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Testing climate NGFS scenarios through the lens of a large-scale ABM for the Italian economy

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ABSTRACT

We apply a data-driven, macroeconomic agent-based model calibrated on the Italian economy to study the green transition — specifically, the shift in electricity production from fossil fuels ("brown" sources) to renewable ("green") technologies — and the process of electrification, defined as the replacement of fossil fuel use with electricity. To better capture the dynamics of the energy sector, we extend the original macroeconomic model by expanding the energy sector into three subsectors, based on the Exiobase database, distinguishing between brown electricity, green electricity, and non-electricity energy sectors. We incorporate detailed information, particularly regarding carbon pricing and electrification, from three NGFS scenarios: Current Policies, Delayed Transition, and Net Zero. Based on these scenarios, we conduct a series of economic policy analyses.

We find that a higher carbon tax leads to significant reductions in emissions while imposing only modest short-term economic costs on certain sectors, particularly those reliant on fossil fuels, along with a moderate increase in inflation. However, the green transition is associated with stronger long-run economic growth, primarily driven by increased investment in the renewable energy sector. Notably, when the carbon tax is combined with higher government consumption, the negative short-term effects on GDP are fully offset. Moreover, if the carbon tax is accompanied by green investment incentives, the resulting cost-push inflationary pressures can be partially mitigated. These findings highlight the potential of well-designed policy mixes to reconcile environmental objectives with sustained economic growth.

1. Introduction

The macroeconomic consequences of the green transition have rapidly become a central issue in both academic research and policy discussions. Governments and central banks are increasingly concerned with how decarbonization policies (particularly carbon pricing and electrification) will affect growth, inflation, sectoral dynamics, and financial stability. Despite a growing body of work, there is still no consensus on the short- and long-run macroeconomic effects of climate transition policies. While some studies emphasize potential transition costs and inflationary pressures, others highlight the possibility of green investment-led growth and productivity gains. Empirical evidence on the macroeconomic effects of carbon pricing remains mixed. Some studies find no or even small positive effects on GDP (Metcalf, 2019; Metcalf and Stock, 2023), while others predict negative short-run impacts (Kanzig, 2023; Coenen et al., 2024). Model-based analyses often suggest that aggressive carbon pricing may reduce GDP and employment, but also show that appropriate revenue recycling can substantially mitigate these effects (Brenner et al., 2007; Conefrey et al., 2013; Allan et al., 2014; Rivera et al., 2016; Vermeulen et al., 2018; Allen et al., 2020; Wieners et al., 2024; Socci et al., 2024). Understanding how these forces interact remains a key open question.

The challenges posed by climate change require robust economic modeling tools to evaluate policy interventions. Among these tools, the NGFS (Network for Greening the Financial System)[1] scenarios stand out for their comprehensive approach, integrating insights from Integrated Assessment Models (IAMs) and macroeconomic frameworks. Moreover, most existing quantitative assessments of climate change rely on Dynamic Stochastic General Equilibrium (DSGE) models or

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Computable General Equilibrium (CGE) frameworks. While these approaches provide valuable insights, they typically rely on strong equilibrium assumptions, representative agents, and linear dynamics, which may not fully capture the complex interactions within an economy transitioning to sustainability. As a result, they often struggle to capture key features of real-world transitions, such as firm-level adjustment, sectoral reallocation, demand-driven dynamics, and the propagation of shocks through production networks. These limitations are particularly relevant when studying out-of-equilibrium phenomena.

Climate change modeling also involves multiple layers of uncertainty. Even if significant progress has been made by scholars in modeling the physical impacts of climate change, with a clear distinction between chronic effects (e.g., rising temperatures) and acute events (e.g., extreme weather), physical uncertainty arises from the difficulty of capturing complex, non-linear, and potentially abrupt interactions between climatic processes and economic systems, including the possibility of tipping points. Transition uncertainty relates to the pace and direction of technological change and structural adjustment in the move toward net-zero targets. A further critical dimension is policy uncertainty: households and firms face uncertainty regarding the durability of climate policies over time, given political cycles and the risk of regulatory reversal, which directly affects investment decisions and resource allocation.

