the bubble) reflecting the timing of the Dot Com bubble as estimated by DeLong (2006).
- The downward phase that follows lasts nearly 3 years, during which equity markets fall, reaching a trough of around -40%, and credit spreads tighten accordingly.

We also add a commodity price shock in a desynchronized way in order to reflect the expected tensions on critical metals due to the increased demand generated by the rise in investment from companies in the green sector. We assume that such tensions start materializing on critical commodity prices slightly before the peak of the bubble (see Figure 7 for the timing of the shocks), reach a peak after the bubble has burst and last for most of the horizon. The magnitude of the rise in metal prices is calibrated following Boer et al. (2021) for individual metals and aggregated to reflect the composition of the index that enters the model. The total shock on the base metals index included in the model reaches a peak of 32%. The pass-through of this commodity shock to production prices is then calibrated outside the model since the production function in NiGEM does not include intermediate goods. We follow Landau and Skudelny (2009) who estimate a pass-through of raw industrial metals prices to PPI intermediate goods of around 0.12 after 4 quarters, and then project this into the model's unit total costs modulo the weight of intermediate goods in overall producer price indices.



(a) Sc. 6. Green bubble: Equity and metal price shocks (% deviation from baseline)

(b) Comparison in credit spread shocks at their peak between scenarios (bp.)

Figure 7: Calibration of Scenario 6 (Green bubble) and comparison in credit spread shocks

4.6 Innovation shocks

Scenario 8 is simulated using Banque de France's sectoral model. We use two types of shocks in order to fully capture "green innovation". First, there is a positive total factor productivity (TFP) shock in all renewable energy producing sectors, i.e. the economy becomes more efficient at producing renewable energy. Second, there is a positive electricity efficiency shock in all sectors, that is, the economy becomes more efficient at using electricity.

Starting in 2022, electricity efficiency in all sectors is assumed to increase by 11.5% per year, a growth rate that is calibrated to be consistent with the reductions in energy demand in IEA's net zero scenario (IEA, 2021) (adjusted for the share of electricity in the energy mix as all energy efficiency gains are attributed to electricity) ; TFP in renewable energy-producing sectors is assumed to increase by 16.9% per year, a growth rate that reflects the trend reduction in renewable energy between 2010-2019 observed in the IRENA (2017) database. As this kind of green innovations is likely to diffuse very quickly, we assume that those shocks are common to all countries.

In the short run, substitution elasticities are assumed to be low; they are slightly increased in the medium run (cf. Appendix B for the calibration of the elasticities of substitution).

5 Results

We simulate our eight scenarios with the suite-of-model described in Section 2, using the calibration of shocks detailed above. We mainly present and comment on the dynamics of GDP and inflation responses in each scenario, but also supplement with information at the sectoral level and financial market output, where appropriate.

5.1 Scenario 1: Abrupt and unanticipated increase in the price of carbon

The abrupt rise in carbon tax in this scenario leads to a rapid increase in the annual rate of inflation in France of up to 1.8 percentage points in the first year, and 0.6 percentage point after five years (Figure 8). This is partly compensated by a gradual increase in policy rates (up to 100 basis points after three years and 140 basis points after five years) since the central bank reacts to the inflationary environment but to some extent with a relative inertia since this scenario is mainly characterized by a negative supply shock (increase in the price of high-carbon goods and services, namely used as input in the production function).[15] The overall effect of this scenario on growth is initially neutral, because the negative impact on activity caused by the carbon tax is partially offset by a positive effect on household income linked to the redistribution of the tax proceeds in the form of direct transfers. Nevertheless, the impact on activity becomes negative after two years, resulting in a decline in GDP of around 1.2% over five years because the recessionary impact of the carbon tax is higher than the positive demand shock induced by the redistribution. This effect is partly due to the fact that the production process does not adapt to the abrupt change in the carbon price. This scenario shows that a carbon pricing policy must be progressive to be less inflationary and to limit its impacts on activity.

The Banque de France's sectoral model also provides a breakdown of the effect of the carbon

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[15] We have performed sensitivity analyses of Scenario 1 results to monetary policy reaction (see Appendix). Other specific cases, such as differences in results under budget neutrality assumptions, or different tax recycling assumptions, could also be studied in the form of sensitivity analysis. This paper however proposes specific scenarios, and has therefore not systematically included these additional particularities. Other previous works, such as NGFS Climate Scenarios Sensitivity Analysis to Macroeconomic Policy Assumptions, provide detailed sensitivity analyses of NGFS scenarios results based on different macroeconomic assumptions.

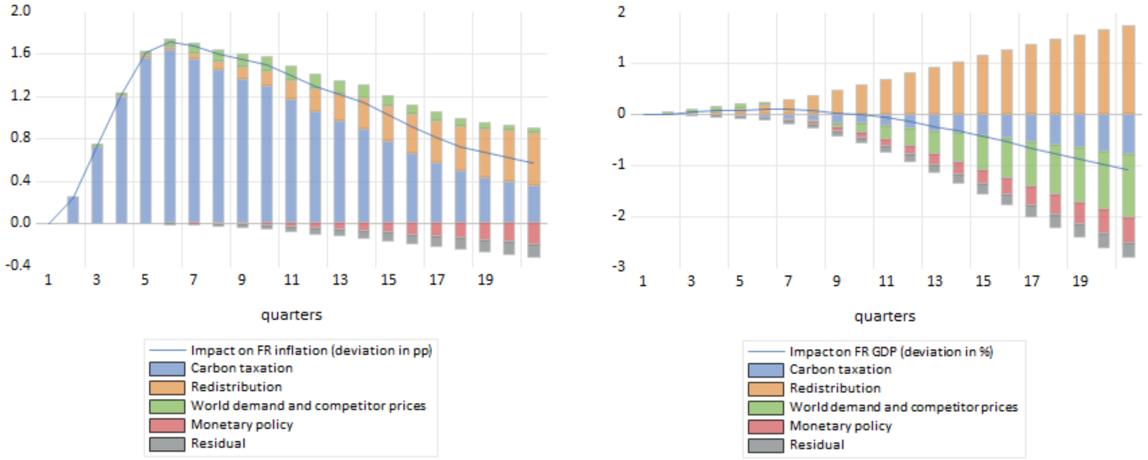
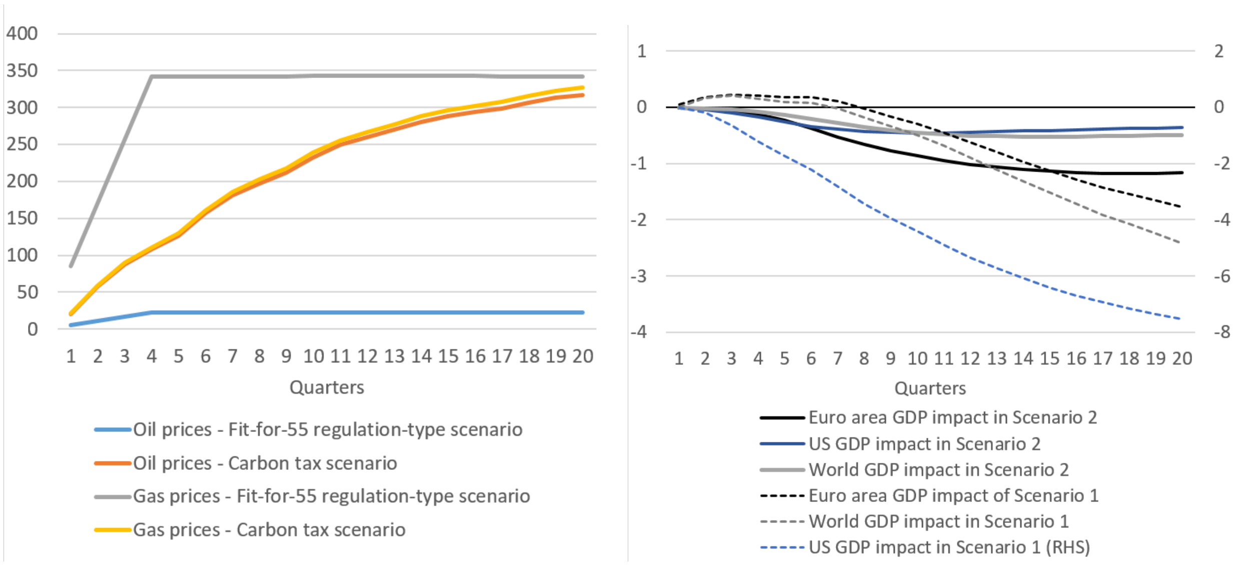


Figure 8: Scenario 1 (Carbon tax): France inflation and GDP impacts, and contributions by source of shock (FR-BDF)



(a) Fossil fuel price shocks in Scenario 1 and 2

(b) GDP Impacts of Scenario 1 and 2

Figure 9: Comparison of Scenario 1 and 2 (Carbon tax and Regulation): Fossil fuel prices and GDP impacts outside France (% deviations from baseline, NiGEM)

tax shock on value added by sectors. The most benefiting sectors in relative terms is biomass (+40% for France and +100% for the rest of the European Union) and nuclear electricity (+65% in the world), while gas extraction (-70% for France), oil extraction (-48% for rest of EU) and manufacture of coke oven products (between -70% for rest of EU and rest of the world and -90% for France and USA) are the most affected sectors (Figure 10).

