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Bridging the Gap in Macroeconomic Analysis of the Energy Transition: Combining Medium- and Long-Term Approaches

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Abstract

The climate transition has long been considered as a long-term challenge, and the tools used to analyse it have been long-term models. At short- to medium-term horizons, forecasting models generally focus on demand effects of such a shock through the purchasing power of households. In this paper, we bridge the gap between these two approaches in order to study the effect of the Fit-for-55 package of the European Commission on the French economy by 2030, using an energy-augmented two-sector real model, FR-GREEN, as a source of shocks for the nominal forecasting model FR-BDF. We show that the benefit of reducing emissions implies some macro costs during the transition. In the short run, inflation increases substantially because of the direct effect of taxes levied on households. In the medium run, most of the total impact on output and inflation is due to large real supply effects from FR-GREEN. These supply effects come from a loss of apparent productivity implied by the transition from brown to green technologies, in the absence of any favourable assumption regarding technological progress potentially driven by the transition.

Keywords: Energy, Climate, Transition, Carbon Tax, General Equilibrium

JEL classification: Q43, Q54, Q58, E37

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This paper is the outcome of a two-parted project. F. Henriet, N. Lisack and H. Turunen developed FR-GREEN. F. Henriet, Y. Kalantzis, M. Lemoine and H. Turunen combined FR-GREEN with FR-BDF.
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NON-TECHNICAL SUMMARY

The paper addresses a significant challenge: understanding the economic effects of the climate transition induced by government policy, not only in the distant future, but also in the next few years. Historically, the climate transition has been treated as a long-term issue, with economic models focusing either on far-off outcomes or short-term factors like its impact on purchasing power and consumer spending. But these separate approaches miss the joint impact of the low-carbon transition on the economy in the medium- and long-run.

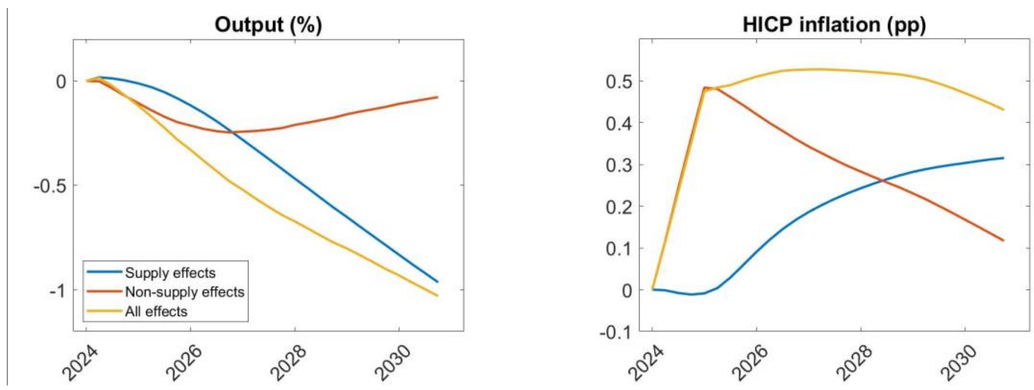
To bridge this gap, we combine two types of economic models: a new real micro-founded general equilibrium model called FR-GREEN that looks at how different types of energy (clean vs. dirty) and technological choices affect the economy; and a more detailed nominal forecasting model for France called FR-BDF, in the spirit of the FRB/US model of the Federal Reserve Board, that accounts for short-term dynamics like inflation and demand. Using this approach, we assess the impact in France by 2030 of the Fit-for-55 package, modelled as a carbon tax. We enrich this tax scenario in FR-BDF with shocks on total factor productivity (TFP) and on the share of consumption devoted to fossil fuel energy obtained from a simulation of FR-GREEN and intended to capture channels missing in FR-BDF, i.e. the usage of energy as an input by firms, reallocation of production across sectors and composition effects within consumption.

We find four key results (see Figure 1):

- The shift from fossil fuels to green energy technologies leads to lower supply of output. In a model where these energies are not modelled explicitly, this corresponds to an apparent productivity loss during the transition, in the absence of any favourable assumption regarding technological progress potentially driven by the transition.
- Carbon taxes raise inflation in the short run, peaking at around 0.5 percentage points higher, at first due to the direct effect of these taxes on final consumer prices and afterward mostly due to supply effects related to higher energy costs for firms.
- Total output falls, by about 1.0% by 2030, primarily due to supply-side disruption as industries adjust to cleaner technologies.
- These results depend on the response of monetary policy. Keeping real interest rates constant, as assumed in the baseline scenario, leads to a moderate inflation surge and output losses. By worsening output losses, a more aggressive monetary response could limit inflation in the medium run, in line with the Phillips curve mechanisms embedded in the model.

This paper provides a more complete picture of how transition policies can ripple through the economy. It shows that while such policies are necessary to fight climate change, they can have substantial economic effects that policymakers must prepare for.

Figure 1. Simulated output level and inflation in a combined approach based on FR-BDF and FR-GREEN following carbon tax shocks, under constant fiscal and monetary policies



Combler le fossé dans l'analyse macroéconomique de la transition énergétique : combiner les approches à moyen et à long terme

RÉSUMÉ

La transition climatique a longtemps été considérée comme un défi de long terme, analysé en utilisant principalement des modèles de long terme. À court et moyen terme, les modèles de prévision se concentrent généralement sur les effets d'un tel choc sur la demande, notamment à travers le pouvoir d'achat des ménages. Cet article comble le fossé entre ces deux approches en utilisant un modèle réel d'équilibre général à deux secteurs augmenté par l'énergie, FR-GREEN, comme source de chocs pour le modèle nominal de prévision FR-BDF. Nous appliquons cette approche pour étudier les effets du paquet Fit-for-55 sur l'économie française à horizon 2030. Nous montrons que les bénéfices de réduire les émissions impliquent des coûts macroéconomiques. Les résultats indiquent que l'inflation augmente substantiellement à court terme en raison de l'effet direct des taxes imposées aux ménages. À moyen terme, la majeure partie de l'impact total sur la production et l'inflation est due à d'importants effets d'offre issus de FR-GREEN. Ces effets d'offre proviennent notamment d'une perte de productivité apparente générée par la transition des technologies brunes vers les technologies vertes, en l'absence d'hypothèse favorable de progrès technique potentiellement induit par la transition.

Mots-clés : énergie, climat, transition, taxe carbone, équilibre général

1 Introduction

Climate change has long been seen as a long-term issue that does not impact the short-term economic performance nor the engines of growth (e.g. education, technology, institutions). However, as pointed out in Pisani-Ferry (2021), climate policy is macroeconomic policy: any policy capable of affecting climate change will also have notable macroeconomic effects beyond the energy sector due to e.g. the enormous need for re-investment in both firm capital and household durables. The longer we wait to implement ambitious environmental policies, the more massive the impact of these policies will be, especially in the short run.

This extra investment will come at a cost, with fewer resources available for other uses, particularly consumption. In the presence of price rigidities, this additional demand may result in higher inflation. Furthermore, some of the existing capital stock cannot be converted or upgraded to operate with low carbon emissions and might remain unused, turning into stranded assets. This obsolescence may affect both firms and households directly through their stocks of capital and durable goods (e.g. housing and vehicles), leaving them with lower wealth levels and pushing demand down. Finally, labour market disruption may occur as some workers' occupations vanish and their skills become obsolete.

Thus, the energy transition is first and foremost a macroeconomic problem, as emphasized by Schubert (2017). More precisely, in examining the role of environmental issues in macroeconomic research, she highlights the distinction between short-term and long-term approaches. She emphasizes that environmental considerations are largely absent from short-term macroeconomics. When they are addressed, the primary focus has been on the macroeconomic effects of oil price shocks and energy price fluctuations (Kim and Loungani, 1992; Bodenstein et al., 2011). More recently, a small body of literature has emerged exploring the short-term costs of environmental policies, particularly carbon taxes and cap-and-trade systems (Heutel, 2012; Annicchiarico and Di Dio, 2015a).

In contrast, long-term macroeconomic models have partially integrated environmental factors. Early growth models, such as those of Solow (1956) and Ramsey (1928), ignored environmental constraints. The integration of natural resources into growth theory began in the 1970s following the oil crises (Dasgupta and Heal, 1974; Stiglitz, 1974). More recent studies focus on the transition to a low-carbon economy and the conditions under which green growth can be achieved (Acemoglu et al., 2012a; Smulders et al., 2014).

From a medium- to long-term perspective, Integrated Assessment Models (IAMs) have been developed to couple economic and climate models, helping policymakers assess the impact of climate policies. The seminal DICE model by Nordhaus (1991, 1994, 2008) remains influential. However, IAMs have faced criticism for their assumptions and limitations (Pindyck, 2013, 2017). In parallel, dynamic stochastic general equilibrium (DSGE) and real business cycle (RBC) models have increasingly incorporated environmental factors to evaluate the macroeconomic effects of carbon pricing and other environmental policies (Fischer and Springborn, 2011; Dissou and Karnizova, 2016). For France, Henriet et al. (2014) have developed a DSGE model in which energy is explicitly considered as a factor of production.

On the short-term side, semi-structural models are widely regarded as effective tools for short- to medium-term forecasting, as they rely on empirical relationships and are less dependent on detailed structural assumptions. However, they are not well-suited for studying long-term dynamics such as the energy transition. This limitation arises because semi-structural models typically lack explicit representations of the energy sector on the supply side and fail to capture key complementarities between capital, labour, and energy.

The approach proposed here seeks to bridge the gap between short term and medium term approaches by leveraging the strengths of a semi-structural nominal model for inflation forecasting while incorporating insights on the macroeconomic effects of the energy transition from a real DSGE model. More precisely, we introduce a total factor productivity (TFP) wedge into the production function that forms the real core of a semi-structural model and a time-varying share of consumption devoted to fossil fuel energy into the basket used for defining consumption prices of households. This wedge and this share, derived from a structural real DSGE model with explicit energy-sector dynamics, serve as proxies for the structural changes associated with the energy transition, allowing us to analyse its macroeconomic implications within a semi-structural nominal framework.

First, the dynamics of the transition and the macroeconomic consequences of climate change policies are computed at the business-cycle frequency through a novel macroeconomic model, the FRance General-Equilibrium Energy-augmented model (FR-GREEN). Recent papers analyzing the optimality of climate policy are typically built such that there is no explicit transition in terms of adapting production and consumption technologies, as for instance firm capital stock is assumed homogeneous irrespective of how polluting its use is and emissions are assumed to depend only on the level of output and abatement effort.[1] Thus the transition in these models is in fact typically just from one level of production and emissions to the other, so that the macroeconomic consequences materialize primarily in the form of cost of abatement.

To accurately capture the costs of transitioning to a sustainable economy, a model must incorporate real rigidities that prevent the seamless conversion of high-emission ("brown") capital and durable goods into their low-emission ("green") counterparts without additional costs. A conceptually straightforward way to introduce these features is by assuming capital and durable goods heterogeneity—explicitly distinguishing between brown and green types—along with investment irreversibility. That is, firms and households cannot simply liquidate stranded brown capital to reinvest in new green capital without incurring substantial costs. The FR-GREEN model, a real DSGE model calibrated for France, incorporates these essential characteristics. Specifically, it differentiates between two types of firm capital and household durables—green and brown—each representing distinct technologies.

Our analysis is then based on applying our new real model, FR-GREEN, together with the semi-structural nominal model FR-BDF[2] to simulate the dynamics of the French economy following carbon tax shocks. More precisely, the modelling strategy is to develop all the additional channels (notably two-sector setup and energy use) needed to study resource reallocation during the energy transition in a satellite real model, FR-GREEN, where we keep the demand side simple as in a traditional DSGE. We then link this real model to FR-BDF, which has a

[1] Most work in the E-DSGE literature, e.g. Annicchiarico and Di Dio (2015b), does not consider the transition for capital and durables, focusing on a model economy which responds to the climate issue solely with emissions abatement, while the IAM literature is focused on very low-frequency questions.

[2] See Lemoine et al. (2019) for a detailed description of FR-BDF.

much richer and more realistic demand side, built around a real core consisting of a simple one-sector CES production function with only capital and labour factors and without any energy input. The TFP wedge and the share of fossil fuel energy in consumption that we take from FR-GREEN and introduce into the real core and the price block of FR-BDF then allow us to simulate FR-BDF while accounting for the effects of these additional channels of the multi-sector energy-augmented real model FR-GREEN.

This two-model approach mitigates the limitations of each individual model. While FR-GREEN captures the real economic consequences of the climate transition at an aggregate level, it lacks nominal dynamics and, as a calibrated DSGE, remains inherently stylized. Conversely, FR-BDF, by design, offers a more granular representation of the economy, particularly on the nominal side, but does not model energy use on the supply side and abstracts from key features of the low-carbon transition by aggregating capital stock and production sectors into a single market sector. Combining the two models avoids the long process of building a multi-sector version of FR-BDF, with energy-augmented production functions, and re-estimating it.

Together, these models offer a comprehensive view of the transition's economic consequences in France. In a first step, we feed FR-GREEN with a carbon tax designed to approximate the European Commission's Fit-for-55 policy package. While this package includes various fiscal and non-fiscal measures—such as regulations and subsidies—our simplified framework interprets it as a linearly increasing tax on fossil fuel use combined with a subsidy on investment. In a second step, we apply sequences of shocks—carbon tax shocks, the wedge and the share derived from FR-GREEN simulations—in FR-BDF. In these simulations, we assume constant economic policies: on the fiscal side, the government budget balance remains unchanged by fully rebating carbon tax revenues to households and firms, while on the monetary side, the interest rate moves one-to-one with inflation to maintain a constant real interest rate. Additionally, we assume that the carbon tax shock is symmetric across the euro area and that carbon tax policies remain unchanged in the rest of the world.

Our key findings indicate that the Fit-for-55 package would have significant real and nominal effects. By 2030, it would lead to a -1% output loss in France and a peak inflationary impact of 0.5 percentage points relative to a no-policy baseline scenario. These effects primarily result from the shift from polluting to clean technologies, which entails a substantial loss in apparent productivity, in the absence of any favourable assumption regarding technological progress potentially driven by the transition. The direct effect of the tax and the induced productivity decline drive price increases, despite some downward pressure from the recessionary impact of the shocks. In the short run, tax-driven price increases notably affect consumer prices and demand, while medium-run inflationary impact as well as output losses stem mainly from supply-side effects. Importantly, our assumption of a constant real interest rate influences the inflation response; a tighter monetary policy would mitigate inflation at the cost of exacerbating the output loss.