Network for Greening the Financial System (2024) hand-book emphasizes the need to match model types to specific questions and underscores the importance of accounting for uncertainty, both in model design and in economic agent responses to climate risks. On this regard, the report highlights three key insights for central banks and regulators. First, climate change modeling is crucial for understanding both physical damages and macroeconomic disruptions resulting from transition policies, which, though outside monetary mandates, have direct implications for financial stability. Second, no single model can capture the full picture: IAMs, DSGEs, and CGEs, address different dimensions and are complementary, not substitutable. A flexible modeling toolkit is therefore necessary. Third, modeling must address multiple complexities: non-linear physical impacts, the reversibility of transition policies, the interactions between climate risks and the financial system, and the critical issue regarding the degree of substitutability of production factors. For example, the production function must realistically reflect the difficulty for substituting capital, labor, and energy, as high elasticities of substitution may underestimate the impact of technology-driven price changes, thus affecting decarbonization policies. Not only technological factors matter in the long and medium run, but also expectations coordination and market imbalances can give additional risk as second round effects in particular for the energy investment/technological/financial nexuses.

Agent-Based Models (ABMs) have increasingly gained traction as a powerful and versatile alternative to traditional modeling frameworks, primarily due to their inherent flexibility in capturing complex economic dynamics driven by heterogeneous agents, decentralized interactions, and non-linear feedback mechanisms. By explicitly modeling individual behaviors and their adaptive responses to changing environments, ABMs are particularly well-suited to explore emergent phenomena that standard representative-agent or equilibrium-based models often fail to address.

Building on the data-driven Agent-Based Model (ABM) calibrated in Di Domenico et al. (2025), which captures the structural and institutional specificities of the Italian economy, this study extends the framework to explicitly engage with the climate transition scenarios developed by the Network for Greening the Financial System (NGFS). To the best of our knowledge, this represents the first data-driven ABM applied to NGFS scenarios. By embedding mitigation policies triggered by a carbon price policy, within a high-resolution micro-founded framework, the model allows us to explore the feasibility and macroeconomic implications of alternative climate pathways, pointing out potential trade-offs between decarbonization and economic growth in the Italian context.

We use this particular ABM model because ABMs are often criticized because they provide mainly qualitative analyses, that is they are calibrated by replicating “stylized facts”, but they difficultly align quantitatively with empirical micro, meso, and macroeconomic data. Moreover, they presents too many degrees of freedom and parameters to calibrate. Instead, a data-driven approach can lead to a high ability to quantitatively replicate micro, meso and macroeconomic empirical data and reduce degrees of freedom in calibration, through the use of official micro, sectoral, and macroeconomic data sources (e.g., Eurostat) for direct calibration. This strategy allows us to achieve a high degree of empirical realism, enabling the model to effectively assess policies aimed at tackling climate change.

The model introduces granular detail on both the technological and demand sides by differentiating firm and household agents across sectors, using a detailed calibration and estimation strategy based on a simplified Social Accounting Matrix (SAM) approach that draws on input–output tables and key data on the secondary distribution of income. The economy is initialized through a data-driven procedure that leverages macro-meso-micro data from Eurostat to set agent population states (e.g., balance sheets) and economic decisions (e.g., consumption, investment). This bottom-up strategy enables a consistent mapping to national accounts, allowing for a potentially one-to-one representation of the real economy. Moreover, by leveraging the ABM’s ability to differentiate individual firms (including the possibility of bankruptcies) and using the Exiobase database, we are able to further refine the energy production sector to model the phenomenon of electrification (exogenously) and the shift in electricity production from fossil to renewable sources (endogenously).

Indeed, to fully complain the NGFS scenarios, we augment the (Di Domenico et al., 2025) model to include the energetic/technological trends as input for the ABM macroeconomic model. In particular, we include the carbon price, labor productivity trend (incorporating a physical chronic climate damage), capture and storage technology and electrification trends as foreseen by the NGFS apparatus of IAMs model. This structure allows us to track shock propagation through sectoral product networks and, based on households’ sectoral demand, to simulate the resulting impacts driven by structural and technological transitions. We complement the set of climate scenarios — namely, the fully early mitigation pathway (Net-Zero scenario), the late and disorderly transition (Delayed scenario), and the continuation of current policies (Current Policies scenario) — with a set of policy experiments aimed at analyzing the short- to long-term impacts on key economic variables.