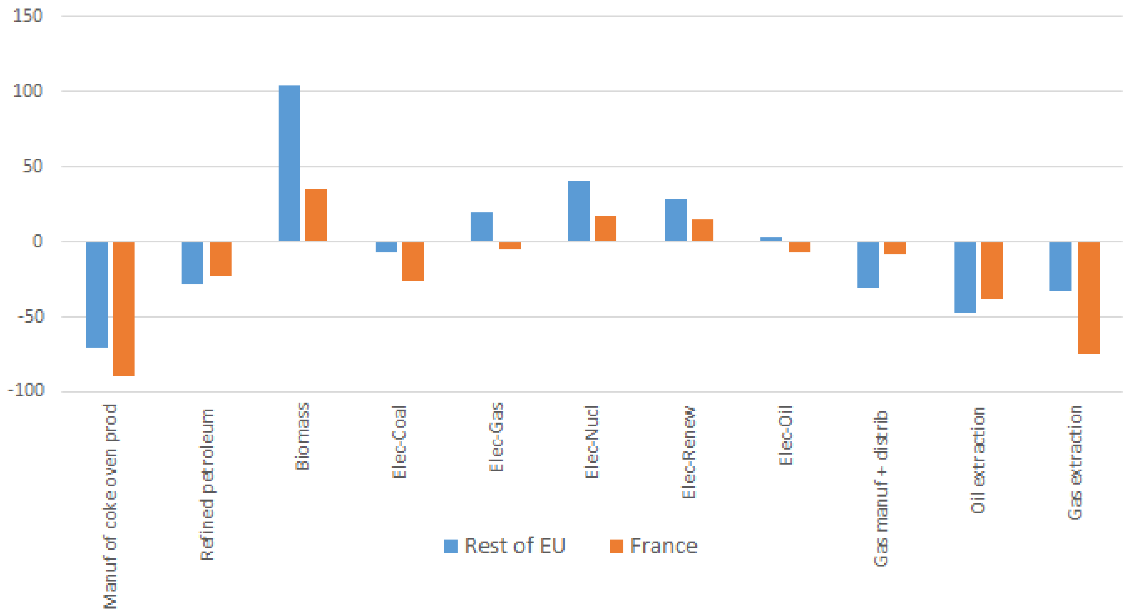


Figure 10: Scenario 1 (Carbon Tax): Impacts on real value added by sector (deviation in %)

5.2 Scenario 2: Regulation shock

The results of the shocks caused by the regulation scenario follow a similar pattern to the abrupt and disorderly carbon tax scenario. The increase in prices of fossil fuels reflects the constraint on quantity of fossil energy consumed and produced by the economy. Since the calibration of this scenario is inspired by the Fit-for-55 policy package, redesigned following the Ukraine war, the constraints are more tilted towards reducing gas consumption in Europe, whereas in Scenario 1, all countries implement the carbon tax which increases the price of fossil fuels depending on their CO2 content. Thus, Scenario 2 results in a higher and more abrupt increase in gas prices compared to oil prices in Europe. Gas markets being fragmented, we assume that the European constraints do not affect gas prices outside Europe. However, oil markets being global, the European constraints affect global oil prices to the extent of the share of Europe consumption in world consumption of oil (see Figure 9 left panel).

In France, the very rapid rise in energy prices due to quantitative constraints on fossil energy volumes causes inflation to rise sharply in the first year (up to +1.5pp after 4 quarters). Energy decarbonization is rapidly completed thanks to these quantitative constraints. Furthermore, it provokes a labor efficiency shock related to frictions in sectoral adjustments that remains inflationary, albeit to a lesser extent. Inflation stabilizes in the -0.4pp range once the effects of strict regulation have been absorbed. In line with the inflationary effect, France's GDP is pulled down by the energy price shock, labor efficiency shock, and the reduced external demand from European trading partners. The GDP impact then stabilizes following the implementation of public subsidies on green energies and reaches -1% at the end of the projection horizon (see Figure 11).

The results for the euro area follow the same dynamics, with an inflation peak triggered by the energy shock (+0.7pp after 9 quarters), and a decline in GDP of -1.2% in deviation from baseline at the end of the projection horizon. However, economies outside Europe are less affected, US GDP for instance decreases by -0.4%, reflecting the stricter policy in Europe. Overall, Scenario 2 has a more adverse impact on euro area GDP compared to the rest of the World, where as in Scenario 1, Europe is the least affected given its lower carbon intensity. Figure 9 (right panel) illustrates this different hierarchy of impacts among countries in Scenarios 1 and 2. As a result the contribution of the world demand shock in France is greater in Scenario 1 than in Scenario 2.

The regulation shock scenario also uses input from Banque de France's sectoral model, which provides the breakdown of the impact on value added by sector (Figure 12). The most affected sectors are biomass (+20-25 % in the short run, +90-100 % in the medium run), renewables (+10-20 % in the short run, +70-75 % in the medium run), gas (-25-30 % for manufacture and distribution, -40-45 % for gas-generated electricity) and coal (-15-25 % for coke oven products, -25-35 % for coal-generated electricity).

5.3 Scenario 3: Temporary increase in uncertainty on transition policies

This scenario features a confidence shock on households and firms leading to an increase in firms' cost of financing and a decrease in household consumption. Aggregate demand in France is thus reduced (by -0.7% compared to baseline at the peak of the shock, Figure 13) as well as inflation (reduction by up to 0.3 percentage point in the annual rate). The contributions of lower consumption due to the confidence shock, together with its international amplification through world demand, explain most of the short-term dynamics. The risk premium shock impact inflation and GDP with delays, while monetary policy helps stabilizing the macroeconomic

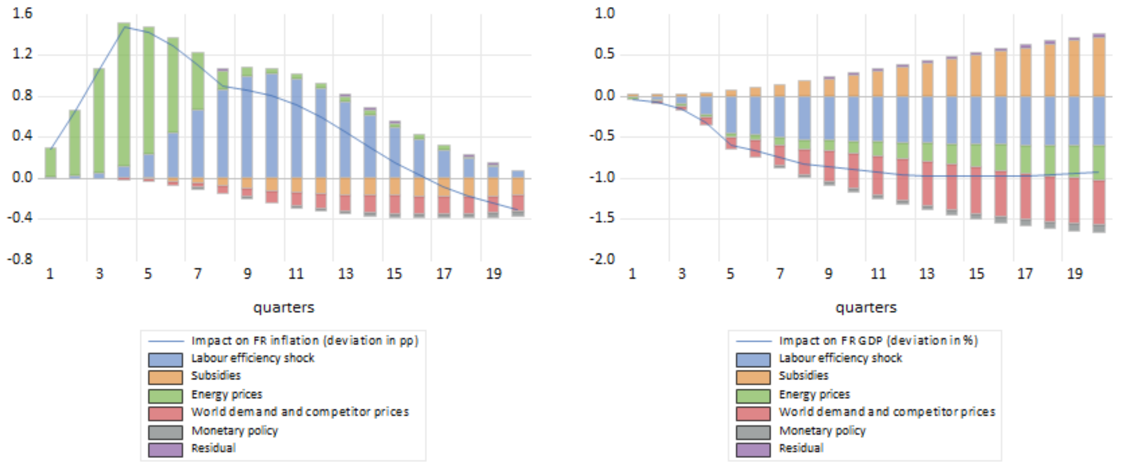


Figure 11: Scenario 2 (Regulation): France inflation and GDP impacts and shock contributions (FR-BDF)

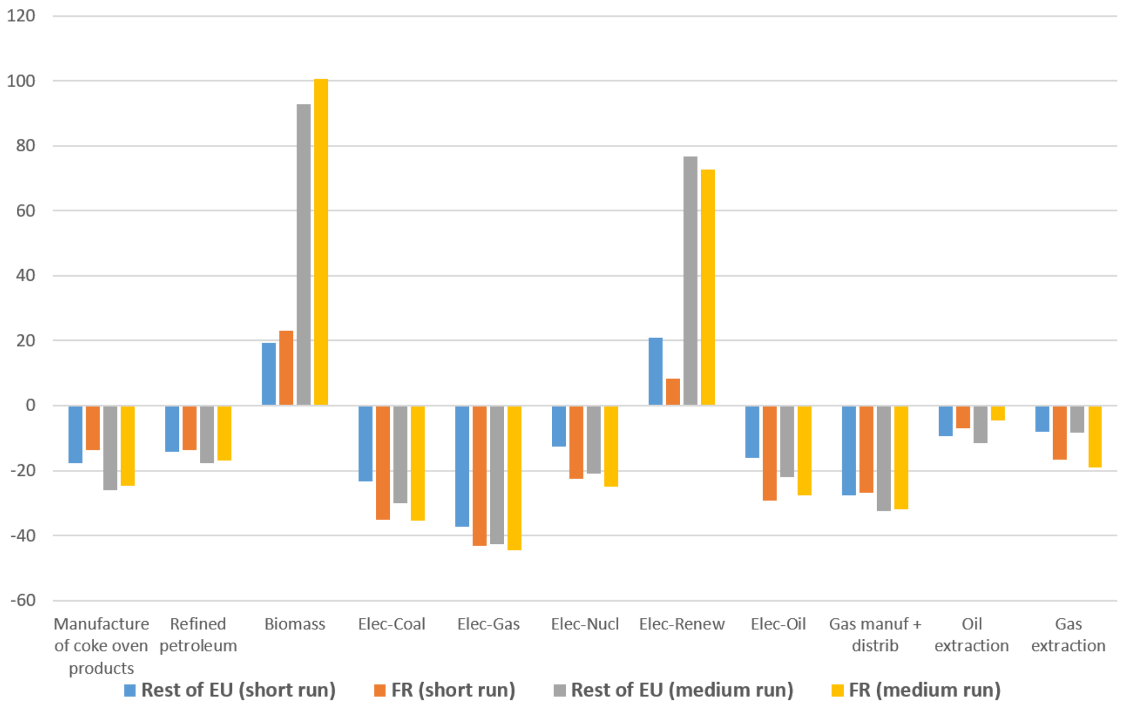


Figure 12: Scenario 2 (Regulation): Impacts on real value added by sector (deviation in %)

effects of the shocks through an accommodative stance.

Overall, the longer the uncertainty over the transition policy, the longer the downward pressures on prices and GDP would last. Nevertheless, after five years, this scenario shows a moderate increase in inflation (0.2 percentage point) and in GDP (0.3%) compared to a trajectory without a transition, thus illustrating the fact that uncertainty about transition policies could essentially translate into higher volatility in inflation and growth.