The remainder of the paper is organized as follows. Section 2 provides a non-technical overview of the FR-GREEN model. Section 3 details our simulation methodology using the two-model approach. Section 4 presents our findings, and Section 5 concludes.

2 Bird's-eye view of the FR-GREEN model

We present here a general overview of the key features and the parametrization of the FR-GREEN model (for technical details about the model, see Appendix A). The model is based on a standard DSGE framework with a representative household who owns and invests into durables for his own use and into capital rented to firms, drawing from Henriet et al. (2014). Our framework further includes some non-standard features. First, the household derives utility from holding wealth, the so-called "wealth-in-utility" in the style of Michaillat and Saez (2021). Second, a key novelty compared to the textbook DSGE is the inclusion of two types of energy, clean and dirty, which both households and firms combine with a matching durable or capital good. The clean energy good, intended to represent electricity, is produced domestically using a specific type of capital, e.g. nuclear plants or wind turbines, while the dirty energy good, intended to represent all fossil fuels, is imported. Notice that we assume exogenous technical progress and we therefore make the conservative assumption that transition policies do not lead to favourable effects on innovation.

Our model hence encompasses two types of durables owned by the households, clean and dirty, each type needing to be combined with the corresponding (clean or dirty) type of energy to be used. Similarly, households can invest in three different types of capital, namely clean capital used for production combined with clean energy, dirty capital used for production combined to dirty energy, and clean electricity capital, used to produce clean energy. Similarly, the production side of the economy consists of two sectors, clean and dirty, each of them using only one specific type of energy and capital, with several production layers that aggregate energy, capital and labour into a final good. Labour also consists of two different types imperfectly substitutable and used, respectively, by the clean and the dirty production sector. Importantly, in the version of the model used in this paper, we assume that the firms are monopolistically competitive, but do not face nominal rigidities. Indeed, FR-GREEN will be used for generating wedges applied to long-run targets of FR-BDF, which are free from nominal frictions. Similarly, we assume that the labour packers who sell aggregated labour to firms are monopolistically competitive but set wages flexibly.

The household

The representative household maximizes his intertemporal utility by choosing his labour supply, a consumption bundle, investment into capital and durables, and a stock of bonds that appears directly in the utility function as wealth (see below for details). The consumption bundle is a Constant Elasticity of Substitution (CES) aggregate of the non-durable consumption good and the durable consumption bundle. The durable consumption bundle is in turn a CES aggregate of the clean and dirty durable consumption bundles, which are in turn CES aggregates of the available stock of the clean (resp. dirty) durable good and clean (resp. dirty) energy good. Figure 1 represents this consumption structure.

The household owns all types of capital and durables, which follow standard laws of motion under capital adjustment costs in the style of Hayashi (1982). All types of investment are also subject to irreversibility, meaning that installed capital and durables of one type can not be converted either into nondurable consumption or any other type of investment goods. This

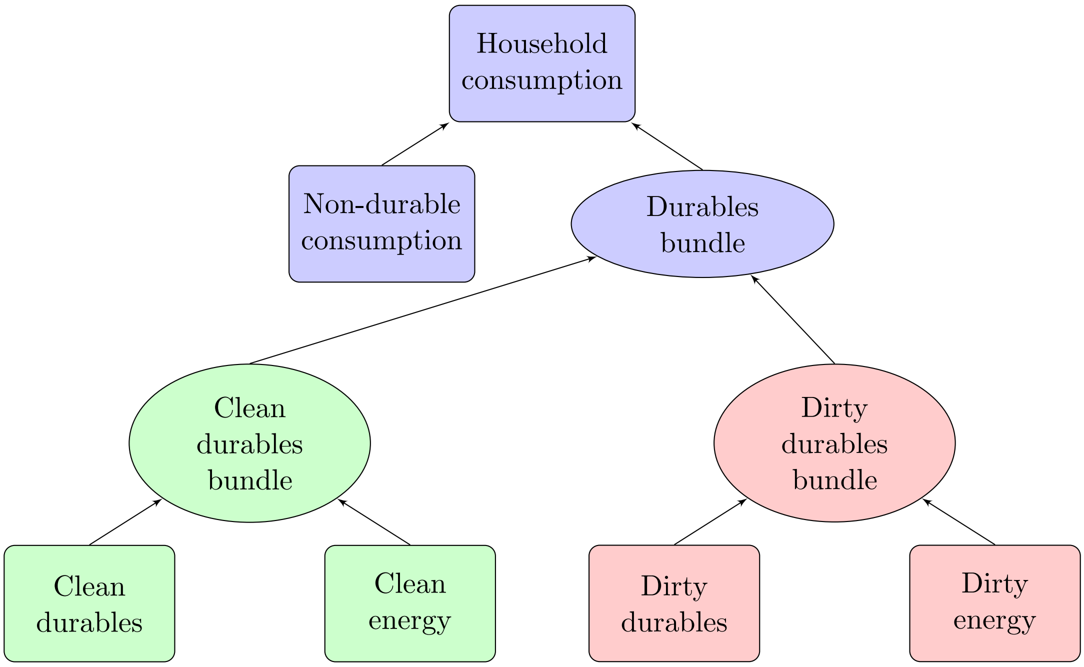


Figure 1: The structure of household consumption in FR-GREEN

assumption is important to account for the difficulties of reallocating capital from dirty to clean sectors along the climate transition.

In the style of Smets and Wouters (2007), the household sells labour to labour packers who operate in a monopolistically competitive market, leading to wages that include a markup. Note that we assume that this wage setting is not subject to any rigidities. Labour packers aggregate the labour into two types, clean and dirty, under imperfect substitutability in the style of Boehm (2020). This aims at capturing reallocation difficulties in the labour market.

The representative household can buy or sell domestic bonds that yield a real interest rate. We assume that the household derives direct utility from these holdings, namely, they have Wealth-in-Utility (WIU). This assumption is consistent with setups considered by Rannenberg (2021) and Michaillat and Saez (2021). As emphasized by Michaillat and Saez (2021), WIU is supported by a broad literature documenting that individuals seek to achieve high social status, and wealth accumulation is a common pathway to attaining it (see for instance Weiss and Fershtman 1998, Heffetz and Frank 2011, Fiske 2010, Anderson et al. 2015, Cheng and Tracy 2013, Ridgeway 2013, Mattan et al. 2017).

The inclusion of WIU in the model has important implications for household decision-making and macroeconomic dynamics. This feature reduces the excess forward-lookingness and consumption smoothing of the standard Euler equation, mitigating the influence of future events on current consumption and savings choices (see Appendix E). As demonstrated by Michaillat and Saez (2021), this adjustment helps resolve the forward guidance puzzle, while Rannenberg (2021) shows that WIU moderates the effects of future income shocks on current consumption. The WIU assumption thus amplifies the focus on short-term outcomes by allowing wealth to directly contribute to current utility. This reduces the incentive for agents to accumulate wealth based solely on future returns or long-term benefits, effectively rationalizing a higher discounting of future periods for a given interest rate. Consequently, WIU dampens the forward-looking nature of expectations in models, aligning predictions more closely with observed short-term decision-making, while still permitting a degree of forward-looking behaviour. In addition to the widespread empirical evidence showing deviations between observed data and the predictions of standard full-information rational expectations models, dampening the emphasis on future outcomes in current decision-making is particularly relevant in the context of the energy transition. This relevance arises from two key factors. First, the lack of prior experience with climate transitions significantly limits agents' ability to form expectations about the long-term consequences of future policy shocks. Second, the credibility of long-term policies is often undermined by political uncertainty, raising doubts about the permanence of these policies and further discouraging forward-looking behaviour.

Production

Figure 2 represents the production structure. It consists of multiple layers of nested CES production functions. The domestic final good producers operate in perfect competition and aggregate intermediate good varieties produced by monopolistically competitive intermediate good producers not subject to nominal rigidities. The production process of the varieties is less standard, with two alternative technologies to produce each variety, either using dirty capital combined with dirty energy and labour, or using clean capital combined with clean energy and labour. Dirty energy is imported from abroad, while clean energy is produced domestically using a specific capital labelled clean electricity capital and a fixed factor called Land. Every step of this variety production takes place in perfect competition.

Exports and trade balance

The home country exports the domestically produced good in exchange for the import of the dirty energy (fossil fuels) under fixed terms of trade (small open economy assumption), in a quantity ensuring balanced trade.

Government policy

The policy instruments set by the government are taxes on the use of fossil fuels by both households and firms. As FR-GREEN does not feature nominal price dynamics, the behaviour of the central bank and the nominal interest rate are left unmodelled.

Calibration

The model calibration combines parameter values derived from French data with elasticity estimates and more standard DSGE parameters drawn from the literature. The CES share parameters, clean electricity production parameters, and wealth-in-utility parameters are calibrated using ratios that reflect structural characteristics of the French economy, such as the fossil fuel expenditure-to-GDP ratio, the clean-to-dirty energy use ratio, the durables-to-output ratio, the capital-to-output ratio, and the electricity capital-to-output ratio. Elasticity parameters, such as substitution elasticities between labour, capital, energy, and durables, are informed by empirical studies to capture realistic dynamics in production and consumption. A detailed

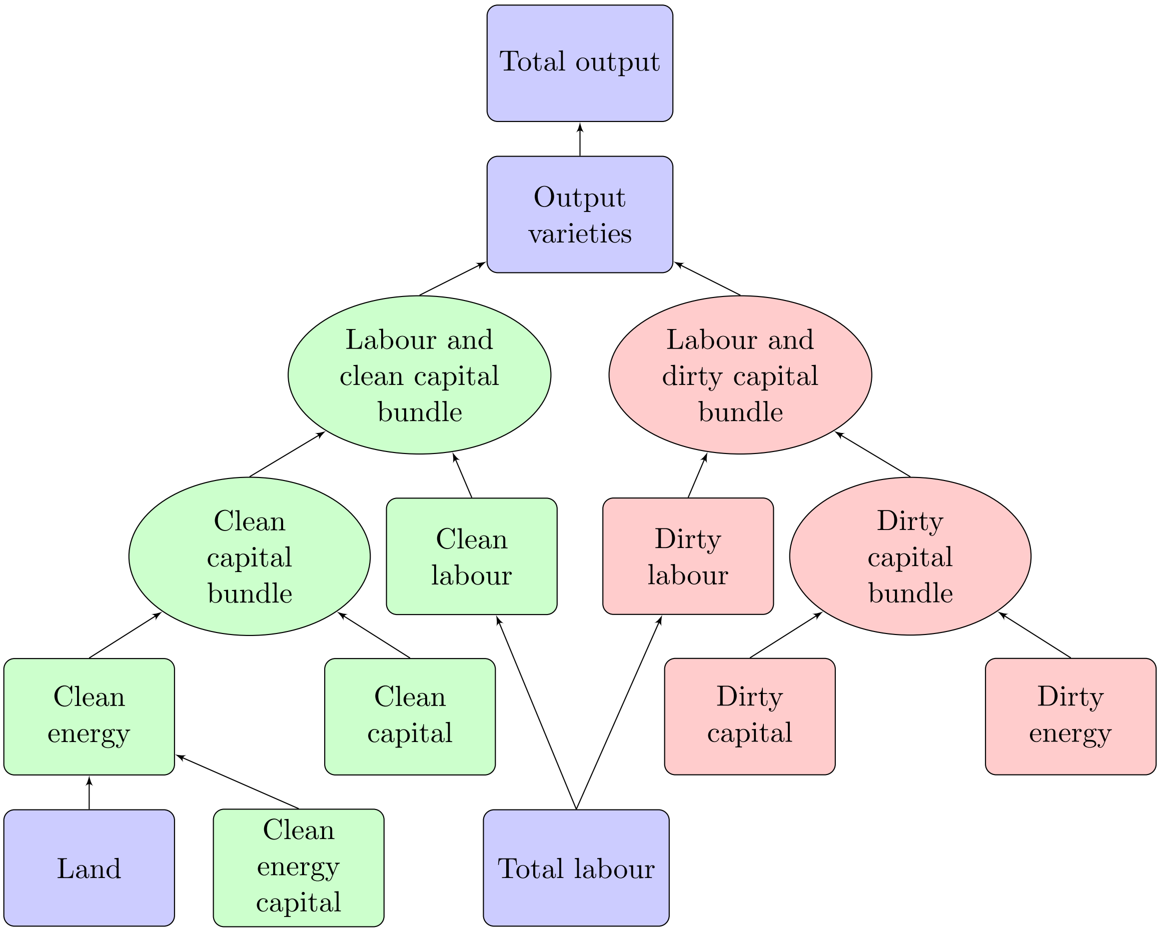


Figure 2: The production structure in FR-GREEN

description of the calibration procedure, including the data sources and empirical references used, is provided in Appendix B.

Model behaviour

Before using FR-GREEN for the permanent carbon tax shock considered in this paper, Appendix C illustrates the behaviour of FR-GREEN in response to standard, persistent but temporary shocks. We consider a temporary 1% increase in the carbon tax, as well as a temporary 1% increase in aggregate production technology and a temporary 1% increase in the household discount factor. As expected, the carbon tax increase is recessionary, triggering a decrease in output and consumption. Dirty capital, dirty durable stocks and dirty labour decrease, while clean ones increase (see Figure 10 in Appendix C). FR-GREEN also exhibits a standard response to a technology shock, with an increase in output, consumption and investment (more so for dirty than clean capital and durables). The increase in energy use is mostly concentrated on dirty energy, as clean energy supply requires clean electricity capital and is therefore less elastic (see Figure 11 in Appendix C). Last, following an increase in the household discount factor, future consumption substitutes for current consumption: in the short run, consumption temporarily decreases while investment increases. In the medium run, the higher levels of capital reached then allow for higher levels of production, which in turn allows for higher consumption. The increase in energy use is again concentrated in dirty energy (see Figure 12 in Appendix C).

3 Combining the FR-BDF and FR-GREEN models

In this section, we present our combined approach based on the joint use of the FR-GREEN and FR-BDF models.

FR-BDF, described in detail in Lemoine et al. (2019), is a semi-structural, large-scale macroeconomic model for France, based on the Polynomial Adjustment Costs (PAC) framework and allowing for several types of expectations, either based on a small Vector Auto-Regressive (VAR) model or model-consistent. This style of modelling is described in Brayton and Tinsley (1996), who discuss the construction of the FRB/US model of the Federal Reserve (Fed). The ECB-BASE model of the European Central Bank (ECB) as presented in Angelini et al. (2019) is also based on this approach.