In particular, this structure makes our ABM well-suited to incorporate a carbon price policy applied to firms’ emission intensity. The carbon price trajectory adopted from the NGFS scenarios should not be interpreted as an additional standalone carbon tax layered on top of existing European policy instruments. Rather, it represents a reduced-form shadow price associated with progressively tightening emission constraints under a cap-consistent transition pathway. At the European level, carbon pricing is primarily implemented through the EU Emissions Trading System (EU ETS),[2] which operates via auctioned emission

[2] The EU ETS represents the first large-scale carbon pricing market and remains the cornerstone of European climate policy. While primarily covering EU Member States, its scope extends to associated countries such as Norway, Iceland, and Liechtenstein, as well as Northern Ireland under specific arrangements. Since its launch in 2005, the system has contributed significantly to reducing greenhouse gas emissions from electricity, heat generation, and energy-intensive industrial sectors.

allowances under a declining cap.[3] The market-clearing permit price emerging from this system reflects the marginal abatement cost consistent with the cap trajectory. In this sense, the NGFS carbon price path can be understood as a macro-consistent representation of such a shadow price under increasingly stringent emission constraints. In addition to the EU ETS, the European climate policy architecture includes complementary instruments such as: (i) the Effort Sharing Regulation (ESR), which governs non-ETS sectors; (ii) the Carbon Border Adjustment Mechanism (CBAM), designed to mitigate carbon leakage; (iii) renewable energy directives and electrification mandates; (iv) national carbon pricing mechanisms in specific sectors; and (v) fiscal recycling of auction revenues. The NGFS carbon price therefore encapsulates, in reduced form, the aggregate effect of this policy mix under a coordinated transition scenario. Our modeling approach abstracts from the institutional micro-details of permit allocation and sectoral coverage, and instead treats the carbon price as the economy-wide marginal emission cost consistent with the tightening of systemic carbon constraints.

Importantly, this interpretation avoids double counting. The model does not impose an additional tax beyond existing mechanisms, but rather embeds the NGFS shadow price as a representation of the equilibrium carbon cost implied by cap compression across the European climate policy framework.

In our simulations, we obtain a small short-term negative deviation for the Italian economy of around −1% level of GDP for the Net-Zero scenario. However, under a fiscally neutral policy design where carbon tax revenues are recycled into public consumption, short- to medium-term growth is sustained, offsetting the negative impact of the carbon price on GDP. Moreover, the Net-Zero scenario implies a positive long-term deviation in GDP growth. Alternatively, under a fiscally neutral policy design where carbon tax revenues are used to incentive green energy production, emission reductions are stronger in the short run, while economic growth is enhanced in the long run. Moreover, we find that the NGFS carbon price trajectory may be structurally insufficient to guarantee full domestic net-zero convergence within a decentralized production network.

The present analysis should not be interpreted as a replication of NGFS macroeconomic projections, nor as an endogenous re-simulation of Integrated Assessment Models. Instead, we adopt NGFS trajectories (carbon prices, electrification paths, productivity assumptions) as systemic constraints and embed them into a data-driven agent-based production network. In this sense, our contribution is also counterfactual and structural: we ask whether NGFS-implied carbon prices and electrification trends are sufficient, once mapped into a decentralized production system, to generate a trajectory compatible with deep decarbonization without relying on a representative agent or equilibrium mechanisms.

The paper is organized as follows: Section 2 reviews the related literature; Section 3 describes the scenarios; Sections 4 and 5 present the model and the calibration procedure; Section 6 discusses the results and Section 7 concludes.

[3] The EU ETS operates as a cap-and-trade mechanism. A declining cap is set on the total volume of emissions allowed within the system, and a corresponding number of emission allowances, each representing one tonne of CO_2 equivalent, is issued. These allowances are allocated partly through auctions and partly through free allocation, depending on sector-specific rules and concerns about carbon leakage. Firms covered by the system must surrender allowances equal to their verified emissions each year. Allowances can be traded on secondary markets, ensuring that abatement occurs where it is most cost-effective. Non-compliance is subject to stringent penalties: firms that fail to surrender sufficient allowances must pay a fine per tonne of excess emissions, in addition to purchasing and surrendering the missing allowances in subsequent periods.