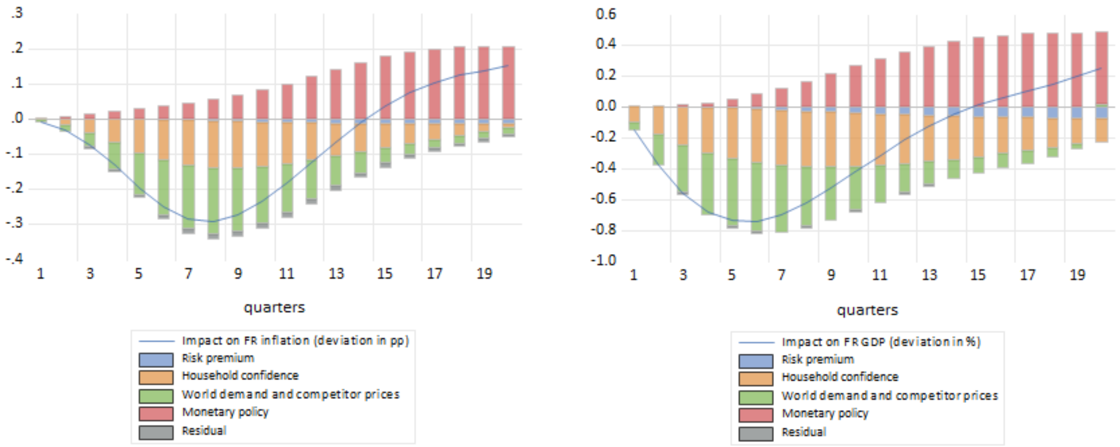


Figure 13: Scenario 3 (Uncertainty): France inflation and GDP impacts and shock contributions

5.4 Scenario 4: Financial market turmoil

The shocks of the financial market turmoil scenario lead to recessionary and disinflationary dynamics over the first half of the projection horizon. In France, inflation falls to a low point of -0.4 pp in deviation, essentially under the influence of the fall in global demand, and the negative shock from spreads and capital depreciation (Figure 14). In a second phase (from 2024), the effect of monetary policy eventually stabilises inflation at +0.1 pp. The same factors of world demand and spread shocks lead symmetrically to a recessionary trend during the first year (up to -1% in deviation), before the recovery in world demand and the effect of monetary policy stabilises GDP at around +0.2% in deviation.

This scenario features a more adverse impact on asset prices, the evaluation of those related to polluting activities being affected by the sudden regulatory announcement. Equity prices in France immediately fall by -23% following the rise in risk aversion and real estate prices gradually fall, reaching a minimum of -2.4% after 7 quarters (see Figure 15).

In the euro area, the trend is similar, albeit to a greater extent, with a rapid fall in GDP of up to -1.6% in quarter 3, which gradually stabilises over the rest of the projection horizon. The shock to demand and capital also causes inflation in the euro area to fall to -1pp in quarter 8, before gradually stabilising over the following 3 years. The macroeconomic impact of this scenario will be by design more adverse in countries most affected by stranded assets linked to carbon regulation. Hence, GDP in Canada for instance would fall by -3% at the peak of the shock, mostly driven by the shock in sovereign spreads and the depreciation of physical capital (see Figure 16).

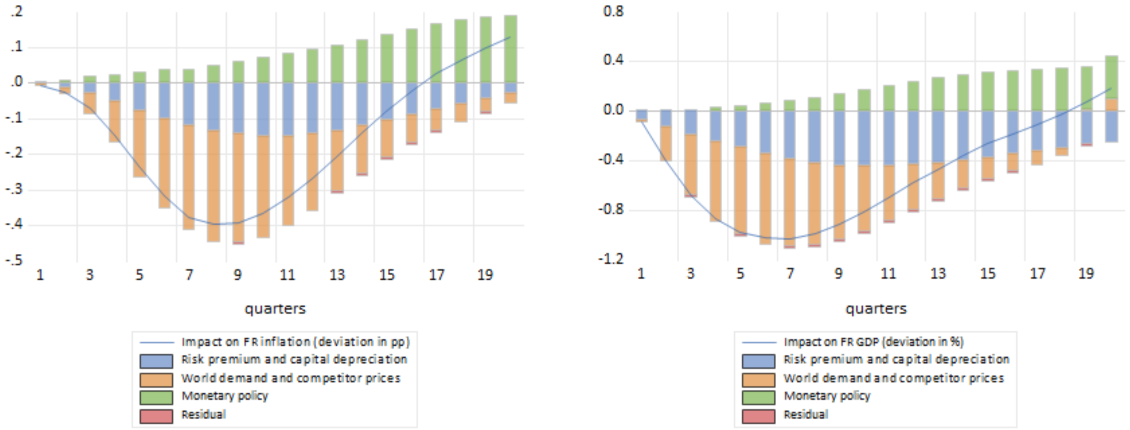


Figure 14: Scenario 4 (Financial market turmoil): France inflation and GDP impacts and shock contributions (FR-BDF)

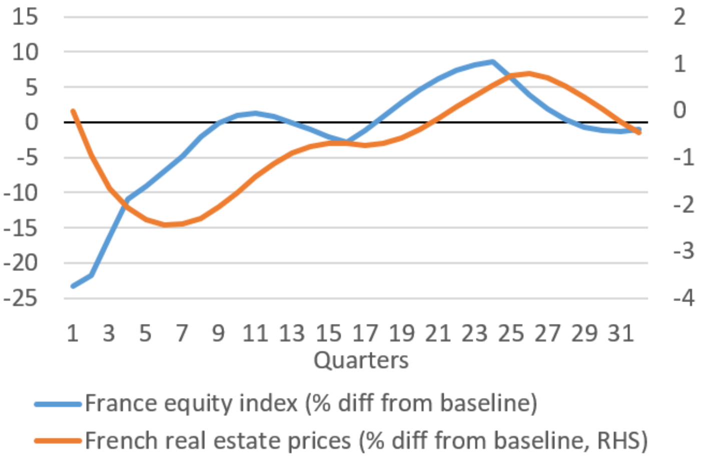
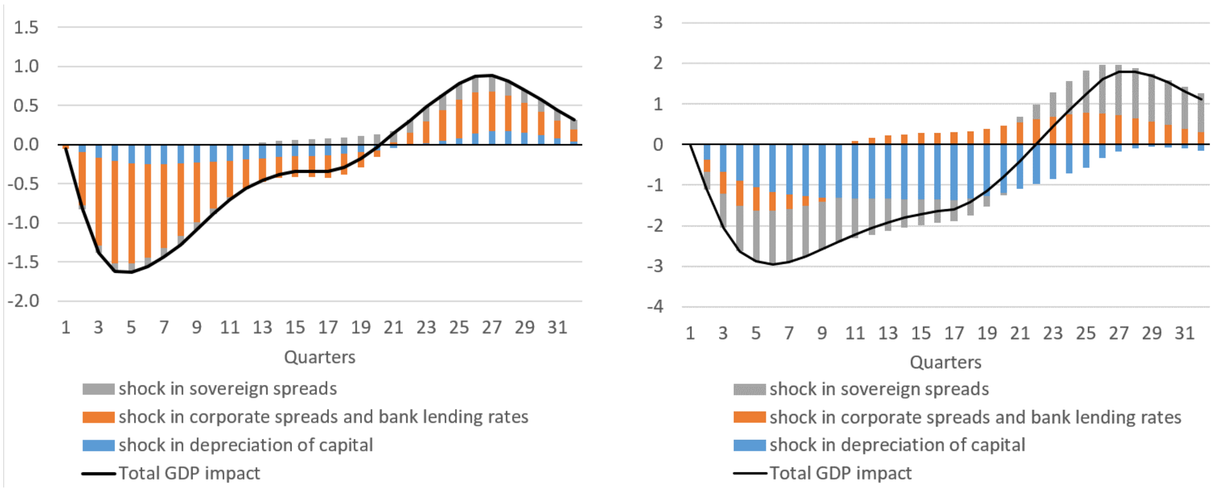


Figure 15: Scenario 4 (Financial market turmoil): Impact on equity and real estate prices in France

5.5 Scenario 5: Strong increase in public investment financed by a carbon tax

In this scenario, the transition is spurred by public investment which ranges between 0.75 percentage points of GDP to over 6 percentage points of GDP in some countries. In France the calibrated investment needs amount to 1.2 point of GDP. This public investment is financed by a



(a) Euro Area GDP impact (% deviation from baseline) (b) Canada GDP impact (% deviation from baseline)

Figure 16: Scenario 4 (Financial market turmoil): Euro Area and Canada GDP impacts and shock contributions (NiGEM)

carbon tax that reaches up to 150 USD/tCO_2e (2010 USD). The shock is phased in over 2 years (see Figure 20). Interestingly, the carbon tax level needed to finance the calibrated investment needs is much lower than the carbon tax in Scenario 1 which has been calibrated according to the NGFS Delayed scenario front-loaded (reaching 450 USD at the end of the horizon).

The impact of this scenario on GDP is among the highest of our range of scenarios with GDP in France increasing by 1.5% after 5 quarters and stabilising more or less at such levels (Figure 17). In terms of contributions to this impact, the shock on public investment has the highest multiplier. Since other countries boost global GDP by simultaneously applying a similar policy, the increased external demand reinforces the public investment multiplier in France. The positive impact is complemented by the small but positive effect of the calibrated productivity gains (up to 0.5 percentage points of GDP at the end of the simulation horizon). On the other hand, the impact of the carbon tax is negative on GDP and dampens the previously-described positive effects but not sufficiently to decrease significantly the overall impact.

This scenario is also among the most inflationary ones, especially in the short term, with French inflation increasing by 1.8 percentage points after 5 quarters but reverting back relatively quickly over the following 4 quarters. The inflationary impact in France comes mainly from the implementation of the carbon tax in the short term while the public investment shock has smaller but more persistent effects on inflation. During the second part of the simulation horizon, the persistent impact on inflation is compensated by the negative effect of the productivity shock and the monetary policy reaction.