The PAC framework models the optimizing behaviour of agents via the minimisation of cost functions over lifetime choices for certain variables of interest, such as consumption and investment. These cost functions are assumed to be a weighted average of the square of the m^{th}-order difference of the decision variable and a quadratic deviation of this variable from its so called target, typically determined using a separate equation strongly based on economic theory. One can then determine from the first order condition of this minimisation a dynamic equation which describes the dynamics of the variable with a role for expectations of the target.

The target variables of the PAC framework derive, among other things, from a CES production function with aggregate labour and capital and the associated first-order conditions. Thus, FR-BDF can be thought of as a detailed behavorial nominal demand-side model built around an underlying neo-classical real supply-side core.

Whereas FR-BDF is very detailed in its description of the French economy—e.g. the modelling of household behaviour, the financial sector and foreign trade is very rich—it has not been built to model phenomena related to the energy transition and climate-related questions. More concretely, while energy plays a direct role on the demand side within the consumption of households, the three supply channels of energy transition—as modelled in FR-GREEN—are missing from FR-BDF. First, the production function—primarily used to determine potential output—does not include any direct role for energy use. Second, because of this unmodelled feature, firm costs depend on costs from other production factors (labour and capital) but not on those from energy. Third, as FR-BDF does not distinguish between the clean and dirty sectors, it cannot take into account any composition effects related to the energy transition.

We address these omissions with a framework where the FR-GREEN and FR-BDF models are used jointly to quantify the macroeconomic impact of climate policy. In this dual-model approach, we extract from FR-GREEN sequences of shocks, or wedges, that we apply to FR-BDF. The first shock is a total factor productivity (TFP) wedge. We compute this TFP wedge as the ratio of value added simulated with FR-GREEN with a carbon tax shock, to a counterfactual value added based on the production function of FR-BDF computed with aggregate non-energy factors (aggregate labour and capital of all sectors). This wedge measures two effects arising from the structure of FR-GREEN: the reduction in total energy use leading to lower supply and a change in the structure of the economy—the technological shift from the dirty sector toward the clean sector. Then, in order to account for these negative supply effects, we feed FR-BDF with this wedge as a multiplicative factor to the production function used in the definition of the potential output of the model. We also multiply the target of the value added price of FR-BDF by the inverse TFP wedge, in order to take into account corresponding increases in firm costs.

We also extract from FR-GREEN energy taxes and prices as well as the energy share in consumption, to be used as additional shocks in FR-BDF. First, they play a role for setting shocks on the VAT rate of FR-BDF, which is applied to the household consumption deflator, taking into account the change in fossil energy share over time. Second, the shocks have a direct impact on energy HICP.

Figure 3 presents an overview of the way the two models interact with each other. The key input into FR-GREEN is the path of the carbon tax paid by firms and households, whereas as output we obtain paths for the wedges described above. These wedges together with assumptions with respect to carbon tax revenue allocation and the path of monetary policy (described in subsection 4.2) are used as inputs in FR-BDF to produce an assessment of the macroeconomic impact on France of the transition policy.

We assume that agents in the FR-BDF model are backward-looking and rely on VAR-based expectations. This assumption is better suited to the application of this study than model-consistent expectations under perfect foresight. While the two-step approach—using a forward-looking DSGE framework to compute shocks and then embedding these as wedges in a backward-looking VAR model—introduces potential consistency issues, these are mitigated by the wealth-in-utility (WIU) assumption featured in the DSGE model. As discussed earlier, the WIU specification inherently implies a high discounting of future utility, which aligns the behaviour of agents in the DSGE model more closely with the myopic tendencies typically as-

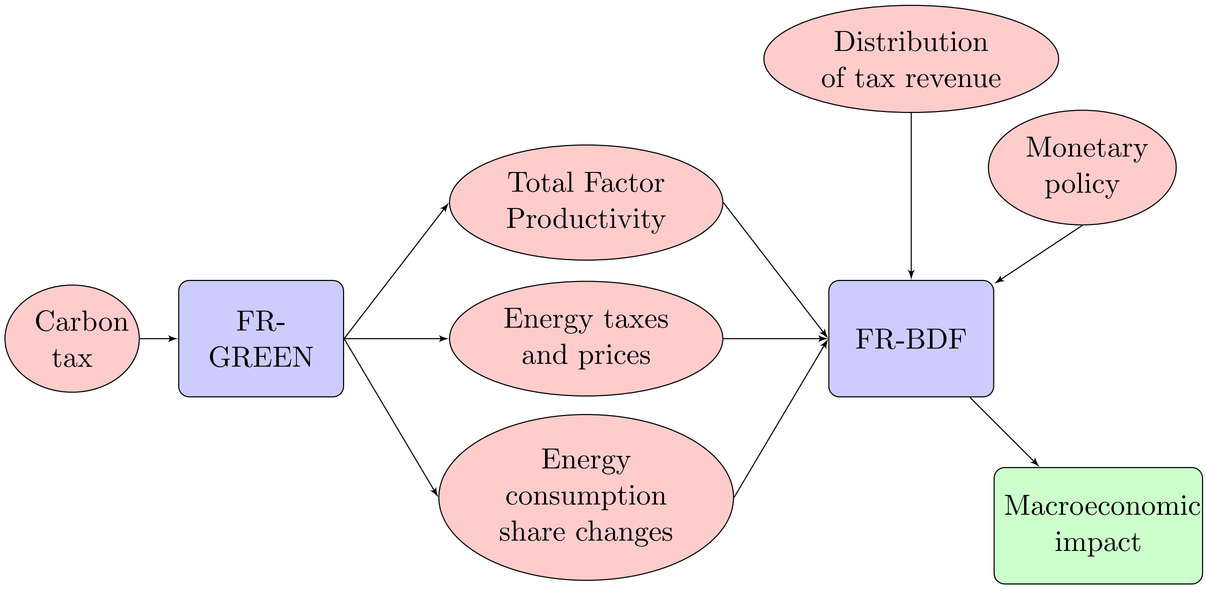


Figure 3: Interaction of FR-GREEN and FR-BDF in producing simulations of the impact of climate policy

sociated with VAR-based expectations. This reduces the forward-looking nature of the DSGE model, smoothing the transition between the two frameworks and enhancing the overall coherence and applicability of the combined approach.

4 Simulation of a Fit-for-55 scenario

Using the modelling approach described above, we simulate a Fit-for-55 scenario. This section describes the implementation of this simulation procedure in detail and provides quantitative results.

4.1 Simulating FR-GREEN

Increasing carbon taxes

Our carbon tax trajectory is inspired by the European Commission's Fit-for-55 agenda, which aims to reduce the Union-wide net and gross carbon emissions by 55% and 50% respectively by 2030 in comparison to 1990. Given that French gross emissions have already decreased by around 25% in 2022 compared to 1990 (HCC, 2023), achieving the 50% target means a further decrease by around 30% compared to their 2022 level. While the Fit-for-55 policy package is very detailed and consists of a broad variety of measures both in the form of explicit tax-like policies (e.g. the changes in the Emissions Trading System (ETS)), regulations (e.g. on land use through "Land-Use, Land Use Change and Forestry", i.e. LULUCF) and subsidies (e.g. the social climate fund), we model this process as a linearly increasing tax on fossil fuels, symmetric on both households and firms.

We assume that at the initial steady state, intended to represent the first quarter of 2024, the tax level is at €90 per $t\text{CO}_2e$ (ton of CO_2 equivalent), which corresponds to the level of the Effective Carbon Rate (ECR) computed by the OECD for France. The level is then assumed to

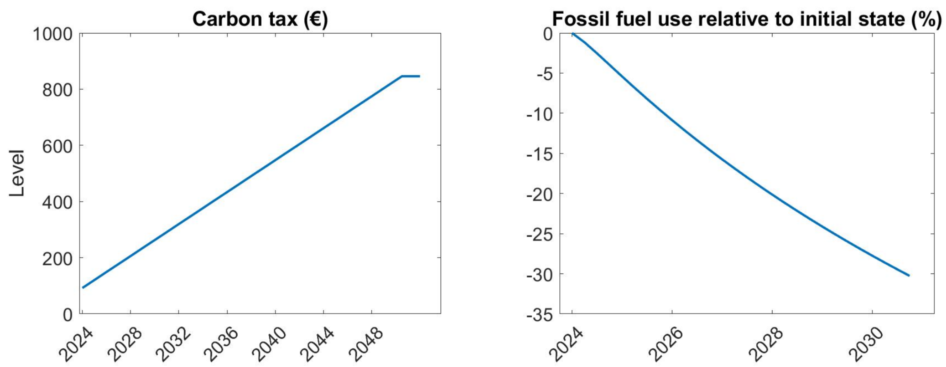


Figure 4: The path of the carbon tax (left panel) and fossil fuel use (right panel) in FR-GREEN

increase with a constant slope calibrated such that, by the end of 2030 fossil fuel use and hence gross emissions will have decreased by 30%. The tax is then assumed to keep increasing at the same pace until 2050 after which it remains constant.

As can be seen in Figure 4, the implied tax levels are roughly €275 per tCO_2e in 2030 and €830 per tCO_2e at the beginning of 2050 (in 2024 euros). We assume that the tax is the same for both firms and households. Furthermore, as FR-GREEN is simulated under perfect foresight, the path of the tax beyond e.g. 2030 or 2050 matters: agents make their choices regarding e.g. investment into capital or durables based on their expectations for the full future path.

Within FR-GREEN we make the additional simplifying assumption that half of the proceeds of the carbon tax is rebated through lump-sum transfers to households and that investment subsidies to firms are adjusted so that the government budget remains balanced. See Appendix Section A.5 for further implementation details.

To put our carbon tax into perspective, other authors have found tax levels in similar ranges to have similar consequences. Examples include the report from the Quinet commission (Quinet et al. (2019)), which notes that a French tax in the range of €175 per tCO_2e to €250 per tCO_2e (in 2018 euros) could achieve the same goal of 30% emission reduction since 2022, and the Network for Greening the Financial System (NGFS), whose Phase V scenarios (NGFS (2024)) indicate that reaching net zero emissions by 2050 would require a carbon tax of \$ 200 per tCO_2e (in 2010 dollars) in 2030 at the global level. They also find that reaching zero net emissions by 2050 would require a carbon tax of roughly \$ 750 per tCO_2e (in 2010 dollars). Using a model similar to FR-GREEN—i.e. a DSGE—Coenen et al. (2024) find that a tax level of €375 (in 2024 euros) per tCO_2e implies a 25% reduction in emissions in the euro area.

The transition in production and consumption from dirty to clean technologies can be seen on Fig. 5. On the durable side, the share of clean durable stock of households increases by almost 20pp. On the capital side, the share of clean capital (including clean energy capital) also increases, but this increase, by around 4pp, is smaller. This contrast between durables and capital stems from the difference between production and consumption structures. The energy-capital bundle is combined with sector-specific labour (clean or dirty). When firms wish to expand clean production, they can adjust not only by reallocating capital but also by shifting labour from the dirty to the clean sector.

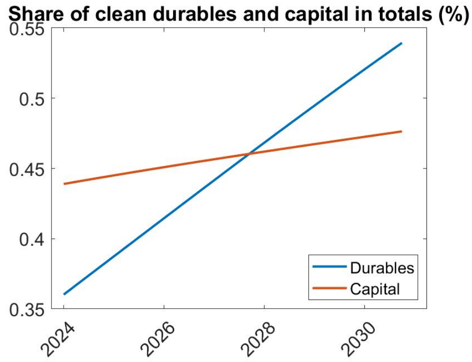


Figure 5: Paths of shares of clean capital stock (including clean energy capital) and clean durables stock within total stocks in FR-GREEN

In these FR-GREEN simulations, we observe a decline in value added of 5% in 2030.[3] This loss results from a combination of supply-side effects, where costly reallocation and energy reduces overall apparent productivity, and demand-side effects, as lower income leads to reduced consumption and investment. While the supply effects are likely to be a reasonable estimate, the demand effects are more uncertain for several reasons. First, FR-GREEN does not account for foreign trade adjustments. Second, forward-looking agents perfectly anticipate large future losses related to the increase of the tax in the longer run (until 2050), while the empirical literature generally finds a low degree of forward-lookingness of expectations. Third, the model is calibrated and, hence, should have a weaker fit to short-term dynamics of French data than estimated models. FR-BDF provides a more accurate description of short-term dynamics, and is able to incorporate a high energy price in consumer prices, which is why we rely on it, combined with wedges from FR-GREEN in order to take into account supply and composition effects, for short- and medium-run responses.

Computation of wedges in FR-GREEN

The TFP wedge (presented in Figure 6) is computed as the ratio

$$\zeta_{TFP} = Q_{FR-GREEN}/Q_{FR-BDF} \tag{1}$$

of simulated value added from FR-GREEN, $Q_{FR-GREEN}$, relative to simulated value added Q_{FR-BDF} computed using the FR-BDF long-run production function. On the one hand, the value added from FR-GREEN is computed from production Y and intermediate consumption of fossil fuel by firms O_f with the formula $Q_{FR-GREEN} = Y - P_o O_f / P_Y$, which also uses the relative price of oil (excluding tax) compared to output price P_o/P_Y.[4] On the other hand, we compute value added based on the FR-BDF production function with the following formula:

$$Q_{FR-BDF} = \gamma \left[\alpha K^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(L\right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \tag{2}$$

[3]For a more detailed analysis of macroeconomic responses to the carbon tax shock in the FR-GREEN model, see Appendix D.

[4]As this relative price does not vary over time (see Appendix A.3), value added is automatically measured at constant prices.

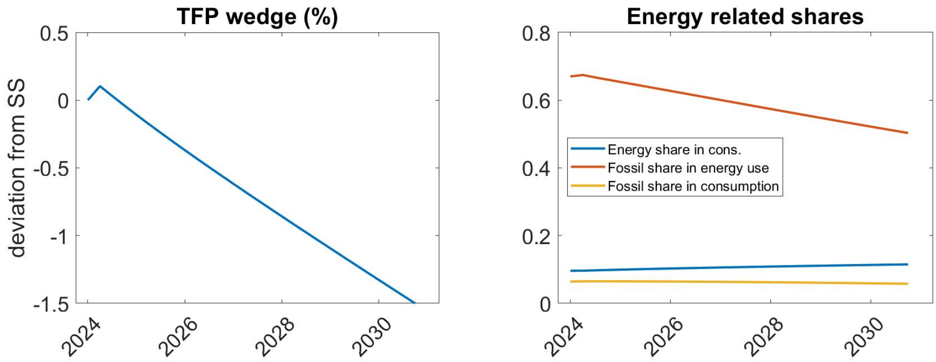


Figure 6: The FR-GREEN TFP wedge (left panel) and shares related to energy use (right panel)

where K and L are the aggregate capital and long-run labour stocks of the different sectors in FR-GREEN. This production function has a CES functional form with capital and labour as factors of production but no role for energy whatever its type. This implies that the wedge measures the loss of output due to the change in energy use and the composition effects related to capital and labour usage in both sectors, all of which are included in the computation of value added in FR-GREEN but not in FR-BDF. More concretely, the aggregation of labour and capital implies that their distinct technological roles and capabilities are omitted from the FR-BDF simulation, together with the fall in energy use.