2. Literature review

Recent literature has developed several multi-model frameworks to link macroeconomic, energy, and environmental models in order to jointly analyze socio-economic and climate dynamics (Nikas et al., 2021; Weyant, 2017). A well-established approach is represented by IAMs, which integrate macroeconomic, energy, and climate components into a single framework to assess long-term mitigation policies (Weyant, 2017). In parallel, heterogeneous models can be connected through *soft-linking* and *hard-linking* techniques. As clearly defined by Bauer et al. (2008), in *soft-linking* models remain separate and exchange outputs iteratively (e.g., a macroeconomic model uses projections from an energy model), whereas in *hard-linking* multiple models are directly integrated into a single jointly solved system. The usefulness of these integrated approaches is evident in transition scenarios such as those proposed by the NGFS (Network for Greening the Financial System), where a multi-model framework combines IAMs (for energy and emissions dynamics) with macro-financial models (for economic impacts), generating internally consistent trajectories for carbon pricing, electrification rates, and energy mix (NGFS, 2021). These outputs can then serve as inputs for ABMs and other sectoral tools, enabling deeper analysis of the microeconomic and sectoral effects of the transition (Lamperti et al., 2018). In summary, the integration of macroeconomic, energy, and climate models — whether through unified IAMs or via linked multi-model architectures — enables a comprehensive understanding of the interdependencies across economy, energy, and environment, thus supporting more robust transition pathway assessments (IPCC, 2022).

The role of IAMs in climate policy analysis has been widely recognized as a key tool for understanding the interplay between economic systems and climate dynamics. Pioneering efforts in this area, such as Nordhaus's DICE model (Nordhaus, 1993), laid the groundwork for integrating economic and climate systems in a single framework. DICE became a benchmark in the cost–benefit analysis of climate policies by simulating the economic consequences of various greenhouse gas (GHG) emissions reduction pathways. This model, which focuses on long-term projections, has been influential in shaping policy debates on carbon pricing, optimal mitigation strategies, and the evaluation of climate risks (Nordhaus, 1993; Pizer, 2002).

Similarly, the PAGE (Policy Analysis of the Greenhouse Effect) model, developed by Hope (2006), expanded upon the DICE framework by incorporating probabilistic risk assessments into the analysis. This addition enabled PAGE to provide a range of possible outcomes, incorporating uncertainties in climate science, future emissions, and policy implementation. The inclusion of stochastic elements in the PAGE model represented a significant advancement, as it allowed for a more nuanced understanding of climate change risks and the potential costs and benefits of mitigation strategies (Hope, 2006; Hope et al., 2013). Other notable IAMs, such as the GCAM (Global Change Assessment Model) and IMAGE (Integrated Model to Assess the Global Environment), further advanced the capabilities of integrated modeling by incorporating sector-specific transitions and region-specific dynamics (Kim et al., 2014; van Vuuren et al., 2011).

Despite their usefulness in evaluating global climate scenarios, IAMs face significant limitations, particularly in their treatment of heterogeneity at the microeconomic level. These models often abstract away sectoral, technological, and geographical variations that play a crucial role in understanding the diverse responses of firms and regions to climate policies. Indeed, IAMs typically rely on representative agents, which assume uniform behavior across economic actors, failing to capture the complexities of decision-making within individual sectors or firms (Brekke et al., 2010; McKibbin and Wilcoxen, 1997). This lack of micro-level detail is especially critical when assessing the effects of climate policies on specific industries or when examining transition pathways that require sector-specific interventions.

In addition to IAMs, other macroeconomic models, such as DSGE models and CGE models, have also been widely used to evaluate the economic impacts of climate change and transition policies. DSGE models are designed to analyze the effects of policy changes on economic variables over time, accounting for agents' expectations and the impact of shocks. DSGE models have been adapted to incorporate climate-related risks and policy interventions, such as carbon taxes and emissions trading systems (e.g. Brock and Xepapadeas (2018), Annicchiarico and Di Dio (2015); Carattini et al. (2023); Comerford and Spiganti (2023)). However, DSGE models have limitations when it comes to sectoral heterogeneity and the representation of technological change. Indeed, they often assume a representative agent or focus on aggregate variables, which can mask the important sectoral differences in responses to climate interventions (Stern, 2007).