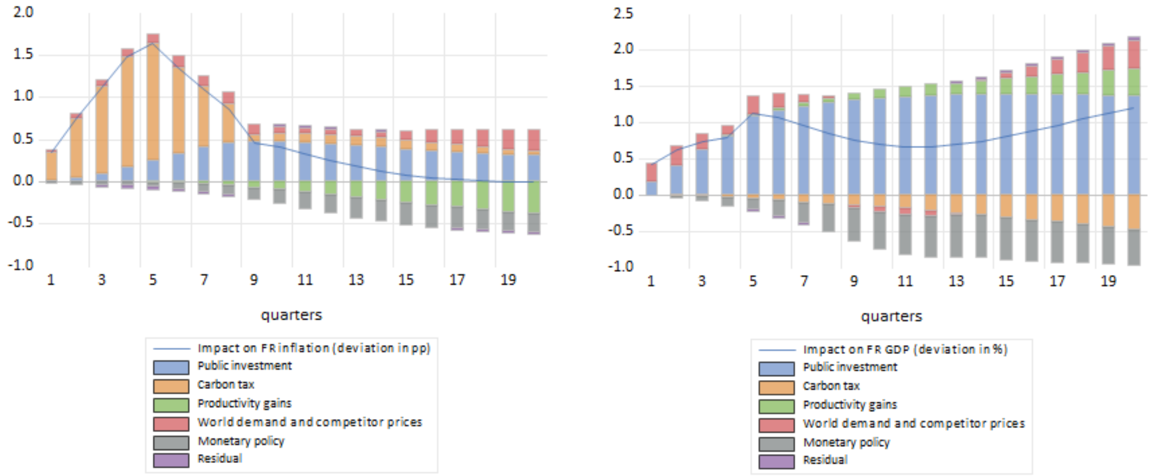


Figure 17: Scenario 5 (Public investment): France inflation and GDP impact and shock contributions

5.6 Scenario 6: Green bubble

As detailed in the previous section, this scenario features an asymmetric shock on financial markets, namely on equity and credit markets. The impact on euro area GDP is thus positive during the first 4 years of the horizon, rising by up to 1 point, then falling more abruptly (Figure 18). The first-phase increase can be explained both by an increase in private investment generated by lower risk premia and by an increase in consumption generated by positive wealth effects. The positive impact can be felt even before the onset of the bubble (a year after the beginning of the simulation horizon) since investors anticipate it and start investing beforehand.[16] This positive effect on activity is however slightly dampened by the rise in critical commodity prices which accompanies the bubble. The latter indeed acts as a negative supply shock by increasing production costs. The estimation of this effect may be underestimated owing to the current low weight of such commodities in production costs, which is expected to increase during the transition. The second phase of the scenario, which includes the bursting of the bubble and the accompanied contagion and rise in risk aversion, features a more abrupt fall in GDP (up to -2.5 % after 26 quarters, so past the simulation horizon of 5 years), since both effects (credit condition tightening and rise in commodity costs) reinforce each other.

The impact on France is smaller (Figure 19), with a maximum increase in GDP of around 0.4%. Similarly, the bursting of the green bubble leads to a decline in activity but to a lesser extent compared to the euro area (-1.4% after 29 quarters). In terms of contribution, most of the impact comes from world demand as the financial shocks have relatively small effects on French GDP. Beyond model differences, this may be largely explained by lower financial wealth effect in France compared to other euro area countries.

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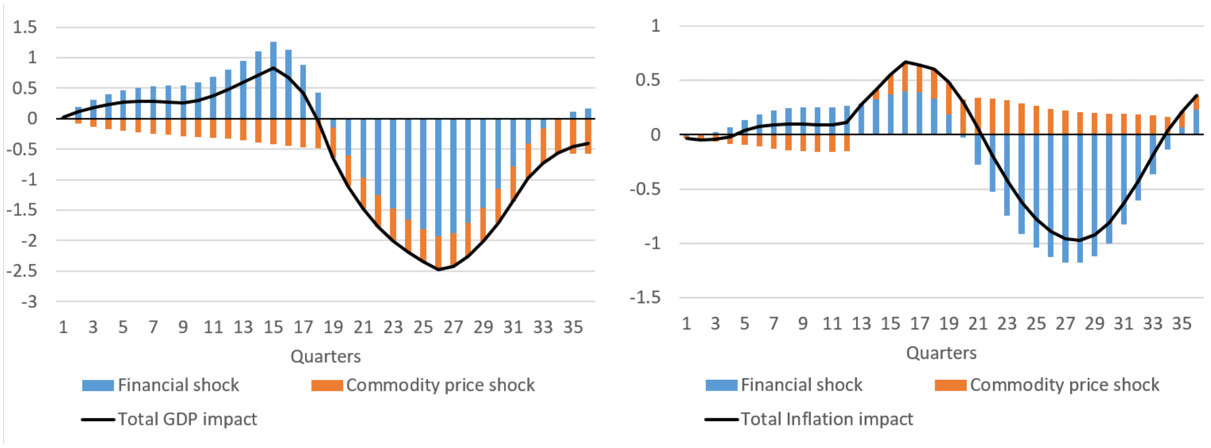
[16] The model is run here in forward mode to reflect this perfect foresight effect

On the inflation side, the first stage of the scenario implies a rise in euro area inflation by 0.7 percentage point after 16 quarters followed by a reversal. The latter is amplified after the end of the simulation horizon with inflation falling by up to -1pp after 7 years, in line with the recessionary impact of the burst of the bubble. As for GDP, the impact on inflation in France is much more limited with an increase by less than 0.2 percentage point after 16 quarters and a maximum fall by around 0.3 pp when the bubble bursts.

Although this scenario ultimately includes a fall in activity, during the most part of the simulation horizon it shows the positive effects of a demand shock associated with a certain euphoria in the green transition. Interestingly, such an euphoria does not have a sufficiently positive effect on private investment to generate as much benefits on growth as obtained in Scenarios 5 and 7 (see Figure 20 right panel, for a comparison of impacts on US investment across scenarios).



(a) Euro Area GDP impact (% deviation from baseline) (b) Euro Area inflation impact (deviation from baseline in pp.)

Figure 18: Scenario 6 (Green bubble): Euro Area GDP and inflation impacts and shock contributions (NiGEM)

5.7 Scenario 7: Sharp rise in private investment at the expense of consumption

Although the increase in private investment is calibrated according to the same amounts used in Scenario 5, the policy instruments are not the same, which explains the differences in impacts on activity and inflation. The sole impact of subsidies on activity in France is lower than that of direct public investment while the impacts of productivity gains and external demand are more or less the same than in Scenario 5. Overall, in the short term, French GDP increases by up to 0.4% after 5 quarters. It decreases afterwards due to the negative impact of the decrease in consumption resulting from the accumulation of private savings needed to finance the transition (Figure 21). Indeed, household consumption is reduced by higher taxation and an incentive to save, such that the financing of private green investment is ensured by household savings surplus.

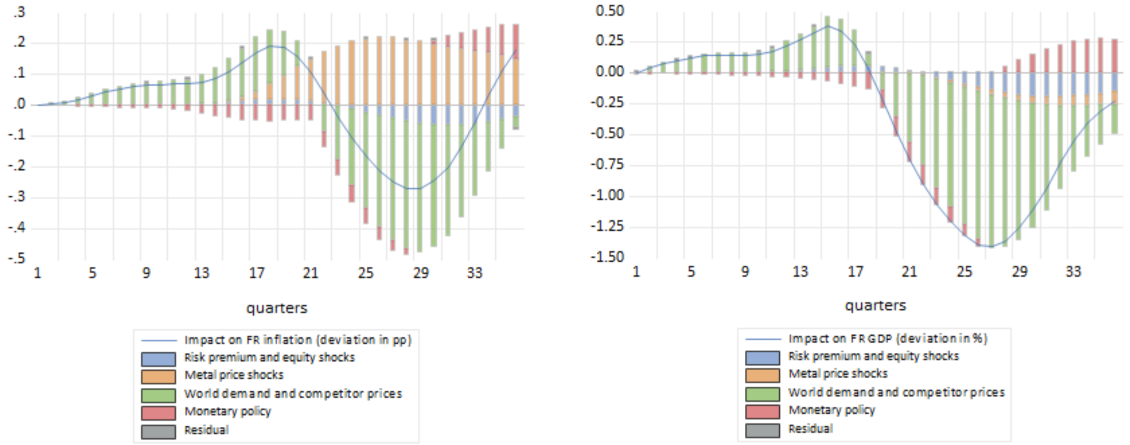
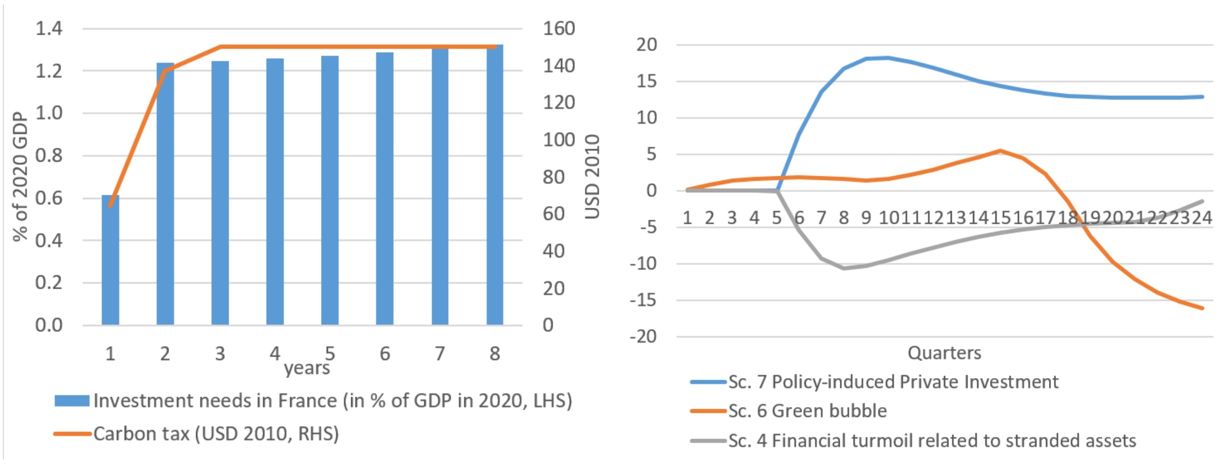


Figure 19: Scenario 6 (Green bubble): France inflation and GDP impact and shock contributions (FR-BDF)



(a) France public investment and carbon tax (b) US private investment (% deviation from baseline)

Figure 20: France Public investment in Scenario 5 and US Private investment across scenarios

During the last 2 years of the scenario, the GDP impacts become positive again as the effects of productivity gains kick in. Overall, such a scenario would be disinflationary and expansionary:

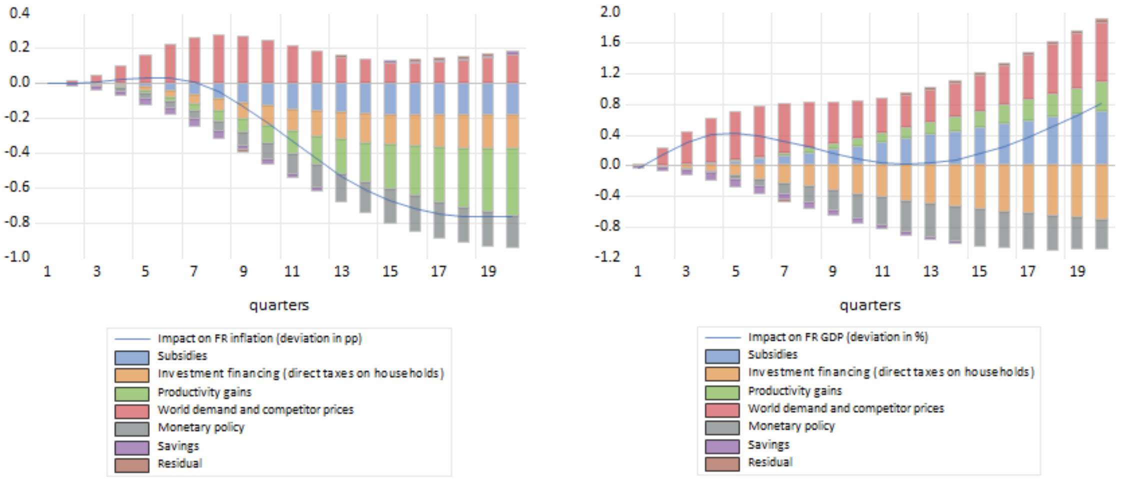


Figure 21: Scenario 7 (Private investment): France GDP and inflation impact and shock contributions (FR-BDF)

France‘s GDP would be 0.8% higher after five years and inflation would be 0.8 percentage point lower year-on-year. Indeed, most shocks are disinflationary, for instance subsidies, savings and productivity gains. Only the external demand shock is slightly inflationary. On the external side, this scenario is somewhat more inflationary in the short term, triggering a relatively mild monetary policy reaction that slightly depresses growth and inflation.

5.8 Scenario 8: Green innovation

The Banque de France’s sectoral model provides projections of GDP by zone in a green innovation scenario. The effects are positive from the first year (+0.08% for France and the rest of the world) and until the end of the projection horizon (+0.25% for France and the rest of the world, see Table 1).

Real GDP (% deviation)	France	Rest of EU
year 1	0,05	0,08
year 5	0,16	0,25

Table 1: Scenario 8 (Green innovation), real GDP impact obtained from the sectoral model (% deviation)

The sectoral model also provides an overview of the consequences of the green innovation shock on real value added by sector. In the European Union, the sector most benefiting from the shock is biomass (+16%), while electricity produced by coal, nuclear and oil (-3,5% each) suffer most (see Figure 22).

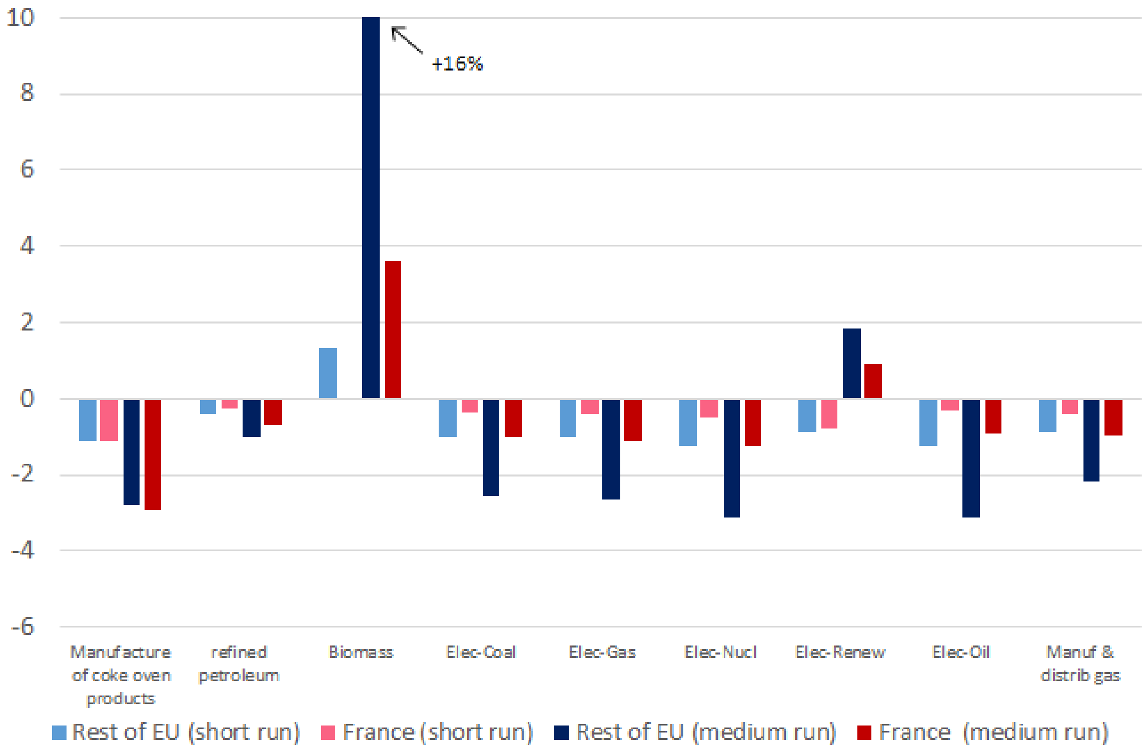


Figure 22: Scenario 8 (Green innovation): Impact on real value added by sector (% deviation)

The simulation of the green innovation scenario in NiGEM and FR-BDF is conducted by imposing productivity shocks that reproduce at aggregate level what the sectoral model gives when aggregating all sector-based results. The macroeconomic simulation also gives the impact on inflation. As expected, the positive supply shocks leads to a slight increase in GDP and a marginal decline in inflation up to -0.2 pp after two years.

5.9 Comments and policy implications

The simulations above show that a disorderly transition triggered by a late and very sudden increase in the price of carbon, a late and abrupt change in regulation or too little substitution by green technologies, could be inflationary in the medium term. Scenarios based on financial turmoil or mispricing of assets by investors could also create large fluctuations in macroeconomic variables that could be difficult to stabilize for policy-makers and could endanger both financial and price stability.

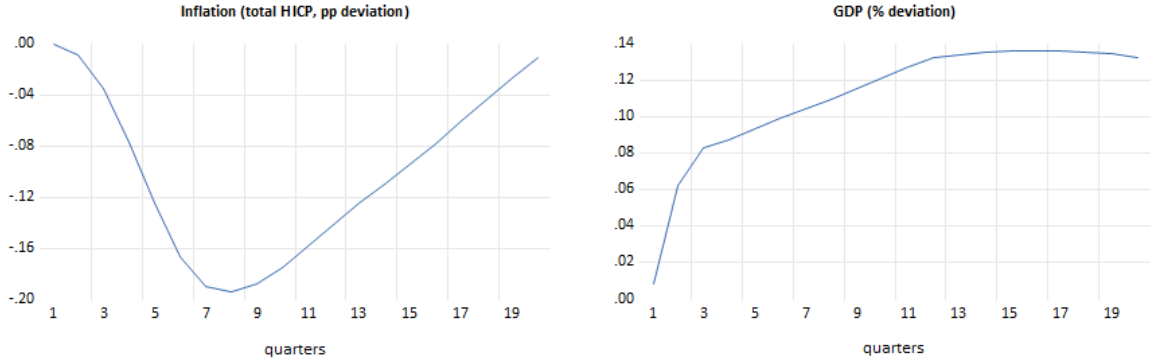


Figure 23: Scenario 8 (Green innovation): France GDP and inflation impact and shock contributions (FR-BDF)

These different scenarios also illustrate the importance of private and public investment and of the support for households in limiting the macroeconomic cost of the transition. If it is poorly anticipated, the transition to carbon neutrality could also lead to a rapid succession of such shocks, leading to increased price volatility. This increased volatility could disrupt economic agents' decisions, deanchor inflation expectations, and thus represent a real challenge for the conduct of a monetary policy adapted to the challenges of the transition. On the contrary, the earlier and more gradual the transition, the lower the risk to inflation and to growth.

Overall, although the results of the various scenarios cover a large range of macroeconomic outcomes, a simple representation of the impacts on GDP and inflation of our eight cases (see Figures 24 and 25 for France) shows a certain bias towards stagflationary effects. Indeed, in terms of magnitude, the inflationary responses are notably stronger than the disinflationary ones, with inflation rates peaking at close to 2 pp above baseline after two years, in France, and receding only gradually afterwards. On GDP, setting aside the strong increase triggered by higher public investment, all other scenarios feature either a decline by up to 1% after one year or, when positive, very limited impacts. The bias towards stagflationary situations might become challenging for central banks, which will have to deal with difficult trade-offs in their stabilisation policy. Moreover, shocks on both activity and inflation will translate into higher volatility. As the impacts of the climate transition could last throughout the decarbonisation of our economy, they are unlikely to be transitory. To maintain a solid anchoring of long term inflation expectations despite higher volatility, central banks may then have to go beyond the usual look-through policy – unlike they do with regular transitory supply-side shocks (Villeroy de Galhau, 2023).