There are two prices in FR-BDF which are affected by the carbon tax shocks: the energy component of the Harmonised Index of Consumption Prices (HICP) and the deflator of household consumption (which is not disaggregated into energy and non-energy components). We extract from FR-GREEN two tax shocks that we apply to these prices in FR-BDF. First, we compute the growth rate in the end-user price of oil (tax included) in FR-GREEN and weight it by the share of fossil fuels in total energy use in order to compute the shock on energy HICP. Second, we weight this energy price shock by the share of total energy use in total household expenditure to obtain the shock on the consumption deflator. The shares applied in this computation are presented in Figure 6.

Finally, we compute from FR-GREEN the changes in the shares of nominal energy expenditures in total consumption to obtain a time-varying weight to be used in the computation of total HICP inflation from energy and non-energy HICP components.

As can be seen from the left panel of Figure 6, the carbon taxes lead to a 1.5% loss in apparent TFP at the end of 2030. There are two main channels for this effect. First, the taxes lead to a reduction in total energy use, which implies a fall in supplied output for given levels of labour and capital inputs. Second, there is a technological transition from polluting to clean technology, i.e. a change in the composition of inputs to a bundle that produces less output. Notice that our assessment of this loss in apparent TFP relies on the conservative assumption that transition policies do not lead to favourable effects on innovation. Furthermore, while Figure 6 also indicates a significant reduction in the share of fossil fuels in total energy use from almost 70% to around 50%, the share of fossil fuels in the total expenditure of households remains essentially constant due to the increase in their price, which largely offsets the drop in their volume.

4.2 Simulating FR-BDF

Implementation of wedges and shocks in FR-BDF

The TFP wedge ζ_{TFP} affects FR-BDF directly in two ways. First, a direct effect affects potential output of FR-BDF through the CES production function:

$$Q^* = \zeta_{TFP}\gamma \left[\alpha K^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\left(EL^*\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{3}$$

where K and L^* are the capital stock and the potential labour of FR-BDF. As shown in its formula, the TFP wedge is applied as a multiplicative shock on the production function.

Second, an additional effect is transmitted through the factor price frontier, itself derived from the production function. As detailed in Lemoine et al. (2019), the desired target of the value added price P^*_Q follows:

$$P^*_{Q,t} = \frac{\mu}{\zeta_{TFP}\gamma}(1-\alpha)^{\frac{\sigma}{1-\sigma}}\left[1-\alpha^{\sigma}\left(\frac{Q'_K}{\gamma}\right)^{1-\sigma}\right]\tilde{W} \tag{4}$$

where Q'_K is the return on capital and $\tilde{W}$ is the efficient cost of labour. As shown in its formula, the inverse of the TFP wedge is applied as a multiplicative shock on the price frontier. The effects of this TFP shock, which is applied in these two equations, will later on be jointly referred to as "supply effects" given that the shock influences the model through the production function and production costs.

The direct demand effects of the carbon tax on the HICP are modeled by relating the apparent rate for the Value Added Tax (VAT) appearing in the equation determining the level of the energy HICP to the fossil fuel price from FR-GREEN. The apparent rates for other components of the HICP are kept at their baseline values. This modified energy HICP is then aggregated with other HICP components to obtain total HICP, using time-varying shares from FR-GREEN. Similarly, the apparent rate used to determine the VAT paid by households through a tax rate applied to the deflator of their consumption (and collected by the government as revenue) is adjusted with the fossil fuel price of FR-GREEN, as explained above. In what follows we call these effects "non-supply effects".

Additional changes to FR-BDF

We further assume that half of the carbon tax receipts are redistributed to households as transfers and that investment subsidies to firms are adjusted so that the government budget remains balanced. Investment subsidies are modeled as a decrease in the investment price paid by firms. To implement these redistribution assumptions, we relate the amount of household transfers and of firm subsidies to VAT receipts. Thanks to this, when the shock on the VAT rate endogenously generates some fiscal receipts, these receipts are also endogenously allocated to households and firms.

As FR-BDF is a model for the French economy, with no explicit modelling of the rest of the euro area, in its baseline version monetary policy is exogenous.[5] In these simulations, we modify the policy rule for the nominal interest rate so that it keeps the real interest rate constant, i.e.

[5] See Aldama et al. (2022) for an extension of FR-BDF that accounts for these questions.

it reacts one-to-one to French inflation. This means that we implicitly assume that the effect of the climate policies on consumer prices is similar across the euro area. Furthermore, consistently with this last point, we also endogenize the export prices of other euro area member states by assuming that they behave as the price of French exports. Similarly, we assume foreign demand from other EA countries to behave as French imports. These last assumptions imply that, for a symmetric shock in the whole euro area and with a symmetric transmission, the French economy would not lose competitiveness with respect to its euro area partners.

4.3 Quantitative results

4.3.1 Headline variables and the role of supply effects

We present here the main results for headline variables, namely output and inflation, in our simulation exercise with FR-BDF. We also describe the relative role of supply and non-supply effects. To do so, we present and analyse three different scenarios that allow us to disentangle and highlight specific channels of the model:

1. A scenario with the full set of shocks
2. A scenario with only the non-supply component of the shocks
3. A scenario with only the supply component of the shocks

Figure 7 presents an overview of our key results in the form of dynamics of output and inflation in these three scenarios in deviation from the shock-free baseline scenario. First, in the medium run, the effects of non-supply shocks on output (and more broadly on the real economy, as will be seen later) are relatively modest compared to the effects of the supply shocks, which by themselves lead to -0.9% out of a total loss of output of -1% in 2030. Second, the non-supply shocks have a sharp but declining impact on inflation. The sharp response is due to the fact that non-supply shocks affect the relevant price indices directly and without any lags. This response is then progressively reduced by the decreasing share of fossil fuel in household expenditures as well as the negative impact of the fall of output on inflation. Third, the effect of supply shocks on inflation materializes much more slowly, but is also more persistent. This is because the supply shocks affect firm price setting through the factor price frontier. Furthermore, such moves in the price frontier affect consumer prices only gradually due to the price stickiness in FR-BDF.

To reiterate earlier points, our key findings in our main scenario with the full set of shocks are that these carbon taxes are notably inflationary, leading to a peak effect of 0.5pp in 2027, and cause a significant output loss of -1% in 2030 compared to the no-policy baseline scenario. In the long run the effects are primarily due to the supply shocks. The rest of this section will proceed by first presenting and analyzing the outcomes of the main scenario with the full mix of shocks, and then study the two decompositions to explain in further detail the main results and the channels at play.

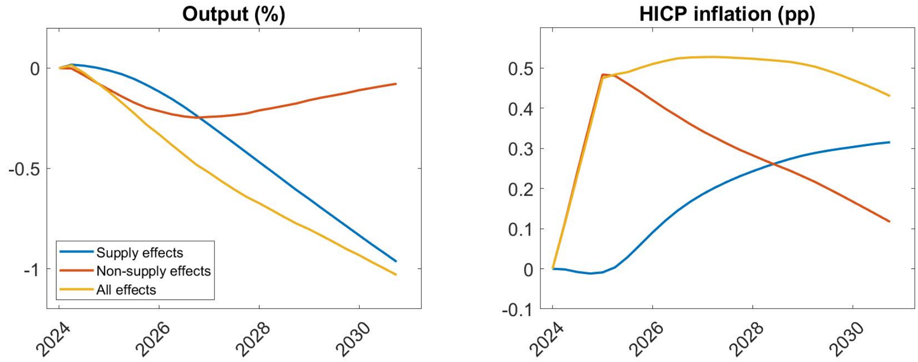


Figure 7: Simulated output level and inflation in a combined approach based on FR-BDF and FR-GREEN following carbon tax shocks, under constant fiscal and monetary policies

4.3.2 Transmission channels of the full cocktail of shocks associated with the carbon tax

In order to have a more detailed analysis of the transmission of carbon tax shocks, Figure 9 presents the responses of several key nominal and real variables in our main scenario 1. Similar detailed results are presented for the two other scenarios 2 and 3 in Appendix F. In broad terms, Figure 9 illustrates the macroeconomic costs of the carbon taxes on the nominal economy[6], in the form of increases in most prices and a deterioration of price competitiveness, and on the real economy in the form of falling consumption, investment and employment.

On the nominal side, the rise of production costs generates an increase in the deflator of value added by roughly 1.5% in 2030Q4. The deflator of household consumption shows a stronger increase (by around 4% in 2030Q4), because it is pushed upward both by this cost channel and by the direct effect of the tax on final prices. The rise in production costs also pushes export prices upward, leading to a deterioration of price competitiveness, as import prices increase less due to extra-EA exporters not being subject to the carbon tax shock. The investment price of households increases less than the price of value added. Because the investment good comprises domestic and foreign production, its price moves much less than that of value added. The investment price of firms is even decreasing, because of the investment subsidy rebated to firms. Finally, because of the recessionary effect of the shocks detailed below, demand falls, putting some downward pressure on prices and attenuating their increase.

On the real side, due to the only partial wage indexation, the real wage is decreasing. Total real household income also decreases, but less so, due to the full indexation of some transfers like pensions and to the part of carbon tax receipts rebated to households through transfers. Consequently, the shocks primarily affect the consumption of households, as well as their investment, because of this fall in real income, even if households partly smooth consumption through a decrease in their saving rate. The carbon tax increase also favors net exports by pushing imports down — due to the drop in internal demand — more than exports, which fall because of the deterioration of price competitiveness. The fall in aggregate demand generated by household spending and net exports also implies a decrease in business investment and a rise of unemployment (due to the lack of labour demand). This rise in unemployment finally

[6]Such costs are motivated by the unmodelled benefits of reducing emissions related to fossil fuel consumption.

amplifies the drop in real income of households and in aggregate demand.

On the fiscal side, the carbon tax shock delivers tax receipts amounting to roughly 1.5% of GDP in 2030. In our simulation setup, by definition, half of these receipts are allocated to transfers to households. In order to ensure ex post a balanced budget, firm subsidies are also increased by a similar amount. As the rise in the nominal short-term interest, equal to the rise in inflation, has a limited effect on the nominal long-term interest rate under backward-looking expectations, the response of interest payments is muted. Due to price indexation, other components of Government expenditure, which correspond to spending such as intermediate consumption, increase by around 0.6% of GDP. This extra spending is almost entirely financed by a similar effect on the tax side: revenues other than those from the carbon tax, such as the personal income tax or social contributions, have a similar increase due to the partial indexation of wages on prices.

4.3.3 Alternative monetary policy approaches

In our earlier analysis we focused on the case where the central bank sets the nominal interest rate such as to keep the real interest rate constant by reacting one-to-one to inflation. In doing so, we attempted to model a situation where monetary policy is as stable as possible. In this section, we consider two alternative cases embodying more active stances: a policy that follows a Taylor rule and a policy calibrated exogenously such as to bring inflation back to target in the medium term[7].

In the first case we assume that instead of the policy rule set out in Lemoine et al. (2019) the policy rate r_t follows a simple rule with conventional coefficients defined as

$$r_t = 1.5\pi_{t-1} + \frac{0.5}{4}\hat{y}_{t-1} \tag{5}$$

where π_t and $\hat{y}_t$ refer to French headline inflation and the French output gap, respectively, i.e. we retain our earlier assumption of the euro area having the same response to the climate policy shocks as France. Notice that we divide the coefficient of the response to the output gap by four, as our model variables are expressed in quarterly terms for the nominal interest rate and inflation[8], not annualized or measured year-on-year unlike in the original definition of the rule as set out in Taylor (1993).

We also retain the assumption of similar macroeconomic dynamics in France and the rest of the euro area in our second alternative exercise. In this case we also assume—as in our baseline experiment—that the policy rate reacts one-to-one to French headline inflation with no weight on the output gap. However, in this experiment the short-term interest rate is also subject to an initial exogenous shock of 200bp, calibrated such that inflation returns to target in the medium term. The shock materializes at the start of the simulation and persists until the end. Note that our simulations of FR-BDF are fully backward-looking and hence the persistence of the shock after the considered time sample has no impact on the results.

[7] As we use a version of FR-GREEN with flexible prices and wages, its simulated wedges are insensitive to monetary policy assumptions and we do not need to change anything in FR-GREEN for these alternative monetary policy experiments.

[8] In contrast, in all graphs of the paper, we plot inflation and interest rates in annualized terms for the ease of the reader.

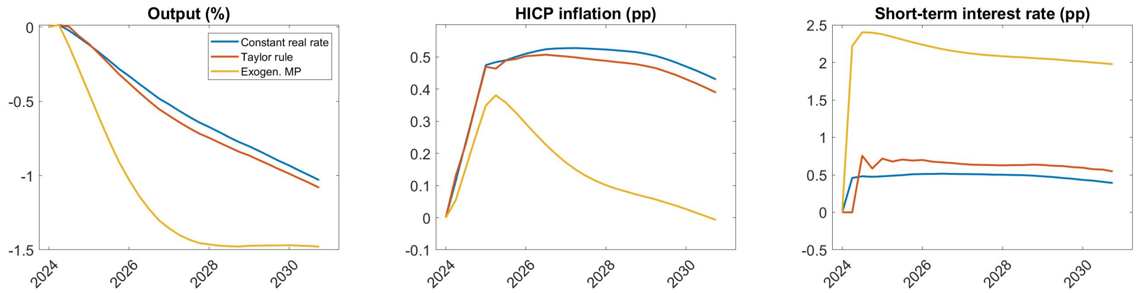


Figure 8: Simulated output level and inflation in a combined approach based on FR-BDF and FR-GREEN following carbon tax shocks, under different monetary policy approaches

Figure 8 presents a comparison of output and inflation between the baseline and these alternative scenarios together with a plot of the short rate. As can be seen, the outcomes under a Taylor rule are relatively close to the baseline—as the response of the short rate is stronger, the fall in output is also stronger, while the increase in inflation is weaker. Furthermore, the plots demonstrate the output-inflation tradeoff. In particular, in the second alternative case the instantaneous 200bp increase in the interest rate is enough to stabilize inflation, but at a significant output cost, as this policy leads to an additional fall of output of roughly 0.5pp in 2030. An implication of this simulation is that the neutral interest rate—the rate that keeps inflation at target—increases by around 200bp during the climate transition.