In contrast, CGE models offer a more detailed approach by modeling the interactions between different sectors and regions of the economy. CGE models explicitly capture the effects of climate policies on production, consumption, and trade across sectors, making them highly useful for evaluating the economy-wide impacts of climate policies, including carbon taxes, subsidies, and trade policies. CGE models have been widely used in global climate policy analysis to assess the economic impacts of mitigation strategies and to identify cost-effective pathways for emissions reductions (Böhringer et al. (2009); Eboli et al. (2010)). Nonetheless, CGE models also focus on a meso-economic level, which does not allow for analysis at the microeconomic level.

In response to these limitations, ABMs have emerged as an important tool for modeling climate change and economic transitions. ABMs simulate the interactions among heterogeneous agents — such as firms, households, and governments — who make decisions based on individual rules and objectives (Farmer et al., 2015). ABMs have been applied to study a range of topics, from financial crises to market dynamics and, more recently, to climate transitions (Farmer and Foley, 2009). These models can capture the nature of climate change impacts and allow for the simulation of complex, non-linear dynamics.

ABMs provide several advantages over traditional IAMs, particularly in their ability to model micro-level responses to policy interventions. For instance, they can capture how firms adjust to carbon pricing or other climate-related regulations, as well as how these adjustments cascade through supply chains and affect broader economic outcomes (Lamperti et al., 2018). Moreover, compared to CGE models, our ABM does not assume perfect competition, but firms set prices by applying a markup over production costs,[4] and the framework allows for detailed agent-level microeconomic analysis. Indeed, in our model, individual firms in the energy sector have an investment function that depends positively on their relative profit rate levels. This enables the endogenous growth, within the model, of firms producing energy from renewable sources with low marginal costs, compared to firms producing energy from fossil fuels. Investments are also linked to demand, in line with the Keynesian literature. This results in the possibility of outcomes that differ from those obtained with CGE models, which are essentially supply-driven, as demonstrated by Bachner et al. (2024) in their analysis of flood events. Additionally, ABMs are well-suited for studying the effects of policy uncertainty and the role of innovation in climate transitions. For instance, by simulating the interactions between firms, governments, and consumers, ABMs can provide insights into how different actors react to uncertain policy environments, such as changes in carbon tax rates or the introduction of renewable energy subsidies (Mercure et al. (2016); Lee et al. (2014)). ABMs could help simulate how an energy sector, including key industries like manufacturing and transport, would adapt to climate policies such as carbon pricing or energy efficiency standards (Gourdel et al., 2024). This approach would allow policymakers to understand the distributional impacts of climate policies and identify sectors that may require targeted support during the transition.

An example of ABM dealing with green transition is the MATRIX model (Multi-Agent Model for Transition Risks, Ciola et al. (2023)). It is designed to assess the impacts of energy shocks and the transition to a low-carbon economy, focusing on how energy price fluctuations, carbon taxes, and policy changes affect sectoral and regional economic outcomes, with particular emphasis on energy-intensive sectors and financial markets.

Lamperti et al. (2020) uses an agent-based integrated assessment model to explore the likelihood of transitioning to sustainable, green growth in the presence of climate damages. The model includes heterogeneous energy plants, firms, and a climate box that links emissions to temperature dynamics and economic shocks affecting labor productivity and energy demand. The results reveal two possible equilibria: a carbon-intensive lock-in and a sustainable growth path. The study also evaluates carbon taxes and green subsidies, finding that their effectiveness is limited and dependent on how climate change affects the economy, suggesting that complementary policies may be necessary to avoid carbon lock-ins.

Reissl et al. (2024) introduces an enhanced, stock-flow consistent version of the "Dystopian Schumpeter meeting Keynes" (DSK) agent-based integrated assessment model. By incorporating a fully specified accounting system, the model enables precise tracking of all balance sheet items and financial flows throughout the simulations. This advancement facilitates a comprehensive analysis of climate change and policy scenarios, focusing on their systemic effects on agent and sector-level balance sheet dynamics and financial stability. A further extension is given by Reissl et al. (2025): they coupled the DSK macroeconomic agent-based model with a process-based IAM (WITCH), which depicts detailed transition dynamics.