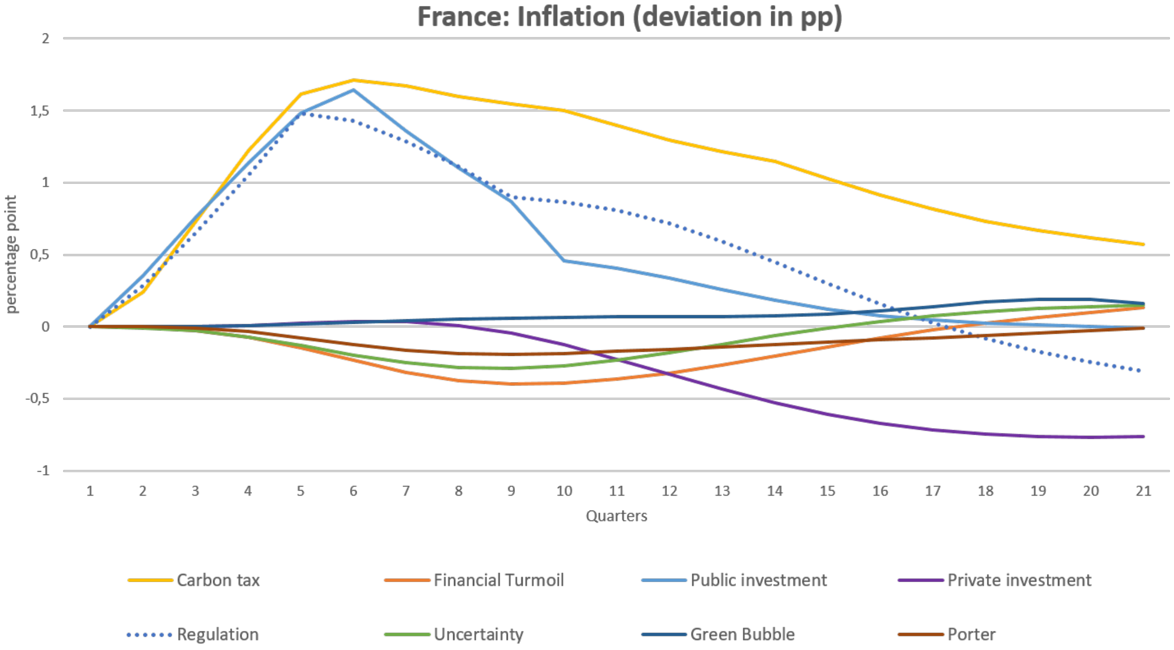


Figure 24: Overview of the impacts on France's inflation for all scenarios (FR-BDF, deviation in pp)

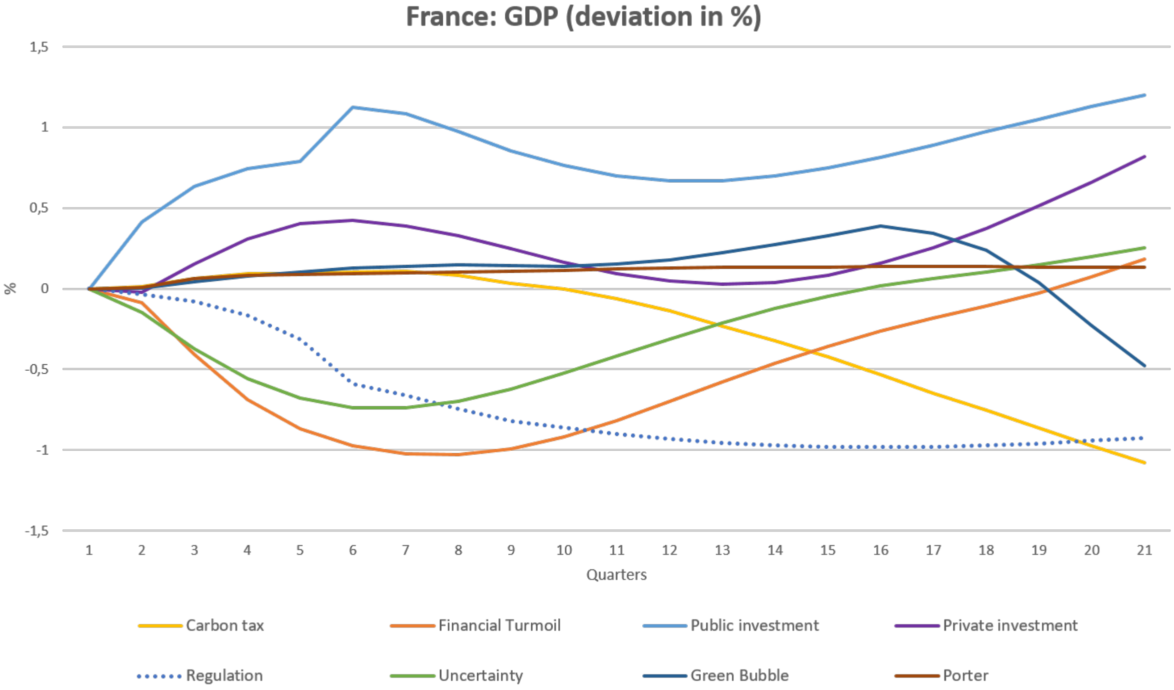


Figure 25: Overview of the impacts on France's GDP for all scenarios (FR-BDF, deviation in %)

6 Concluding remarks

This paper gives a widespread account of the diversity of transition paths in short horizons and how disorderly policies or misperception by agents can trigger significant fluctuations in macroeconomic variables. Contrary to long-term scenarios, whose dynamics are generally smooth and gradual, the short-term scenarios simulated in this paper show how the transition to a low-carbon economy can become critical for policy-makers to achieve their objective to stabilize growth and inflation and ensure financial stability.

These short-term scenarios have also shown the diversity of macroeconomic outcomes depending on the nature of the shocks underlying the narratives envisaged. The transition shocks encompass positive and negative shocks, both on the demand and supply sides, implying in some cases disruptive movements in activity at sectoral level and strong financial market reactions. According to the predominance of some of these key shocks, the macrofinancial consequences could be drastically different. Although it adds to the general uncertainty around the transition paths, this paper is a first attempt to quantify the range of outcomes that could be expected in the future.

Additional research is needed to quantify further such uncertainty. First, attributing probabilities of occurrence to each scenario would be a necessary step. However, as past data on transition-related shocks are rare, it remains challenging to quantify the likelihood of such scenarios. Methods based on expert judgement could be a possible way forward. Second, statistical methods to combine scenarios could also be envisaged, giving not only weights to each scenario, but also combining various shocks and their timing of occurrence. We could have therefore “scenarios of scenarios” that make them less polar and more complex. Third, another valuable contribution would be to associate each of these scenarios with the probability of achieving the emission reduction targets set out in the Paris Agreement and in the European ”Fit for 55” package. This would also encourage the use of these scenarios in policy work. Finally, transition risks have to be addressed together with the physical consequences of climate change, the acute weather events in particular. Even though the increase in the frequency and severity of extreme weather events might concern longer horizons than those envisaged here, it would be necessary to combine, in a consistent manner, transition narratives and the occurrence of severe perils, such as floods or heatwaves.

Although these possible extensions are left to future research, with the aim of making climate-related scenarios even more useful for policymakers, particularly in their projection exercises, the diversity of scenarios provided here already gives a “library” of future transition-related events that could entail significant risks to financial and macroeconomic stability. These scenarios are particularly useful for providing practical means for supervisory authorities to test the resilience of the financial system (e.g., in climate stress-testing exercises) or for policy-makers to inform their ability to stabilize the economy at relevant policy horizons (e.g., the effectiveness of their actions can be assessed through sensitivity analyses). This is also necessary to prepare economic agents for the macroeconomic and financial challenges linked to climate-related risks that await them in the near future.

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Appendix A Modelling details for the sectoral model

Production

In each country $A \in \mathcal{C}$, there are N sectors, $N_E < N$ of which are energy-producing sectors (indexed by $j \in \{1, ..., N_E\}$) and $N - N_E$ are producing non-energy goods (indexed by $j \in \{N_E + 1, ..., N\}$). There is a representative firm within each sector, which is operating in a perfectly competitive environment. In each country $A \in \mathcal{C}$, the representative firm of sector $i \in \{1, \ldots, N\}$ combines energy and non-energy intermediate inputs $\{Z_{Aji}\}$ from all sectors $j \in \{1, \ldots, N\}$ as well as labour L_{Ai} to produce good i in quantity Q_{Ai}. Intermediate inputs of good j, Z_{Aji}, is an aggregate of good j produced domestically, Z_{AAji}, and imported from all other countries, $\{Z_{ABji}\}$ for all $B \neq A$ (aggregated into Z_{AMji}). The production technology is modelled using nested CES functions, with multiple layers. The energy (non-energy) inputs are aggregates of intermediate inputs of all energy (non-energy) sectors. $\{\eta_X, \xi_X\}_{X \in E,I}$, σ, ϵ, θ are the respective elasticities of substitution in each aggregation step.

The production function of a firm in sector $i \in \{1, \ldots, N\}$ and country A can be thus characterized by the following equations:

$$Q_{Ai} = A_{Ai} \left(\mu_{Ai}^{\frac{1}{\theta}} L_{Ai}^{\frac{\theta-1}{\theta}} + \alpha_{AEi}^{\frac{1}{\theta}} E_{Ai}^{\frac{\theta-1}{\theta}} + \alpha_{AIi}^{\frac{1}{\theta}} I_{Ai}^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}} \tag{4}$$

where:

$$E_{Ai} = \left(\sum_{j=1}^{N_E} \left(\frac{\alpha_{Aji}}{\alpha_{AEi}} \right)^{\frac{1}{\sigma}} \left(A_{AEij} Z_{Aji} \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{5}$$

$$I_{Ai} = \left(\sum_{j=N_E+1}^{N} \left(\frac{\alpha_{Aji}}{\alpha_{AIi}} \right)^{\frac{1}{\epsilon}} Z_{Aji}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}} \tag{6}$$

$$Z_{Aji} = \left(\left(\frac{\alpha_{AAji}}{\alpha_{Aji}} \right)^{\frac{1}{\eta_X}} Z_{AAji}^{\frac{\eta_X-1}{\eta_X}} + \left(\frac{\alpha_{AMji}}{\alpha_{Aji}} \right)^{\frac{1}{\eta_X}} Z_{AMji}^{\frac{\eta_X-1}{\eta_X})} \right)^{(\frac{\eta_X}{\eta_X-1})} \tag{7}$$

$$Z_{AMji} = \left(\sum_{B \in \mathcal{C}, B \neq A} \left(\frac{\alpha_{ABji}}{\alpha_{AMji}} \right)^{\frac{1}{\xi_X}} Z_{ABji}^{\frac{\xi_X-1}{\xi_X}} \right)^{\frac{\xi_X}{\xi_X-1}} \tag{8}$$

where: $X = E$ if $j \leq N_E$ and $X = I$ if $j > N_E$

Where A_{Ai} is a country-sector-specific total factor productivity shock (TFP) and A_{Eij} is an country-sector-energy-specific efficiency shock. Parameter α_{ABji} is the share of intermediate good j produced in country $B \in \mathcal{C}$ used by sector i in country A, α_{AMji} is the total share of inputs j that are imported by firm i in country A, α_{Aji} is to the share of input j used to produce output i in country A; α_{AEi} is the total energy share, α_{AIi} is the total non-energy share and μ_{Ai} is the labour share used by firm i in country A. By construction, these shares must satisfy the following restrictions:

$$\alpha_{AEi} + \alpha_{AIi} + \mu_{Ai} = 1; \quad \sum_{j=1}^{N_E} \alpha_{Aji} = \alpha_{AEi}; \quad \sum_{j=N_E+1}^{N} \alpha_{Aji} = \alpha_{AIi}$$

$$\alpha_{AAji} + \alpha_{AMji} = \alpha_{Aji}; \quad \sum_{B \in \mathcal{C}} \alpha_{ABji} = \alpha_{AMji};$$

The representative firm in sector $i \in \{1, \ldots, N\}$ country $A \in \mathcal{C}$ maximises its profit taking its production function as well as prices and wages as given:

$$\max_{L_{Ai}, \{Z_{ABji}\}} \pi_{Ai} = P_{Ai}(1 - \tau_{Ai})Q_{Ai} - w_A L_{Ai} - \sum_{B \in \mathcal{C}} \sum_{j=1}^{N} P_{Bj}(1 + \zeta_{ABji}) Z_{ABji}$$

s.t. equations (4) to (8) are verified.