5 Conclusion

This paper presents an analysis of the macroeconomic impact of climate change policies on France using a two-model approach, based on the new Banque de France DSGE, FR-GREEN, which is applied as a source of wedges and shocks for the Banque de France semi-structural model, FR-BDF. First, our results show significant short-run effects on inflation arising directly from taxes imposed on households, i.e. ignoring any structural effects relating to e.g. supply. Second, we also find that most of the total medium-run impact on output and inflation is due to the supply effects extracted from FR-GREEN, i.e. structural change, particularly in production, induced by the carbon tax. These supply effects come in particular from a loss of apparent productivity generated by the technological adjustment, triggered by the transition from brown to green technologies, in the absence of technological progress potentially driven by the transition.

In further research, we envisage to deal with four additional issues. First, we would like to explore the sensitivity of results to alternative assumptions with respect to expectations. We could in particular study the possibility of having hybrid expectations, i.e. respectively forward- and backward-looking expectations for financial and non-financial agents, instead of assuming that all agents are backward-looking. Second, we could refine the modelling of the euro area, in order to have a refined analysis of expectations with respect to euro area monetary policy. Third, we could explore alternative fiscal policies, notably the sensitivity of the results to different usages of tax receipts. Fourth, we could enrich FR-GREEN in several dimensions, like incorporating hand-to-mouth agents for redistribution purposes and enriching foreign trade

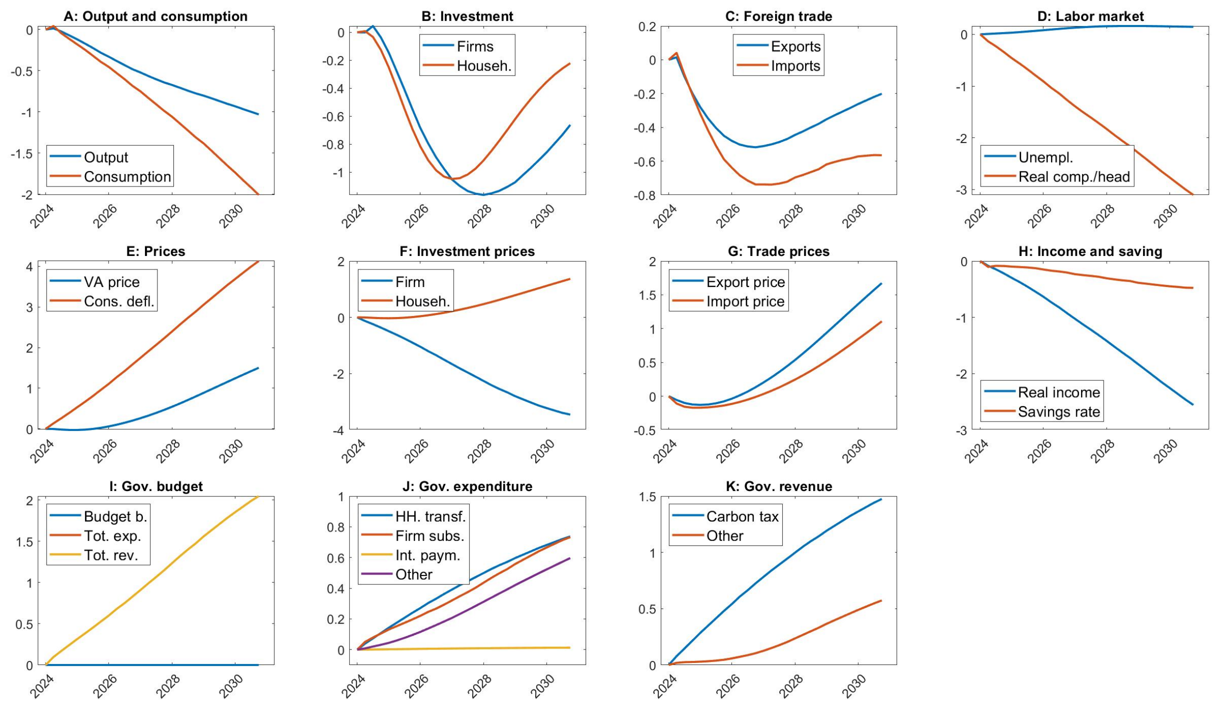


Figure 9: The effects of the full set of carbon tax shocks on the French economy, under constant fiscal and monetary policies

Note: "Real comp./head" in plot D refers to total real compensation per employee. Unemployment and saving rate are measured as absolute difference from baseline, in percentages of the labour force and disposable income, respectively. Variables in plots I, J and K are in absolute difference from baseline and relative to baseline nominal GDP. All other variables are in percentage deviation from baseline.

for taking into account exchange rate dynamics.

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A The FR-GREEN model

A.1 The household

The consumption structure

The structure of the household consumption bundle is described in equations (6) to (9)

$$C_t = \left(\chi^{\frac{1}{\omega}} N_t^{\frac{\omega-1}{\omega}} + (1-\chi)^{\frac{1}{\omega}} Z_{h,t}^{\frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \tag{6}$$

$$Z_{h,t} = \left(\gamma_{zh}^{\frac{1}{g}} Z_{ch,t}^{\frac{g-1}{g}} + (1-\gamma_{zh})^{\frac{1}{g}} Z_{dh,t}^{\frac{g-1}{g}} \right)^{\frac{g}{g-1}} \tag{7}$$

$$Z_{ch,t} = \left(\nu_c^{\frac{1}{\xi}} D_{c,t-1}^{\frac{\xi-1}{\xi}} + (1-\nu_c)^{\frac{1}{\xi}} E_{ch,t}^{\frac{\xi-1}{\xi}} \right)^{\frac{\xi}{\xi-1}} \tag{8}$$

$$Z_{dh,t} = \left(\nu_d^{\frac{1}{\xi}} D_{d,t-1}^{\frac{\xi-1}{\xi}} + (1-\nu_d)^{\frac{1}{\xi}} O_{h,t}^{\frac{\xi-1}{\xi}} \right)^{\frac{\xi}{\xi-1}} \tag{9}$$

where C_t denotes the consumption bundle, N_t the non-durable consumption, $Z_{h,t}$ the durable consumption bundle, $Z_{ch,t}$ the clean durable consumption bundle, $Z_{dh,t}$ the dirty durable consumption bundle, $D_{c,t-1}$ the available stock of the clean durable good, $D_{d,t-1}$ the available stock of the dirty durable good, $E_{ch,t}$ the clean energy and $O_{h,t}$ the dirty energy.

Equations (10) to (13) define the prices of the corresponding bundles.

$$p_{C,t} = \left(\chi p_{Y,t}^{1-\omega} + (1-\chi) p_{Zh,t}^{1-\omega} \right)^{\frac{1}{1-\omega}} \tag{10}$$

$$p_{Zh,t} = \left(\gamma_{Zh} p_{Zch,t}^{1-g} + (1-\gamma_{Zh}) p_{Zdh,t}^{1-g} \right)^{\frac{1}{1-g}} \tag{11}$$

$$p_{Zch,t} = \left(\nu_c p_{cD,t}^{1-\xi} + (1-\nu_c) p_{e,t}^{1-\xi} \right)^{\frac{1}{1-\xi}} \tag{12}$$

$$p_{Zdh,t} = \left(\nu_d p_{dD,t}^{1-\xi} + (1-\nu_c)(p_{o,t} + \tau_{oh,t})^{1-\xi} \right)^{\frac{1}{1-\xi}} \tag{13}$$

The numeraire is defined as the price of the consumption basket, including the price of durables:

$$1 = \frac{p_{Y,t}(J_{d,t} + J_{c,t} + N_t) + (p_{o,t} + \tau_{oh,t})O_{h,t} + P_{e,t}E_{ch,t}}{(J_{d,t} + J_{c,t} + N_t) + O_{h,t} + E_{ch,t}} \tag{14}$$

Laws of motion for durables and capital

The accumulation process for clean (resp. dirty) durables is :

$$D_{y,t} = (1-\delta_D) D_{y,t-1} + J_{y,t}, \quad \forall y \in \{c, d\} \tag{15}$$

with $J_{y,t}$ the investment in durable goods of type y at period t and δ_D the rate of depreciation of durables.

Similarly the law of motion of the three types of capital is:

$$K_{y,t} = (1-\delta_K) K_{y,t-1} + I_{y,t}, \quad \forall y \in \{c, d, cE\} \tag{16}$$

where $I_{y,t}$ is the investment in capital goods of type y at period t and δ_K the rate of depreciation of capital.

The household faces adjustment costs for each type of durables and capital, specified in terms of capital as:

$$AC_{t,xy} = \frac{\kappa_x}{2}\left(\frac{X_{y,t}}{X_{y,t-1}} - 1\right)^2 X_{y,t-1} \quad \forall x \in \{h, f\}, \forall y \in \{c, d, cE\}, \forall X \in \{K, D\}$$

The household budget constraint

The numeraire is the price of the consumption bundle P_t. the budget constraint expressed in real terms at period t is then:

$$\begin{aligned}
&p_{Y,t}N_t + p_{Y,t}J_{c,t} + p_{Y,t}J_{d,t} + p_{Y,t}\left(1-\tau_{I,t}\right)I_{d,t} + p_{Y,t}\left(1-\tau_{I,t}\right)I_{c,t} + p_{Y,t}\left(1-\tau_{I,t}\right)I_{cE,t}\\
&\quad + (p_{o,t} + \tau_{oh,t})O_{h,t} + p_e E_{ch,t} + b_t + p_{Y,t}(AC_{hd,t} + AC_{hc,t} + AC_{fd,t} + AC_{fc,t} + AC_{fcE,t}) \quad (17)\\
&= w_t L_t + p_{kd,t}K_{d,t-1} + p_{kc,t}K_{c,t-1} + p_{kcE,t}K_{cE,t-1} + \Gamma_t + T_t + r_{t-1}b_{t-1}
\end{aligned}$$

where b_t denotes domestic real bond holdings and variables in lower case are expressed in real terms, r_t is the real interest rate earned on domestic bonds from period t to $t+1$, w_t the real wage, $p_{o,t}$ is the real price of oil, $p_{kx,t}$ the real user cost of capital of type x, $AC_{xy,t}$ is the real adjustment cost for dirty $(y = d)$ or clean $(y = c)$ capital $(x = f)$ or durables $(x = h)$. $\tau_{oh,t}$ is a real excise tax on dirty energy consumption by households. Households revenues include labour income, capital income, firms' real profits Γ_t and real lump-sum transfers from the government T_t.

The household's utility is specified as a CRRA function and includes external habits in consumption and wealth in utility as in equation (18).

$$U(C_t, L_t, b_t) = \frac{{C_t - h\bar{C}_{t-1}}^{1-\psi}}{1-\psi} - \phi_w \frac{L_t^{1+\nu_L}}{1+\nu_L} + \gamma_b \frac{{a_t}^{1-\eta_b}}{1-\eta_b}$$

where a_t is the total real wealth accumulated by the households, including bonds b_t but also capital and durable stocks.

Household program and first-order conditions

The program of the household can be written as follows:

$$\max_{C_t, N_t, Z_{h,t}, Z_{ch,t}, Z_{dh,t}, D_{c,t}, D_{d,t}, K_{c,t}, K_{d,t}, K_{cE,t}, b_t} \sum_{t=1}^{\infty} \beta^t U(C_t, L_t, b_t) \quad (18)$$

subject to equations (6) to (17) and the transversality condition and $\lim_{t \to +\infty} \frac{b_t}{\Pi_{s=1}^t r_s} = 0$. Let Λ_t be the Lagrange multiplier associated with the budget constraint at date t. Equations (19) to (26) are the first order conditions derived from the household program.

$$\Lambda_t = \gamma_b a_t^{-\eta_b} + \beta E\left(r_t \Lambda_{t+1}\right) \tag{19}$$

$$w_t = \frac{\eta_w}{\eta_w - 1} \frac{\phi_w L_t^{\nu_L}}{\Lambda_t} \tag{20}$$

$$\frac{\partial U(C_t)}{\partial D_{x,t-1}} = \Lambda_t p_{xD,t} \quad \forall x \in \{c, d\} \tag{21}$$

$$p_{xD,t+1} = r_t p_{Y,t} \left[(1 - \tau_{I,t}) + \frac{\partial AC_{hx,t}}{\partial D_{x,t}}\right] - p_{Y,t+1}\left(1 - \tau_{I,t+1}\right)\left(1 - \delta_D\right) + p_{Y,t+1} \frac{\partial AC_{hx,t+1}}{\partial D_{x,t}} \quad \forall x \in \{c, d\} \tag{22}$$

$$p_{kx,t+1} = r_t p_{Y,t} \left[1 + \frac{\partial AC_{fx,t}}{\partial K_{x,t}}\right] - p_{Y,t+1}(1 - \delta_k) + p_{Y,t+1} \frac{\partial AC_{fx,t+1}}{\partial K_{x,t}} \quad \forall x \in \{c, d, cE\} \tag{23}$$

$$\Lambda_t p_{Y,t} = (C_t - h\bar{C}_{t-1})^{-\psi} \chi^{1/\omega} \left(\frac{C_t}{N_t}\right)^{1/\omega} \tag{24}$$

$$\Lambda_t(p_{o,t} + \tau_{oh,t}) = (C_t - h\bar{C}_{t-1})^{-\psi}(1 - \chi)^{\frac{1}{\omega}}(1 - \gamma_{zh})^{\frac{1}{g}}(1 - \nu_d)^{\frac{1}{\xi}} \left(\frac{C_t}{Z_{h,t}}\right)^{\frac{1}{\omega}} \left(\frac{Z_{h,t}}{Z_{dh,t}}\right)^{\frac{1}{g}} \left(\frac{Z_{dh,t}}{O_{h,t}}\right)^{\frac{1}{\xi}} \tag{25}$$

$$\Lambda_t p_{e,t} = (C_t - h\bar{C}_{t-1})^{-\psi}(1 - \chi)^{\frac{1}{\omega}} \gamma_{zh}^{\frac{1}{g}}(1 - \nu_c)^{\frac{1}{\xi}} \left(\frac{C_t}{Z_{h,t}}\right)^{\frac{1}{\omega}} \left(\frac{Z_{h,t}}{Z_{ch,t}}\right)^{\frac{1}{g}} \left(\frac{Z_{ch,t}}{E_{ch,t}}\right)^{\frac{1}{\xi}} \tag{26}$$

where:

$$\frac{\partial U(C_t)}{\partial D_{d,t-1}} = (C_t - h\bar{C}_{t-1})^{-\psi}(1 - \chi)^{\frac{1}{\omega}}(1 - \gamma_{zh})^{\frac{1}{g}} \nu_d^{\frac{1}{\xi}} \left(\frac{C_t}{Z_{h,t}}\right)^{1/\omega} \left(\frac{Z_{h,t}}{Z_{dh,t}}\right)^{1/g} \left(\frac{Z_{dh,t}}{D_{d,t-1}}\right)^{1/\xi} \tag{27}$$

$$\frac{\partial U(C_t)}{\partial D_{c,t-1}} = (C_t - h\bar{C}_{t-1})^{-\psi}(1 - \chi)^{\frac{1}{\omega}} \gamma_{zh}^{\frac{1}{g}} \nu_c^{\frac{1}{\xi}} \left(\frac{C_t}{Z_{h,t}}\right)^{1/\omega} \left(\frac{Z_{h,t}}{Z_{ch,t}}\right)^{1/g} \left(\frac{Z_{ch,t}}{D_{c,t-1}}\right)^{1/\xi} \tag{28}$$

Equations (19) is the Euler equation with respect to domestic bonds. Equation (20) is the first order condition with respect to labour supply. The first order conditions with respect to clean and dirty durables are defined in equation (21), while equations (22) and (23) define the price of durables and capital, which can also be interpreted as their user cost. Finally, equations (24), (25) and (26) are the first order conditions with respect to non-durables, dirty energy and clean energy.