Other macroeconomic modeling approaches have been expanded to incorporate energy and climate dimensions. These include post-Keynesian ecological models that explicitly address financial and environmental interactions (e.g., Dafermos et al. (2018); Monasterolo and Raberto (2019); Semieniuk et al. (2022)), as well as non-linear behavioral frameworks (e.g., Campiglio et al. (2024)) and network-based representations of macro-financial-environmental linkages (e.g., Stangl et al. (2024)). One paper that studies electrification and transition to green energy production in a data-driven approach, as in our paper, is (Pettena and Raberto, 2024); this paper builds a stock-flow consistent model of the global economy (without a labor market).

In conclusion, while all these kinds of models offer valuable insights into the economic impacts of climate change and transition policies, no single model can fully capture the complexities of climate policy analysis. Bachner et al. (2020), in their macroeconomic assessments of low-carbon transition pathways, demonstrated that "the choice of model, i.e., which macroeconomic theory strand it arises from, influences the sign and magnitude of macroeconomic effects" (even more than assumptions about economic development and climate policies) and they call for multi-model comparisons. Frameworks that link macroeconomic, energy, and/or environmental models are often characterized by several assumptions, leading to potentially more variable results. Indeed, model risk is well recognized in economics (see, for example, Danielsson et al. (2016), in the context of financial models, where the authors state that "better understanding of model risk should lead to more robust policymaking"). It is even more evident in the hard sciences, such as meteorology, where the reliability of a weather forecast is assessed through the convergence of results from different models and simulations (meteorologists use ensembles, and if all simulations yield similar results, the forecast is considered more reliable, whereas large divergences indicate high uncertainty). Our

[4] Prices follow a cost-plus rule with a sector-specific markup treated as exogenous and not endogenously optimized (e.g., demand-reactive). Firms generate positive profits that do not systematically converge to zero over time, reflecting the imperfect competition embedded in the market structure. Introducing an endogenous markup choice represents a possible avenue for future research.

work produces results already found in the literature, but this does not make it any less relevant: being able to confirm the same type of result with different models greatly strengthens its reliability. As such, a multi-model approach that combines the strengths of different methodologies is essential for providing robust and comprehensive insights into the challenges and opportunities presented by climate change.

3. NGFS scenarios

The NGFS Phase IV scenarios define seven global climate trajectories grouped into four overarching classes based on combinations of transition and physical risks:

- Orderly Transition (e.g., Net Zero 2050, Below 2 °C, Low Demand): Early, coordinated policies minimize both risk types.
- Disorderly Transition (Delayed Transition): Late and abrupt actions create high transition risks.
- Hot House World (Current Policies, Nationally determined contributions NDCs): Weak or absent policy response leads to severe physical damages.
- Too Little, Too Late (Fragmented World): Ineffective, fragmented policies result in both high transition and physical risks.
  Each scenario reflects differing assumptions on policy ambition, technological progress, and international coordination.

Some central banks and financial regulators (such as the European Central Bank, the Banque de France, the National Bank of Austria) already use the NGFS scenarios for climate stress-test (Allen et al. (2020); Guth et al. (2021)).[5]

Aiello et al. (2024) analyzes how Italy's economy might respond to climate-related risks under seven NGFS Phase IV scenarios, with a focus on three key trajectories:

- Orderly Transition (e.g., Net Zero 2050): Prompt and coordinated policy action limits global warming to 1.5 °C. Short-term GDP losses are modest (~–1% by 2050), with rising inflation and interest rates in the near term. Government investment peaks at over 40% above baseline to support the transition. Private investment and consumption temporarily contract but gradually recover.
- Delayed Transition: Climate policy is postponed to after 2030, causing steeper carbon pricing and greater uncertainty. GDP falls by ~–3% by 2050, with more pronounced inflationary pressures and interest rate volatility. Both public and private investment shrink relative to the baseline.
- Hot House World (Current Policies): Inaction leads to high physical risks. GDP declines by up to –7%, primarily due to acute (heatwaves, droughts) and chronic (rise in temperature and sea level) physical shocks. Inflation rises modestly due to energy disruptions, and public investment remains subdued, limiting mitigation or adaptation.