Here, w_A is the wage in country A; ζ_{ABji} is a tax on country A sector i's intermediate inputs of good j originating from country B.[17] τ_{Ai} is a production tax that charges the GHG emitted during the production process besides energy input consumption, whereas ζ_{ABji} charges the CO_2 emitted when burning fossil energy inputs during production.

The first-order optimality conditions of the representative firm in country A sector i are then:

$$\frac{L_{Ai}}{Q_{Ai}} = \frac{\mu_{Ai}}{A_{Ai}^{1-\theta}} \left(\frac{P_{Ai}(1 - \tau_{Ai})}{w_A} \right)^{\theta} \tag{9}$$

$$\frac{Z_{AAij}}{Q_{Ai}} = \frac{\alpha_{Aji}}{A_{Ai}^{1-\theta} A_{AXji}^{1-El_X}} \frac{(P_{Ai}(1 - \tau_{Ai}))^{\theta}}{(P_{AAji}(1 + \zeta_{AAji}))^{\eta_X}} P_{AXi}^{El_X - \theta} P_{Aji}^{\eta_X - El_X} \tag{10}$$

$$\frac{Z_{ABji}}{Q_{Ai}} = \frac{\alpha_{Aji}}{A_{Ai}^{1-\theta} A_{AXji}^{1-El_X}} \frac{(P_{Ai}(1 - \tau_{Ai}))^{\theta}}{(P_{ABji}(1 + \zeta_{ABji}))^{\xi_X}} P_{AXi}^{El_X - \theta} P_{Aji}^{\eta_X - El_X} P_{AMji}^{\xi_X - \eta_X} \tag{11}$$

where: $X = E, El_X = \sigma$ if $j \leq N_E$ and $X = I, El_X = \epsilon, AIij = 1$ if $j > N_E$

where the corresponding price indices for the energy and non-energy intermediate input bundles as well as intermediate input of type j and imported intermediate input of type j sub-bundles

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[17] As detailed in the upcoming household and market clearing sections, there is one labour market per country, so that firms (sectors) face a wage that is country-specific.

are defined as follows:

$$P_{AEi} = \left(\sum_{j=1}^{N_E} \frac{\alpha_{Aji}}{\alpha_{AEi}} \left(\frac{P_{Aji}}{A_{AEij}} \right)^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \tag{12}$$

$$P_{AIi} = \left(\sum_{j=N_E+1}^{N} \frac{\alpha_{Aji}}{\alpha_{AIi}} P_{Aji}^{1-\epsilon} \right)^{\frac{1}{1-\epsilon}} \tag{13}$$

$$P_{Aji} = \left(\frac{\alpha_{AAji}}{\alpha_{Aji}} \left(P_{AAji}(1+\zeta_{AAji})\right)^{1-\eta_X} + \frac{\alpha_{AMji}}{\alpha_{Aji}} P_{AMji}^{1-\eta_X} \right)^{\frac{1}{1-\eta_X}} \tag{14}$$

$$P_{AMji} = \left(\sum_{B\in\mathcal{C}, B\neq A} \frac{\alpha_{ABji}}{\alpha_{AMji}} \left(P_{Bji}(1+\zeta_{ABji})\right)^{1-\xi_X} \right)^{\frac{1}{1-\xi_X}} \tag{15}$$

$$\text{where: } X = E \text{ if } j \leq N_E \text{ and } X = I \text{ if } j > N_E$$

As markets are competitive, firms make zero profit, implying the following equality:

$$P_{Ai}(1-\tau_{Ai}) = \frac{1}{A_{Ai}} \left(\mu_{Ai} w_A^{1-\theta} + \alpha_{AEi} P_{AEi}^{1-\theta} + \alpha_{AIi} P_{AIi}^{1-\theta} \right)^{\frac{1}{1-\theta}} \tag{16}$$

Final demand

There is a representative household in each country $A \in \mathcal{C}$. She consumes a CES bundle of goods from all sectors and all countries, with elasticity ρ, and inelastically supplies a fixed amount of labour L_A. Her preferences are represented by a constant-relative-risk-aversion utility function:

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

Where $\varphi > 0$ measures her degree of risk-aversion and the consumption shares γ_{ABj} satisfy: $\sum_B \sum_{j=1}^{N} \gamma_{ABj} = 1$.

Households from all countries trade Arrow-Debreu securities for every possible state of nature on a perfectly competitive international financial market. In our static model, this implies that cross-country risk-sharing is perfect.

In addition to financial flows related to security trading, country A's household receives labour income $w_A L_A$ and lump-sum transfers from her government T_A. Labour is assumed to be perfectly mobile across sectors within countries, but fully immobile across countries, so that the wage w_A differs across countries but is the same across sectors within a given country. This is akin to assuming no international migration. The representative household in each country pays a tax κ_{Ai} on her final consumption of good i. Thus, the budget constraint of the representative household of country A writes as:

$$\sum_{B\in\mathcal{C}}\sum_{j=1}^{N} P_{Bj}(1+\kappa_{Aj})C_{ABj} = w_A L_A + T_A + \Phi_A$$

where Φ_A is the net financial gain from security trading.[18]

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

$$\forall A, B \in \mathcal{C},\ \forall j \in \{1,\dots,N\}, \qquad \frac{C_{ABj}}{C_A} = \gamma_{ABj}\left(\frac{P_{Bj}(1+\kappa_{Aj})}{P_A}\right)^{-\rho} \tag{17}$$

$$\forall B \in \mathcal{C}, \qquad \frac{C_B}{C_A} = \nu_{AB}\left(\frac{P_A}{P_B}\right)^{\frac{1}{\varphi}} \tag{18}$$

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

$$P_A = \left(\sum_{B\in\mathcal{C}}\sum_{j=1}^{N}\gamma_{ABj}\left[P_{Bj}(1+\kappa_{Aj})\right]^{1-\rho}\right)^{\frac{1}{1-\rho}} \tag{19}$$

And the parameters $\{\nu_{AB}\}_{B\in\mathcal{C}}$ determine relative aggregate consumption across countries in the initial steady state (we use the convention that $\nu_{AA} = 1$).

Market clearing

In each country, there is one labor market and N sectoral good markets. The market clearing conditions are:

$$\forall i \in \{1,\dots,N\}, \qquad Q_{Ai} = \sum_{A\in\mathcal{C}}\sum_{B\in\mathcal{C}}\sum_{j=1}^{N} Z_{ABij} + \sum_{A\in\mathcal{C}}\sum_{B\in\mathcal{C}} C_{ABi} \tag{20}$$

$$L_A = \sum_{j=1}^{N} L_{Aj} \tag{21}$$

The government collects taxes and redistributes proceeds to the household in a lump-sum fashion. To keep the model parsimonious, the government doesn't consume nor provide public goods. Transfers are taken as given by the households. As the government of each country $A \in \mathcal{C}$ runs a balanced budget, the lump-sum transfer is equal to:

$$T_A = \sum_{j=1}^{N}\tau_{Aj}P_{Aj}Q_{Aj} + \sum_{B\in\mathcal{C}}\sum_{j=1}^{N}\kappa_{jA}P_{Bj}C_{ABj} + \sum_{A\in\mathcal{C}}\sum_{B\in\mathcal{C}}\sum_{i=1}^{N}\sum_{j=1}^{N}\zeta_{ABji}P_{Bj}Z_{ABji} \tag{22}$$

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[18] See Devulder and Lisack (2020) for a complete description of financial markets.

At the international level, financial market clearing implies the following resource constraint for the world economy:

$$\sum_{A\in\mathcal{C}} P_A C_A = \sum_{A\in\mathcal{C}} w_A L_A + \sum_{A\in\mathcal{C}} T_A \tag{23}$$

Equilibrium

Without loss of generality, labour in country 1 is chosen as the numéraire and the corresponding wage is normalized: $w_1 = 1$. Labour supply in each country $\{L_A\}_{A\in\mathcal{C}}$ is calibrated to define the scale of the model and the relative size of each country. An equilibrium is a set of quantities $\{Q_{Ai}, L_{Ai}\}$, $\{Z_{ABij}\}$, $\{C_{ABi}\}$, $\{C_A, T_A\}$ and prices $\{P_{Ai}, P_{AEi}, P_{AIi}\}$, $\{P_{Aij}, P_{AMij}\}$, $\{P_A\}$, $\{w_A\}_{A\in\mathcal{C}\setminus\{1\}}$ such that equations (4) and (9) to (23) are verified.

Appendix B Elasticities of substitution in the sectoral model

There are two calibrations for the elasticities of substitution, depending on the time horizon. In the short run (the impact is estimated less than 3 years after the shock), substitutions possibilities are limited and elasticities are therefore relatively low (cf. column "low" of Table 2 below) ; in the medium run (3-to-5 years after the shock), elasticities are slightly higher (cf. column "high" of Table 2 below). All scenarios are evaluated with high elasticities, unless specifically mentioned.

The elasticies are calibrated from the literature - note that the "true" value of these elasticities remains very uncertain: the literature usually offers a wide range of possible values.

- The values of θ, ϵ and ρ in the baseline (i.e. high) calibration are in line with the calibration of Baqaee and Farhi (2019);
- The elasticity between energy inputs (σ) is slightly above 1: since we are analyzing short run impacts, we chose a relatively conservative calibration that nevertheless treats energy types as substitutes rather than complements (by comparison, Papageorgiou et al. (2017) find an elasticity of 2 for electricity-producing sectors and 3 for non-energy sectors);
- The value of trade elasticities (ηs, ξs) are in line with the estimates of Feenstra et al. (2018); elasticities of subsitution between energy goods are lower than average following the results of Broda and Weinstein (2006).