A.2 Production

Final good producer—perfect competition

The final good Y is a standard CES aggregate of varieties Y_i, with elasticity of substitution $\eta < 1$. We assume a continuum of fully competitive final good producers who purchase their inputs from monopolistic intermediate goods producers. The final good producer's profit maximisation is:

$$\max_{Y_{i,t}} p_{Y,t} Y_t - \int_0^1 p_{i,t} Y_{i,t} di$$
$$\text{s.t. } Y_t = \left(\int_0^1 Y_{i,t}^{\frac{\eta-1}{\eta}} di \right)^{\frac{\eta}{\eta-1}}$$

By solving this maximisation program, we can derive the relative demand functions and the price index of aggregate output, as described in equations (29) and (30):

$$Y_{i,t} = Y_t \left(\frac{p_{i,t}}{p_{Y,t}} \right)^{-\eta} \tag{29}$$

$$p_{Y,t} = \left(\int_0^1 p_{i,t}^{1-\eta} di \right)^{\frac{1}{1-\eta}} \tag{30}$$

Variety i producer

The variety producers aggregate intermediate goods, capital and labour via a series of nested CES functions described in equations (31) to (35).

$$Y_{it} = \left(\mu^{\frac{1}{\epsilon}} Z_{lcf,it}^{\frac{\epsilon-1}{\epsilon}} + (1-\mu)^{\frac{1}{\epsilon}} Z_{ldf,it}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{(\epsilon-1)}} \tag{31}$$

$$Z_{ldf,it} = \left(\gamma_{ld}^{\frac{1}{\sigma_{ld}}} Z_{df,it}^{\frac{\sigma_{ld}-1}{\sigma_{ld}}} + (1-\gamma_{ld})^{\frac{1}{\sigma_{ld}}} L_{d,it}^{\frac{\sigma_{ld}-1}{\sigma_{ld}}} \right)^{\frac{\sigma_{ld}}{\sigma_{ld}-1}} \tag{32}$$

$$Z_{df,it} = \left(\gamma_{d}^{\frac{1}{\sigma_{d}}} K_{d,it-1}^{\frac{\sigma_{d}-1}{\sigma_{d}}} + (1-\gamma_{d})^{\frac{1}{\sigma_{d}}} O_{f,it}^{\frac{\sigma_{d}-1}{\sigma_{d}}} \right)^{\frac{\sigma_{d}}{\sigma_{d}-1}} \tag{33}$$

$$Z_{lcf,it} = \left(\gamma_{lc}^{\frac{1}{\sigma_{ld}}} Z_{cf,it}^{\frac{\sigma_{ld}-1}{\sigma_{ld}}} + (1-\gamma_{lc})^{\frac{1}{\sigma_{ld}}} L_{c,it}^{\frac{\sigma_{ld}-1}{\sigma_{ld}}} \right)^{\frac{\sigma_{ld}}{\sigma_{ld}-1}} \tag{34}$$

$$Z_{cf,it} = \left(\gamma_{c}^{\frac{1}{\sigma_{d}}} K_{c,it-1}^{\frac{\sigma_{d}-1}{\sigma_{d}}} + (1-\gamma_{c})^{\frac{1}{\sigma_{d}}} E_{cf,it}^{\frac{\sigma_{d}-1}{\sigma_{d}}} \right)^{\frac{\sigma_{d}}{\sigma_{d}-1}} \tag{35}$$

This implies the expression for the real marginal cost mc_{it} presented in equation (36):

$$mc_{it} = \left(\mu p_{Z_{lcf},t}^{1-\epsilon} + (1-\mu) p_{Z_{ldf},t}^{1-\epsilon} \right)^{\frac{1}{1-\epsilon}} \tag{36}$$

and the price includes a mark-up:

$$p_{Y,t} = \frac{\eta}{\eta - 1} mc_{it} \tag{37}$$

where

$$p_{Z_{ldf},t} = \left(\gamma_{ld} p_{Z_{df},t}^{1-\sigma_{ld}} + (1-\gamma_{ld}) w_{d,t}^{1-\sigma_{ld}}\right)^{\frac{1}{1-\sigma_{ld}}} \tag{38}$$

$$p_{Z_{lcf},t} = \left(\gamma_{lc} p_{Z_{cf},t}^{1-\sigma_{ld}} + (1-\gamma_{lc}) w_{c,t}^{1-\sigma_{ld}}\right)^{\frac{1}{1-\sigma_{ld}}} \tag{39}$$

$$p_{Z_{df},t} = \left(\gamma_d p_{K_d,t}^{1-\sigma_d} + (1-\gamma_d)(p_{of,t} + \tau_{of,t})^{1-\sigma_l}\right)^{\frac{1}{1-\sigma_d}} \tag{40}$$

$$p_{Z_{cf},t} = \left(\gamma_c p_{K_c,t}^{1-\sigma_d} + (1-\gamma_c) p_{e,t}^{1-\sigma_d}\right)^{\frac{1}{1-\sigma_d}} \tag{41}$$

$w_{c,t}$ and $w_{d,t}$ are the real wages in the clean and dirty sectors respectively.

Labour market

Labour is only imperfectly substitutable between the clean and dirty sectors, so that the total labour supply has to be equal to an aggregate of clean and dirty labour demand.

$$L_t = \left(L_{c,t}^{\frac{\eta_L-1}{\eta_L}} + L_{d,t}^{\frac{\eta_L-1}{\eta_L}}\right)^{\frac{\eta_L}{\eta_L-1}} \tag{42}$$

The relative wages are defined by the following first order condition:

$$\left(\frac{L_{d,t}}{L_{c,t}}\right)^{\frac{1}{\eta_L}} = \frac{w_{c,t}}{w_{d,t}} \tag{43}$$

And the average wage is:

$$W_t = \left(W_{c,t}^{1-\eta_L} + W_{d,t}^{1-\eta_L}\right)^{\frac{1}{1-\eta_L}} \tag{44}$$

Clean energy producer

The production of clean energy takes place competitively using clean energy capital $K_{cE,it}$ and land La_{it}. The quantity of land is fixed at 1. The production function is:

$$E_{c,t} = \alpha_E \left(s^{\frac{1}{\sigma_{ec}}} K_{cE,t-1}^{\frac{\sigma_{ec}-1}{\sigma_{ec}}} + (1-s)^{\frac{1}{\sigma_{ec}}} La_t^{\frac{\sigma_{ec}-1}{\sigma_{ec}}}\right)^{\frac{\sigma_{ec}}{\sigma_{ec}-1}} \tag{45}$$

Solving for the profit maximisation of the clean energy producer, we can define the relative demand for capital and land, and the price of clean energy as follows:

$$\frac{K_{cE,t-1}}{E_{c,t}} = \frac{1}{\alpha_E} s \left(\frac{P_{kcE,t}}{p_{e,t}}\right)^{-\sigma_{ec}} \tag{46}$$

A.3 Trade balance

Fossil fuels are entirely imported. Their real foreign (producer) price $\overline{p}_o$ is exogenous and constant through time, so that the real domestic price of fossil fuels is as follows:

$$p_{o,t}/p_{Y,t} = Q\overline{p}_o \tag{47}$$

The term Q is a fixed ratio which represents the steady state ratio of prices of foreign and domestic GDP goods expressed in domestic currency $p_{Y^*,t}/p_{Y,t}$.

The home country exports the domestically produced good in quantity X_t at each date as to ensure the equilibrium of the trade balance in equation (48).

$$p_{Y,t}X_t = p_o O_t \tag{48}$$

A.4 Market clearing

Clean energy and dirty energy

The imported dirty energy is used by the domestic firms and households. The clean energy produced domestically is also used by domestic firms and households.

$$O_t = O_{f,t} + O_{h,t} \tag{49}$$

$$E_{c,t} = E_{ch,t} + E_{cf,t} \tag{50}$$

Consumption and investment good

$$Y_t = N_t + J_{d,t} + J_{c,t} + I_{d,t} + I_{c,t} + I_{cE,t} + X_t + AC_{hd,t} + AC_{hc,t} + AC_{fc,t} + AC_{fd,t} + AC_{fcE,t} \tag{51}$$

A.5 Government budget constraint

In the simplified version of FR-GREEN used in this paper, the government has one single tax instrument available, namely the excise tax on consumption of fossil fuels, that is set at the same level for both intermediate consumption by firms and final consumption by households. In addition the government can subsidize firm investment. We assume that this subsidy $\tau_{I,t}$ is determined endogenously such that half of the additional tax revenue collected by changing the fossil fuel tax is allocated to these subsidies, while the other half is allocated to lump-sum transfers T_t to the household,ensuring a balanced budget. The government real budget constraint is as follows:

$$T_t + p_{Y,t}\left(I_{d,t} + I_{c,t} + I_{cE,t}\right)\tau_{I,t} = \tau_{oh,t}O_{h,t} + \tau_{of,t}O_{f,t} \tag{52}$$

while the change in tax revenues Rev_t is determined as deviation from revenues in the initial steady state Rev_0 as

$$Rev_t = \tau_{oh,t}O_{h,t} + \tau_{of,t}O_{f,t} - Rev_0 \tag{53}$$

implying that transfers are determined with

$$T_t = \left(1 - S_{I,t}\right)Rev_t + Rev_0 \tag{54}$$

where $S_{I,t}$ is the exogenous share of investment subsidies, set to zero in the initial steady state and 0.5 afterwards.

B Calibration of FR-GREEN

Both the production and the consumption are modeled using Constant Elasticity of Substitution (CES) functions, parameterized by expenditure share parameters (technical coefficients) and an elasticity parameter. While the technical coefficients can be easily derived from data through simple ratios (as discussed later), the elasticities require external empirical estimates from the literature, which are more challenging to compute.

Elasticities drawn from the literature

The production structure incorporates six key elasticities. First, ϵ represents the elasticity between clean and dirty labour-capital-energy bundles. Second, σ_{ld} reflects the substitution elasticity between labour and capital-energy bundles, assumed to be the same for clean and dirty bundles. Third, σ_d captures substitution between energy and capital types, again assumed equal for both bundles. Finally, σ_{ec} measures substitution between the green factor (land) and clean electricity capital. Estimates for ϵ in the literature are sparse. Acemoglu et al. (2012b) consider values of 3 and 10, noting that lower values slow the green transition, while Varga and Roeger (2021) calibrate this parameter at 6. For the aggregation of clean and dirty energy, Papageorgiou et al. (2017) estimate a range of 1.8 to 3, however this does not exactly correspond to our elasticity ϵ between the entire clean and dirty bundles instead of just the clean and dirty energies. Overall, a plausible range for ϵ lies between 3 and 10. For the substitution between labour and the capital-energy bundle, σ_{ld}, estimates using French data from Henriet et al. (2014) suggest a value of 0.5, consistent with Varga and Roeger (2021). Similarly, Koetse et al. (2008) report values around 0.4, and Airaudo et al. (2022) use 0.35 in their calibrations. A reasonable range for σ_{ld} is therefore between 0.4 and 0.5. Regarding capital-energy substitution, σ_d, Henriet et al. (2014) and meta-analyses like Labandeira et al. (2017) converge on estimates around 0.5, suggesting a plausible range of 0.4 to 0.5. Finally, substitution between the green factor and clean electricity capital, σ_{ec}, varies between 0.25 in Coenen et al. (2023) and 0.42 in Airaudo et al. (2022), indicating a plausible range of 0.25 to 0.42.

The consumption side of the model involves another CES structure where the final consumption good C is an aggregate of non-durable goods and a durables bundle. The durables bundle itself combines energy and durable goods, classified as either clean or dirty. The elasticity ω governs the substitution between non-durables and the total durables bundle. According to Ogaki and Reinhart (1998), ω is generally estimated to be greater than 1, consistent with theoretical work by Barsky et al. (2007), Fernandez-Villaverde and Krueger (2011), and Henriet et al. (2014), which often use $\omega = 1$. Within the durables bundle, the elasticity g determines the substitution between the clean and dirty energy-durables bundles, analogous to ϵ in production. Theoretical and empirical studies suggest high elasticity values, with a plausible range of 3 to 10. Finally, the elasticity ξ measures the substitution within the bundles combining energy and durables. Estimates by Labandeira et al. (2017) and Henriet et al. (2014) suggest values ranging from 0.4 to 0.5, consistent with Koetse et al. (2008). A plausible range for ξ is therefore 0.2 to 0.5.

B.1 Calibrated parameters

Production function technical parameters

The shares in the CES functions and the parameters of the clean electricity production functionare calibrated based on ratios derived from French data. Specifically, the following parameters are included in this calibration:

- **CES share parameters:** χ, γ_{zh}, μ, γ_d, γ_c, γ_{ld}, γ_{lc}, ν_c, ν_d
- **Clean electricity production parameter:** α_E, s

This calibration ensures that the model reflects key structural features of the French economy. The targeted ratios are summarized in Table 1.