Across scenarios, acute physical risk is the most significant driver of GDP loss, especially post-2040. Transition scenarios tend to front-load costs but are less damaging in the long-term. The study emphasizes that ambitious early policy action reduces both macroeconomic and climate damages, while delayed or fragmented transitions exacerbate them.

This result is in line with the findings of the climate scenario analysis performed in many jurisdictions ("Many exercises do not find severe impacts under an orderly scenario, but report more significant GDP and financial losses for disorderly transition scenarios, as well as more sizeable losses in the case of a no-transition scenario with high physical risks", FSB and NGFS (2022)), such as the ECB findings obtained with the stress test performed with the NGFS scenarios ("By comparing different transition scenarios, the results of the exercise show that acting immediately and decisively would provide significant benefits for the euro area economy and financial system, not only by maintaining the optimal net-zero emissions path (and therefore limiting the physical impact of climate change), but also by limiting financial risk", Emambakhsh et al. (2023)).

The NGFS scenario framework integrates physical risk models, IAMs, and the NiGEM macroeconomic model to assess the impacts of climate change and transition policies on national economies. IAMs simulate energy system changes and policy costs and provide GDP estimates and semi-endogenous adjustments based on transition costs, and NiGEM, while aligning its baseline with IAM outputs, expands the model to include other macro-financial indicators. NiGEM simulates the broader macroeconomic effects of both transition risks (e.g., policy costs) and chronic physical risks (e.g., climate damages).[6] However, NiGEM has notable limitations: it lacks sectoral detail, assumes static equilibrium, and applies inflation shocks in a simplified, top-down way. In the context of NGFS scenarios, adopting a data-driven ABM macroeconomic framework instead of NiGEM highlights significant methodological and analytical differences, particularly in handling inflationary shocks and sectoral interactions. The limitations of NiGEM compared to a potential ABM are: (a) lack of sectoral granularity. As a macroeconomic model, NiGEM does not explicitly represent economic sectors. Inflationary shocks, such as those caused by carbon taxes or climate damages, are applied at an aggregate level, neglecting how these impacts propagate through individual industries and supply chains. This can obscure crucial dynamics, such as sectoral vulnerabilities or cascading effects. At the opposite, ABMs can model heterogeneity at the sectoral level, capturing how specific industries react to inflationary pressures or policy changes and how their responses ripple through the economy. (b) Limited interaction dynamics and static assumptions. Being a general equilibrium model, NiGEM may oversimplify how economies evolve over time under disruptive scenarios, lacking the capability to represent emergent behaviors and inter-agent interactions. It is less equipped to handle non-linear transitions or tipping points triggered by climate shocks or rapid policy changes. ABMs inherently model out-of-equilibrium dynamics, allowing for the simulation of non-linear transitions and the exploration of how shocks disrupt economic stability over time.

An example of integrating the NGFS scenarios into a non-general equilibrium framework is provided by Gourdel et al. (2024), who use the EIRIN macroeconomic model to assess transition dynamics in the Euro area. Their results show that an orderly transition leads to both emission reductions and output growth, whereas a disorderly transition — characterized by higher physical risks — undermines economic performance and financial stability. The study also underscores the importance of credible climate policies in shaping investment decisions toward low-carbon sectors, thereby accelerating economic decarbonization and reducing the risk of carbon-stranded assets.

Differently from Gourdel et al. (2024), we integrate the NGFS scenarios in ABM framework. We start from the data-driven ABM firstly developed in Poledna et al. (2023) and we focus on Italy with the calibration developed by Di Domenico et al. (2025). Following

[5] For a review on climate scenario analysis, see FSB and NGFS (2022)

[6] The NGFS scenarios provide a detailed framework for analyzing climate-related risks and their economic implications through a suite-of-model approach. This approach integrates: (i) Physical Risk Models (e.g., ISIMIP, CLIMADA): Assess climate change impacts on sectors and regions; (ii) Transition Risk Models (IAMs: REMIND-MAgPIE, GCAM, MESSAGEix-GLOBIOM): Evaluate policy impacts, such as carbon taxes, on energy systems, emissions, and land use; (iii) Macroeconomic Model (NiGEM): Expands on IAM outputs by incorporating energy-related variables like carbon taxes and GDP shocks from physical risks, derived using temperature-based damage functions, to project macro-financial indicators such as inflation, unemployment, and housing market trends.