Elasticies of substitution	**Low**	**High**
Labor, Intermediate inputs and Energy (θ)	0.25	0.5
Intermediate non-energy inputs types (ϵ)	0.3	0.3
Domestic and imported non-energy inputs (η_I)	1.1	1.5
Non-energy inputs imported from different countries (ξ_I)	2	2.5
Energy types (σ)	1.1	1.2
Domestic and imported energy inputs (η_E)	1.5	2
Energy inputs imported from different countries (ξ_E)	3	4
Final consumption goods (ρ)	0.8	0.8

Table 2: Sectoral model - Calibration of the elasticities of substitution, low and high

Appendix C Calibration of taxes in the sectoral model

Appendix C.1 Scenario 1: carbon taxation

There are three types of taxes in the model: on intermediate fossil fuels consumption by producers, on sectoral production and on final fossil fuels consumption by households. As explained in the main text, the carbon tax applies only to firms such that the final consumption tax is nil in this scenario.

Regarding the production and intermediate consumption taxes, we attribute total sectoral CO_2 emissions to the use of fossil fuels (e.g. coal, oil, gas, ...). Sectoral non-CO_2 GHG emissions, obtained by subtracting CO_2 emissions from total emissions expressed in tCO_2e in the data are attributed to the sectoral production process besides the use of energy inputs. Formally, this amounts to setting:

$$g_{Ai} = \frac{GHG_{Ai} - CO_{2Ai}}{Q^I_{Ai}}; \qquad f_{Ai} = \frac{CO_{2Ai}}{\sum_{B \in \mathcal{C}} \sum_{j \in \mathcal{F}} emit_j Z^I_{ABji}} \text{ and } f_{Aij} = emit_j f_{Ai}$$

where CO_{2Ai} is the CO_2 emissions of sector i in country A, GHG_{Ai} is the total GHG emissions of sector i in country A, superscript I denotes variables values at the initial steady state, $\mathcal{F}$ is the set of fossil fuels-producing sectors, $emit_j$ is a proportionality coefficient of CO_2-intensity between various fossil fuels (which captures the fact that each fossil fuel, e.g. gas or oil, has a different CO_2 intensity), f_{Ai} is the sector-specific CO_2 intensity and f_{Aij} is the fossil fuel- and sector-specific CO_2 intensity.

Calibration of tax rates in Scenario 1

Carbon taxation is characterized by the price of a ton of CO_2, denoted by $P^A_{CO_2}$ in country A in each country implementing the tax. As made explicit below, tax rates are calibrated such that the corresponding tax proceeds amount to the cost of the targeted GHG emissions at the initial steady state, given the carbon price.

Intermediate consumption taxes. For each sector i located in a country A implementing the tax, the rates ζ_{ABji} on its intermediate consumption of fossil fuels doesn't depend on the country producing these fossil fuels, i.e. $\zeta_{ABji} = \zeta_{Aji}$ for all $B \in \mathcal{C}$. They verify:

$$\zeta_{ABji} = \zeta_{Aji} = \begin{cases} 0 & \text{if } j \notin \mathcal{F} \\ emit_j \zeta_{Ai} = P^A_{CO_2} f_{Aij} & \text{if } j \in \mathcal{F} \end{cases} \tag{24}$$

$$\text{where} \quad \zeta_{Ai} = \frac{P^A_{CO_2} CO_{2Ai}}{\sum_{B \in \mathcal{C}} \sum_{j \in \mathcal{F}} P^I_{Aj} emit_j Z^I_{ABji}} = P^A_{CO_2} f_{Ai}$$

since all prices are equal to 1 in the initial steady state. Note that tax rates are set based on the observation of the tax-free steady state equilibrium and are not revised over time. Since prices adjust once the tax is implemented, at the new equilibrium (24) will not be exactly verified. The same is true for the other taxes τ and κ.

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

$$\tau_{Ai} = \frac{P^A_{CO_2} GHG^I_{Ai}}{P^I_{Ai} Q^I_{Ai}} = P^A_{CO_2} g_{Ai}$$

Remarks. This calibration strategy prompts two observations. First, the tax rates ζ, τ obtained in a given country and sector do not depend on whether other countries are or not implementing a carbon tax. Second, the tax rates ζ_{ABji} take into account the CO_2-intensity of specific fossil fuels: for instance, coal has a higher CO_2-intensity than oil and will hence face a higher tax rate.

Appendix C.2 Scenario 2: regulation

In Scenario 2, the tax rates on the various energies are calibrated so as to match consumption targets for each type of energy. These targets are given by the EU "Fit for 55" objectives, adjusted for the Ukrainian crisis (RePower EU) and brought to 2027. The targets as well as the corresponding tax rates are presented in Table 3.

Note that the tax rates depend only on the energy type and the consuming country: the tax rates are the same for domestically-produced and imported energy. Furthermore, intermediate and final consumption are taxed at the same rate.

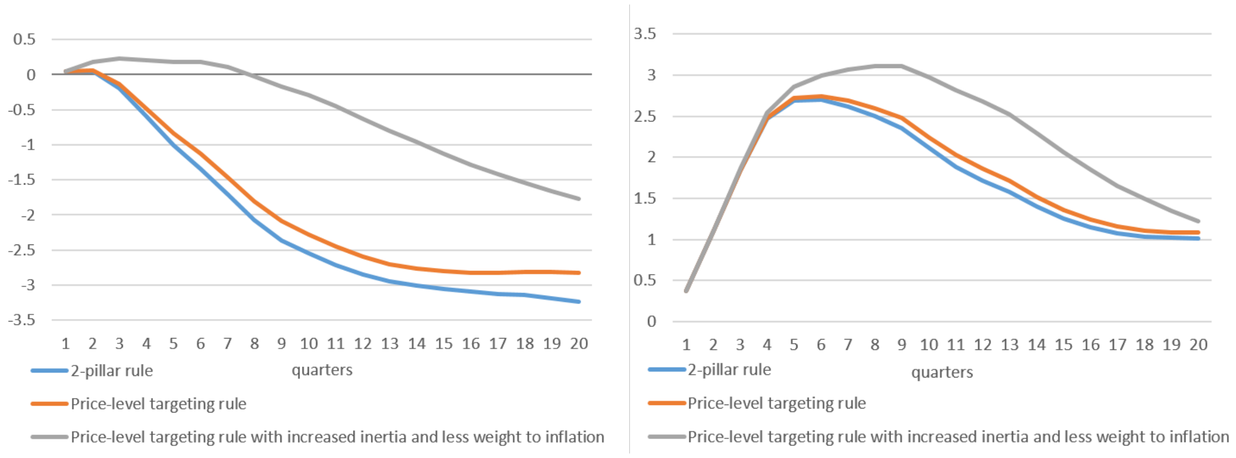
Energy	Consumption target	Tax rate FR	Tax rate RoEU
Coal	-30-40 %	56 %	56 %
Oil	-20-30 %	34 %	34 %
Gas	-40-60 %	66 %	60 %
Electricity (coal)	-30-40 %	56 %	56 %
Electricity (oil)	-20-30 %	35 %	35 %
Electricity (gas)	-40-60 %	80 %	80 %
Electricity (nuclear power)	-20 %	40 %	40 %
Renewable energy	80 %	-33 %	- 35 %
Biomass	80 %	-40 %	-38 %

Table 3: Sectoral model - Calibration of tax rates in Scenario 2

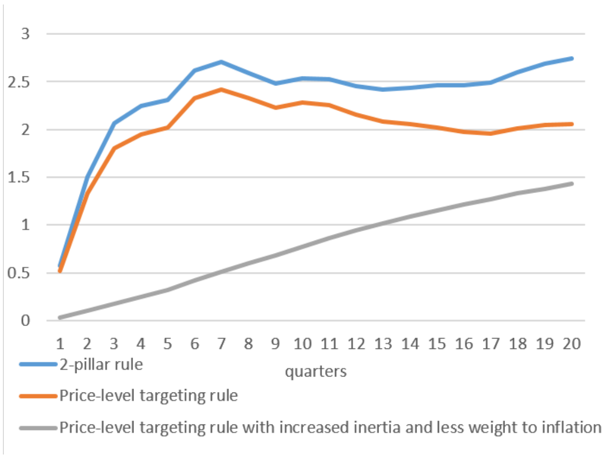
Appendix D Sensitivity analysis to monetary policy reaction

In all scenarios, we assume an endogenous monetary reaction according to standard Taylor-type rules included in NiGEM. In supply-led inflationary scenarios however, such as Scenario 1 which features an abrupt rise in carbon taxes, we adjust the standard monetary rule to include more inertia and decrease sensitivity to inflation. We present here a sensitivity analysis for Scenario 1 where we show the impacts of the scenario on euro area GDP, inflation and the central bank target rate according to different monetary policy rules (see section 3.2 for a description of the rules) namely i) the model's standard 2-pillar rule, ii) the model's price-level targeting rule (PLT), iii) a modified price-level targeting rule to reflect the increased inertia and decreased sensitivity to inflation (coefficients at respectively 0.9 and 0.2). All simulations are carried out here under backward expectations due to the short horizons considered and the abruptness of the shocks.

Figure 26 shows that the impacts on euro area GDP and inflation are relatively close for the first two types of rules (2-pillar and PLT) although the central bank's target rate is on average 36 bp lower in the PLT case compared to the 2-pillar case. Modifying the parameters of the rule (inertia and inflation weight) however yields different results, with euro area GDP on average 1.3 percentage points higher in the Modified PLT case compared to standard PLT over the simulation horizon. Euro area inflation is on average 0.4 pp. higher over the same horizon in Modified PLT compared to standard PLT. The profile of the central bank's target rate is also very different with a more progressive rise in key rates since they reach 100 bp after 13 quarters in Modified PLT where as they exceed this level after the second quarter in standard PLT and subsequently reach 208 bp after 13 quarters. At the end of the simulation horizon, target rates reach 142 bp when using Modified PLT compared to 206 bp in standard PLT and 274 bp in the 2-pillar rule.



(a) Euro area GDP (% deviation from baseline) (b) Euro area inflation (deviation from baseline in pp.)



(c) Euro area target rate (deviation from baseline in pp.)

Figure 26: Impact of Scenario 1 on euro area GDP, inflation and central bank target rate with different monetary policy rules (backward expectations - NiGEM)