Table 1: Fixed Targets used for calibration

Target	**Value**	**Description**
P_oO/Y	0.05	Fossil fuel spending as a share of GDP.
K_{cE}/Y	0.03	Capital in clean electricity as a share of GDP.
D_c/D_d	0.56	Clean to dirty durables ratio.
D/Y	0.50	Durables as a share of GDP.
$(K_c + K_d)/Y$	3	Total capital scaled by GDP.
K_d/K_c	1.31	Dirty to clean capital ratio.
O_f/O	0.75	Share of oil used by firms.
E_c/O	0.60	Clean energy relative to oil.
E_{cf}/E_c	0.77	Clean energy share for firms.
L_d/L_c	1.27	Dirty labour over clean labour.
r_n	1.02	Gross real interest rate (annualized)

The ratios are derived using datasets from SDES, French National Accounts, PEFA, WIOD, and Household Expenditure Surveys. Fossil fuel spending over GDP (P_oO/Y) is estimated at 5% using 2022 data from SDES. Imports of gas, oil, and coal amount to 110 billion euros, with a GDP of 2.35 trillion euros. Capital over GDP is calculated from French National Accounts, using investment data and a 5% depreciation rate, yielding a ratio of approximately 3. For electricity capital, WIOD data indicate 1.7% of total capital in 2014, equivalent to 5% of GDP; adjusting for clean electricity components gives ($K_{cE}/Y \approx 3\%$). The parameter $\overline{P}_o$ is set at 1.

Energy use is classified into clean and dirty categories using PEFA data. Dirty energy includes coal, manufactured gases, and petroleum products, while clean energy comprises nuclear, biofuels, and electricity. These classifications provide estimates for ratios such as E_c/O, E_{cf}/E_c, and O_f/O. Clean and dirty capital shares are derived by assuming that energy shares in production sectors mirror capital shares ($E_c/K_c = E_d/K_d$ within each sector). Aggregating across sectors yields K_c/K_d and L_d/L_c. For households, durable and non-durable consumption data are obtained from expenditure surveys. Durables are defined as items such as housing repairs, appliances, and vehicles. Total durables are calculated as investments divided by depreciation, which is assumed equal to 0.1, scaled by the number of households, and normalized by GDP to estimate D/Y. The clean-to-dirty durables ratio (D_c/D_d) is assumed proportional to clean-to-dirty energy use by households.

Wealth-in-utility parameters

The wealth-in-utility parameters γ_b and η_b are calibrated as follows. First, we set $\eta_b = 0$ as done by Michaillat and Saez (2021). Second, we follow Rannenberg (2021) in setting the value of γ_b and β, given the values of the steady state inflation and interest rate. We also target a discounting wedge $\theta = \beta\bar{r}$ and set it to 1 when there is no wealth in utility, and to 0.96 when there is wealth in utility, as in Rannenberg (2021). This implies a value of the discount factor equal to 0.9964 without WIU and equal to 0.9565 with WIU. The Euler equation at steady state then defines the value of $\gamma_b = 0$ without WIU and $\gamma_b = 0.0012$ with WIU.

Other parameters

Other parameters are more usual in the DSGE literature. Eberly et al. (2008) estimate the investment adjustment cost parameter, denoted as ξ in their work, to be 0.4 under a single-regime generalized Hayashi specification and 4.0 under a simpler Hayashi framework. In our setup, these correspond to κ values of 0.8 and 8.0, respectively. Given this range, we opt for $\kappa = 5$ as a reasonable midpoint, balancing the estimates provided by their analysis. There are very few estimates of elasticities of substitution between clean and dirty labour. We take these as very substitutable.

B.2 Recapitulation of values of parameters

Parameter	**Description**	**Value**
ϵ	Elasticity of substitution (clean/dirty bundles in output)	10
σ_d	Elasticity of substitution (capital/energy in clean/dirty bundles)	0.3
σ_{ld}	Elasticity of substitution (capital-energy and labour)	0.5
σ_{ec}	Elasticity of substitution (clean electricity capital/land)	0.2
ω	Elasticity of substitution (durables/non-durables)	0.9
g	Elasticity of substitution (clean/dirty durable bundles)	10
ξ	Elasticity of substitution (energy/durables)	0.3
β	Household discount factor	0.9
ψ	CRRA utility parameter	1
h	Habit persistence	0.6
ν_L	labour disutility	2
η_L	Elasticity of substitution between labour types	-5
η	Demand elasticity for good varieties	6
δ_D	Durables depreciation rate	0.1
δ_K	Capital depreciation rate	0.05
κ_D	Adjustment cost for durables	5
κ_k	Adjustment cost for capital	5

Parameter	**Description**	**Value**
$\text{tax}_{\text{nom}_f}$	Nominal carbon tax on firms	0.42
$\text{tax}_{\text{nom}_h}$	Nominal carbon tax on households	0.42

C Impulse responses of FR-GREEN to standard temporary shocks

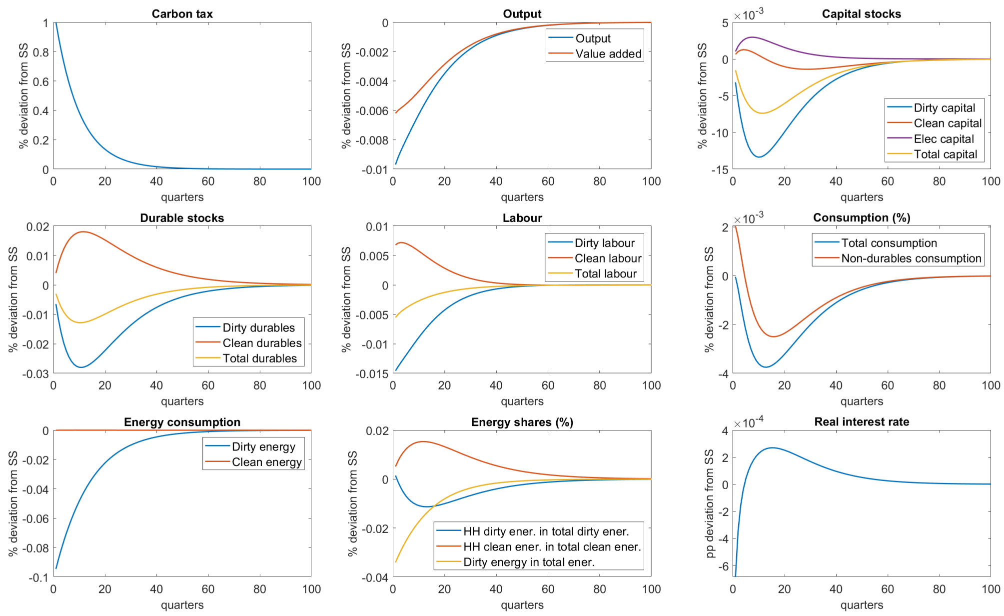

Figure 10: Impact of a temporary carbon tax shock in FR-GREEN

Note: All variables are in percentage deviation from the baseline except the real interest rate that is in percentage points deviation from the baseline.

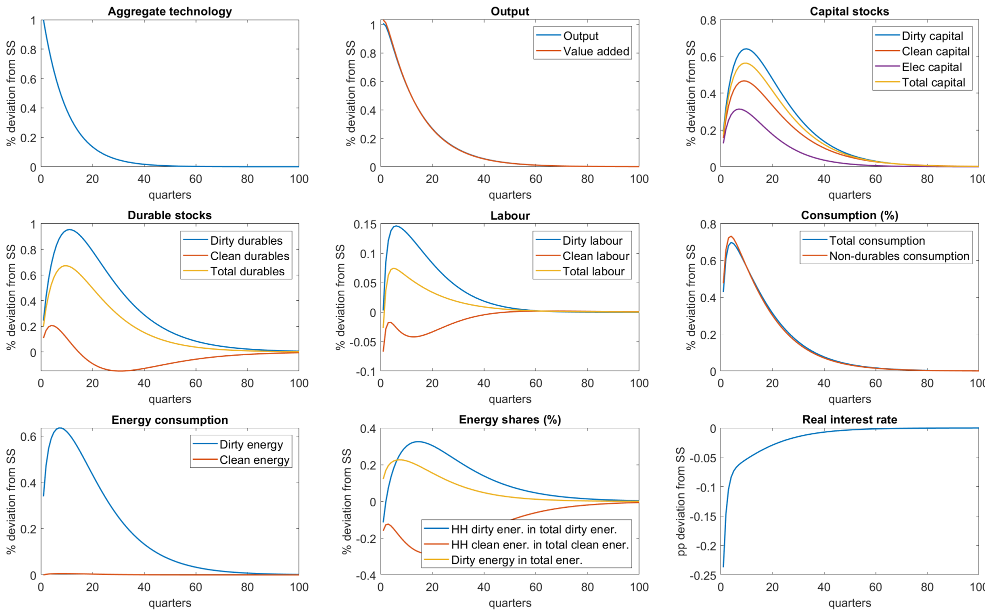

Figure 11: Impact of a temporary aggregate productivity shock in FR-GREEN

Note: All variables are in percentage deviation from the baseline except the real interest rate that is in percentage points deviation from the baseline.

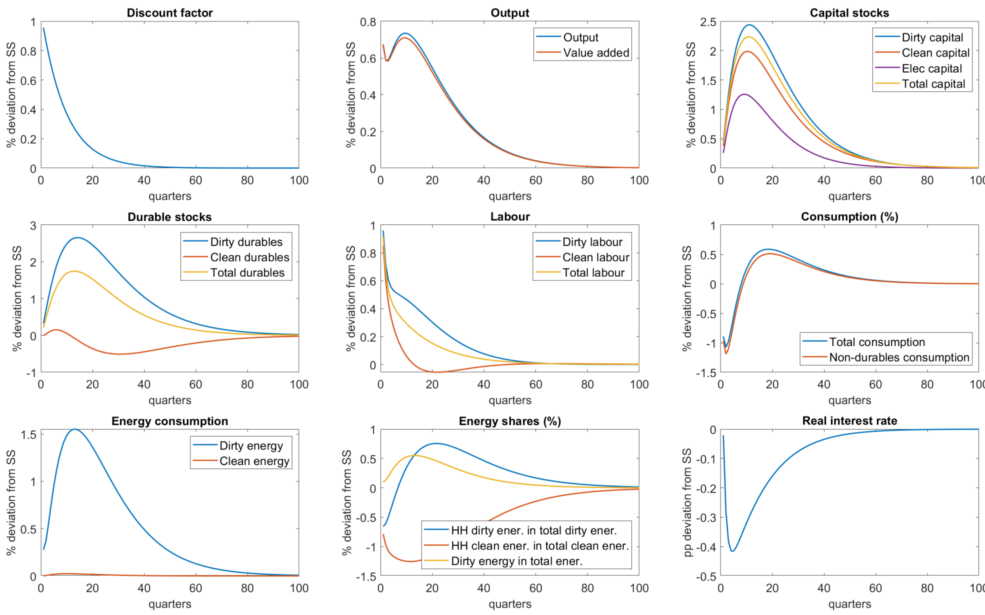

Figure 12: Impact of a temporary discount factor shock in FR-GREEN

Note: All variables are in percentage deviation from the baseline except the real interest rate that is in percentage points deviation from the baseline.

D Simulation results of Fit-for-55 scenario with FR-GREEN for headline variables

Figure 13 presents plots of an FR-GREEN simulation subject to our carbon tax shock. The tax shock is calibrated to trigger a decline in fossil fuel use equal to -30% by the end of 2030. It causes a notable decline in output. This loss results from a combination of supply-side effects, where costly reallocation and energy reduce overall apparent productivity, and demand-side effects, as lower income leads to reduced consumption and investment. As we also obtain a reduction in the imports of fossil fuels and an increase of the domestic production of clean energy due to the change in their relative price, the fall in the French value added calculated as output net of these imported fossil fuels is smaller than the output loss.

The transition in production from dirty to clean has some consequences in terms of reallocation of durable and capital stocks, as well as labour. On the durable side, the clean durable stock of households increases by more than 30% and the decrease in the dirty durable stock is even greater (around -40%). The total stock of durables is decreasing due to the fall in aggregate income. On the capital side, we also get a fall of the total stock, due to the fall of output, and a composition change in favour of clean capital (including clean energy capital), but the stock of clean capital is not increasing. This contrast between durables and capital stems from the difference between production and consumption structures. The energy-capital bundle is combined with sector-specific labour (clean or dirty). While firms wants to expand clean production, they can adjust not only by reallocating capital but also by shifting labour from the dirty to the clean sector. Indeed, the simulation shows such a composition shift of labour. Similarly to capital, the decrease in output also implies a decrease in total labour.

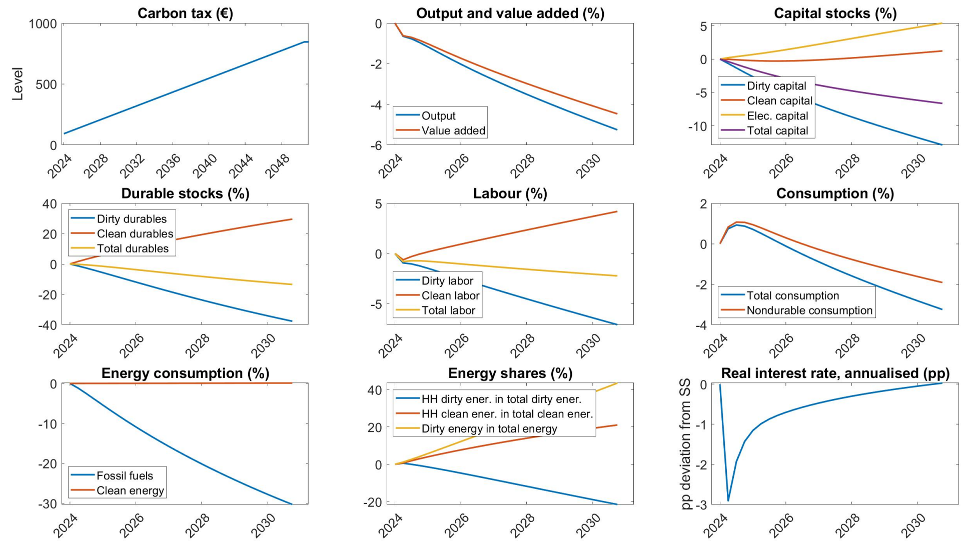

Figure 13: The effects of the carbon tax shocks on the French economy in FR-GREEN simulation

Note: All variables are in percentage deviation from baseline except the real interest rate that is in percentage points deviation from the baseline.

E Sensitivity of FR-GREEN to the calibration of wealth-in-utility

In this section we evaluate the importance of our calibration of the WIU-related parameter γ_b on FR-GREEN properties. We contrast three cases: the baseline, where $\gamma_b = 0.0012$ and two alternatives, where γ_b is set higher to 0.003 (as implied by setting $\beta = 0.9$) and lower to 0, i.e. the ordinary no-WIU case. The results of this comparison are presented in two figures, which present the same results at different horizons – Figure 14 displays results until 2050, while Figure 15 zooms in on 2024-2030. Our simulations are similar to those seen in Appendix D, but in order to emphasize how WIU changes the intertemporal dynamics of agent's choices, we study an experiment where the carbon taxes are announced in 2024, but only implemented with a delay at the beginning of 2031. This implies that there is an anticipatory period where the agents adjust their choices to the tax increase not yet in effect.

As illustrated below, a notable impact of WIU on e.g. consumption choices is the reduction of consumption smoothing when faced with shocks that have long-term consequences. This feature allows dampening the strong forwardlookingness, which occurs with a standard utility under perfect foresight. As shown by Rannenberg (2021), the WIU-augmented Euler equation (19) can be loglinearized as

$$\hat{c}_t = \theta E_t \hat{c}_{t+1} - \theta \hat{r}_t \tag{55}$$

where $\theta = \beta \bar{r} < 1$ accounts for the effect of WIU due to the calibration of β. Thus shocks that affect future consumption $\hat{c}_{t+1}$ and shocks that affect the contemporaneous real rate r_t have a weaker effect on current consumption than in a WIU-less calibration.

In order to understand the short-run impact of the WIU calibration, it is useful to start with an explanation of its impact at longer horizons. The anticipatory increase in consumption is due to the fact that the agents are aware that once the tax increase materializes, they will wish to reduce their investment; this leads them to reduce investment already during this period by several percent to avoid a portion of the adjustment costs. Notably this reduction in investment is the greatest in the case of high WIU. A key mechanism behind this phenomenon is the fact that the higher the WIU, the higher the long-run impact of the carbon tax on the real interest rate, investment and output, as can be seen from Figure 14 and hence the greater the need for anticipatory disinvestment.[9]

These dynamics are also behind the differences in consumption across calibrations in the short run: without WIU, the anticipatory increase in consumption is smaller as the far-future drop in consumption matters relatively more for current consumption than in the case with WIU. Figure 15 shows the economic impact arising at the 2030 horizon from the expected upcoming shock. The differences between the three calibrations are particularly visible in the case of consumption and the real interest rate, where e.g. in the case case of consumption, moving from a no-WIU calibration (dashed line) to a high-WIU ($\gamma_b = 0.003$) calibration (dotted line) amplifies the impact in 2030Q4 from 0.16% to 0.26%, i.e. by over 50%. That is, the higher the WIU calibration, the stronger the impact of the carbon taxes on consumption in the anticipatory period, i.e. the less consumption smoothing.

[9] The real interest rate does not reach its final steady state in 2050 as the carbon tax has not yet converged.

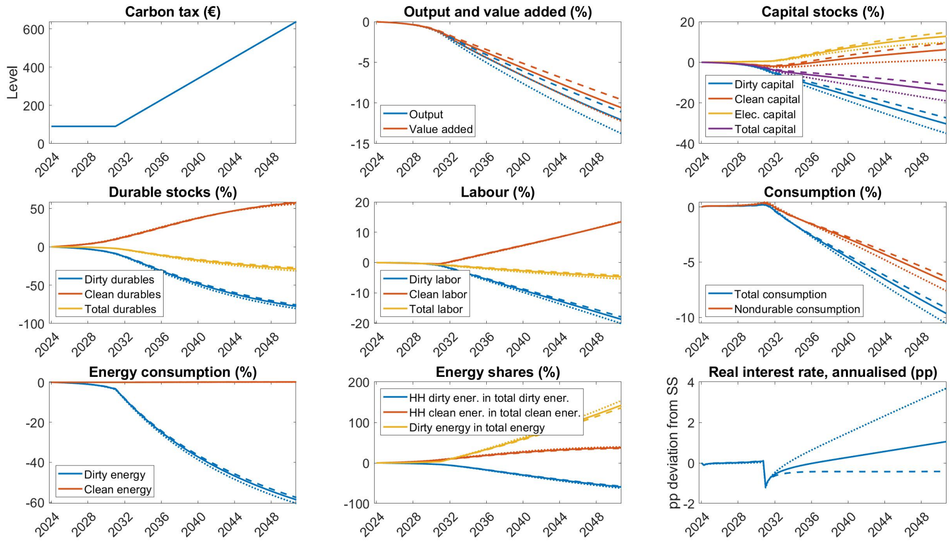

Figure 14: The effects of a pre-announced carbon tax shock on the French economy in FR-GREEN simulation, 2024–2050.

Note: All variables are in percentage deviation from baseline except the real interest rate that is in percentage points deviation from the baseline. The solid line refers to the baseline case $\gamma_b = 0.0012$, the dotted line to $\gamma_b = 0.003$ and the dashed line to $\gamma_b = 0$.

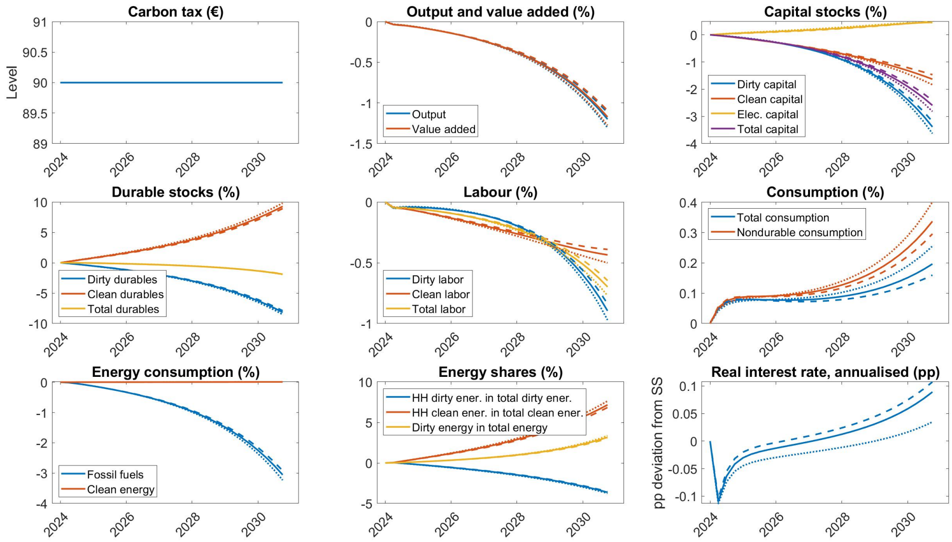

Figure 15: The effects of a pre-announced carbon tax shock on the French economy in FR-GREEN simulation, 2024–2030.

Note: All variables are in percentage deviation from baseline except the real interest rate that is in percentage points deviation from the baseline. The solid line refers to the baseline case $\gamma_b = 0.0012$, the dotted line to $\gamma_b = 0.003$ and the dashed line to $\gamma_b = 0$.

F FR-BDF scenarios with subsets of shocks

Figures 16 and 17 present plots similar to Figure 9 in the scenarios focusing on the non-supply and supply shocks, respectively. As these simulations consist of just a part of the whole cocktail, in general the effects are smaller in magnitude.

In the case of only non-supply shocks affecting the economy—presented in Figure 16—the most notable difference is the decrease of the price of value added, driven by the fall in output, which is significantly reduced, and by the loss of household purchasing power. This move of the value added price, together with a fall in the price of imports, yields a decrease in the price of investment, that in the case of firms is already notably reduced by the government subsidy. This leads to an investment boom in the medium to long term. Furthermore, even if we assume a symmetric shock across the euro area (EA), this fall in the output price translates into extra-EA price-competitiveness gains, which dampens the decrease in exports compared to the one of imports.

Figure 17 shows results of the other alternative scenario, the case of supply shocks. In this case the outcomes are in general more in line with those seen in Figure 9, reflecting the fact that the majority of the effects of the shocks, particularly on the real economy, arises from this subset of shocks. Notably the dynamics of the price of firm investment is now increasing instead of decreasing, as in this case as investment is not subsidized and there is no demand effect arising from the tax shock, meaning that the price is only affected by the negative supply shock.

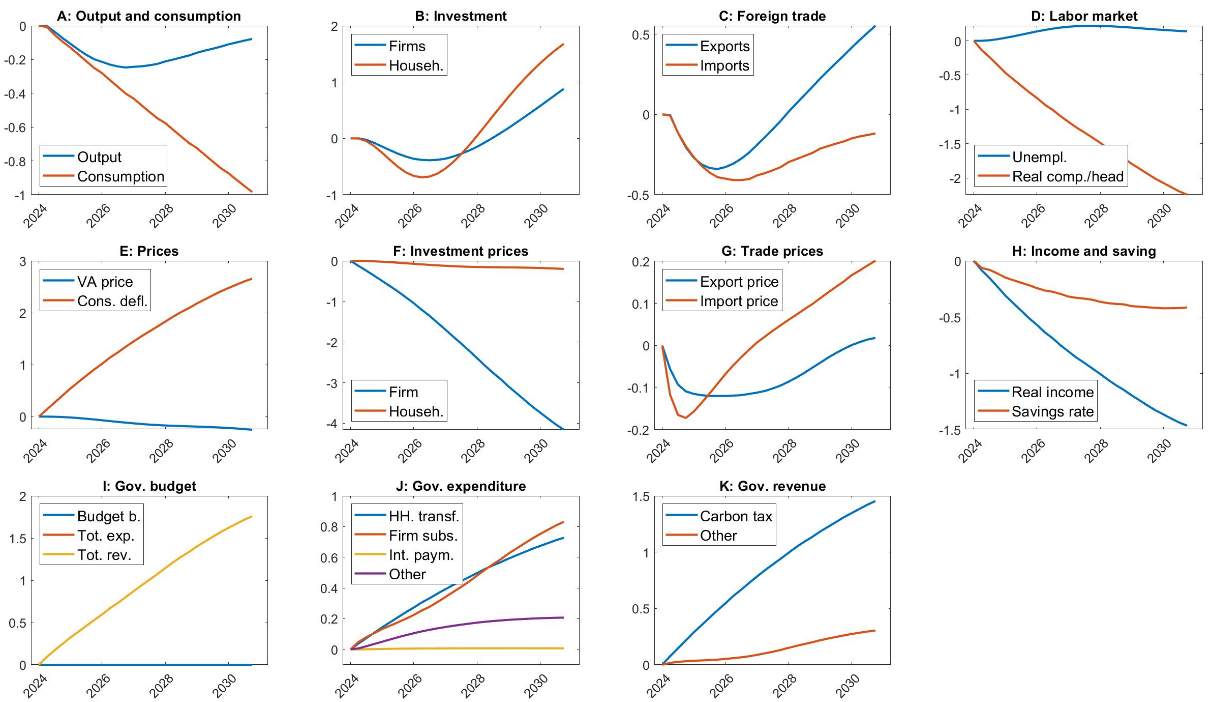

Figure 16: The effects of the non-supply component of carbon tax shocks on the French economy, under constant fiscal and monetary policies

Note: "Real comp./head" in plot D refers to total real compensation per employee. Unemployment and saving rate are measured as absolute difference from baseline, in percentages of the labour force and disposable income, respectively. Variables in plots I, J and K are in absolute difference from baseline and relative to baseline nominal GDP. All other variables are in percentage deviation from baseline.

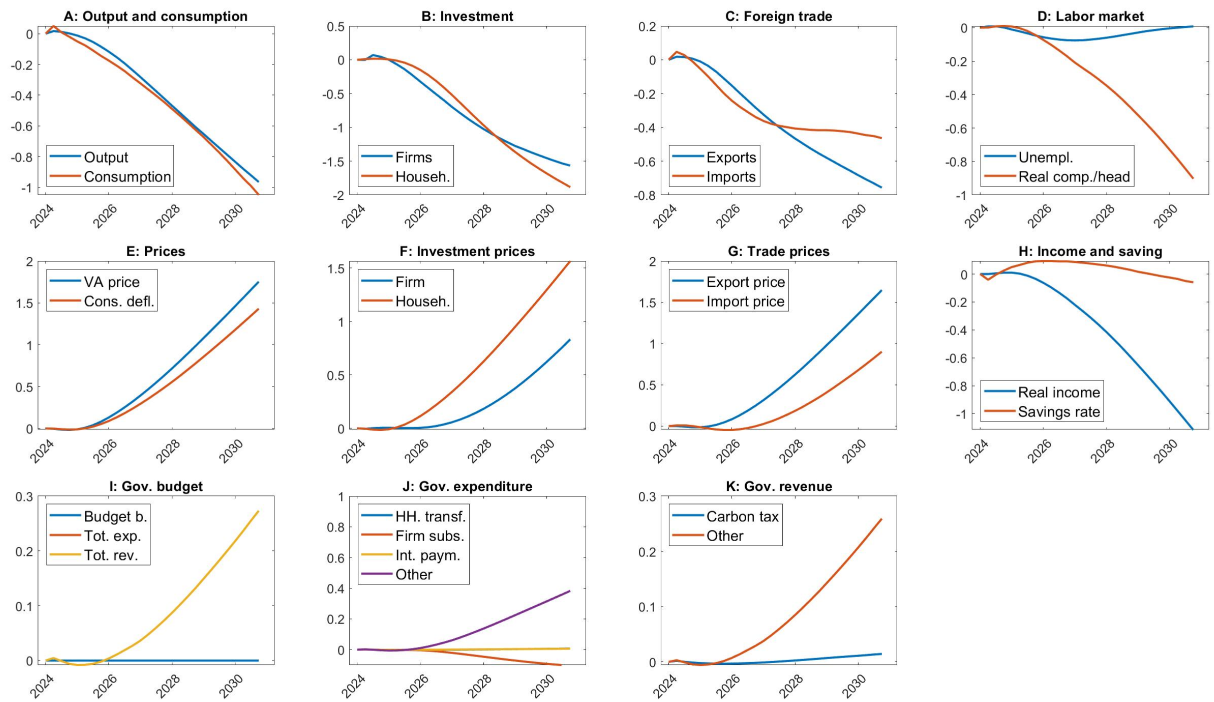

Figure 17: The effects of the supply component of carbon tax shocks on the French economy, under constant fiscal and monetary policies

Note: "Real comp./head" in plot D refers to total real compensation per employee. Unemployment and saving rate are measured as absolute difference from baseline, in percentages of the labour force and disposable income, respectively. Variables in plots I, J and K are in absolute difference from baseline and relative to baseline nominal GDP. All other variables are in percentage deviation from baseline.