(Aiello et al., 2024), we focused on three of the seven NGFS Phase IV scenarios: Net Zero 2050, Delayed transition, and Current Policy. The choice indeed fell on the two "extreme" scenarios (Net Zero 2050 and Current Policy) and on one intermediate scenario (Delayed transition) as physical risk .

4. The model

This section describes the core structure of the model, which draws on the framework developed by Poledna et al. (2023). The economy is represented as a complex system comprising four institutional sectors: households, firms, government and the banking sector. These institutional sectors interact with the rest of the world through imports and exports. Firms populate 64 sectors based on the NACE 2-digit classification, and the model emphasizes the dynamic and interconnected nature of economic activities across these sectors. Markets are characterized by search and matching processes. The probability of a successful match depends on price competitiveness and firm size. Realized transactions are constrained by budget limitations and supply availability. Below, we describe the main equations governing the agents' behavior. For a comprehensive understanding of the model structure, see Poledna et al. (2023).[7] [8] To carry out our analysis, we introduced a set of modifications, which are detailed in Section 5.4. A complete list of used symbols is reported in Appendix A.

4.1. Households

Households act as consumers and suppliers of labor and capital. Households can be: (i) employed, earning a gross nominal wage $w_h(t)$; (ii) unemployed, receiving benefits at replacement rate θ^{UB}; or (iii) inactive (e.g., retirees, students), receiving $sb^{\mathrm{inact}}(t)$. Other lump-sum transfers are collected in $sb^{\mathrm{other}}(t)$. Disposable income accounts for the employee social-insurance rate τ^{SIW}, the income-tax rate τ^{INC}, and the consumption goods price index $\bar{P}^{\mathrm{HH}}(t)$; expected inflation $\pi^{\mathrm{e}}(t)$ follows an AR(1). Households may also receive dividends at payout ratio θ^{DIV} (subject to income rate τ^{INC} and the corporate rate τ^{FIRM}). The expected disposable income is

$$Y_h^{\mathrm{e}}(t) = \begin{cases} \left(w_h(t)\left(1-\tau^{\mathrm{SIW}}-\tau^{\mathrm{INC}}(1-\tau^{\mathrm{SIW}})\right) + sb^{\mathrm{other}}(t)\right)\bar{P}^{\mathrm{HH}}(t-1)(1+\pi^{\mathrm{e}}(t)) & \text{if employed} \\ \left(\theta^{\mathrm{UB}}w_h(t)+sb^{\mathrm{other}}(t)\right)\bar{P}^{\mathrm{HH}}(t-1)(1+\pi^{\mathrm{e}}(t)) & \text{if unemployed} \\ \left(sb^{\mathrm{inact}}(t)+sb^{\mathrm{other}}(t)\right)\bar{P}^{\mathrm{HH}}(t-1)(1+\pi^{\mathrm{e}}(t)) & \text{if not economically active} \\ \theta^{\mathrm{DIV}}(1-\tau^{\mathrm{INC}})(1-\tau^{\mathrm{FIRM}})\max(0,\Pi_i^{\mathrm{e}}(t)) + sb^{\mathrm{other}}(t)\bar{P}^{\mathrm{HH}}(t-1)(1+\pi^{\mathrm{e}}(t)) & \text{if investor in firm } i \\ \theta^{\mathrm{DIV}}(1-\tau^{\mathrm{INC}})(1-\tau^{\mathrm{FIRM}})\max(0,\Pi_k^{\mathrm{e}}(t)) + sb^{\mathrm{other}}(t)\bar{P}^{\mathrm{HH}}(t-1)(1+\pi^{\mathrm{e}}(t)) & \text{if a bank investor,} \end{cases} \quad (1)$$

where $\Pi_i^{\mathrm{e}}(t)$ and $\Pi_k^{\mathrm{e}}(t)$ are the expected profit based on the profit of the previous period of firm i and the banking sector, respectively.

Household consumption is modeled according to a Keynesian behavioral rule, whereby expenditure depends on expected disposable income rather than on intertemporal optimization (Keynes, 1936). This approach is consistent with post-Keynesian and stock–flow consistent macroeconomic frameworks (Godley and Lavoie, 2007).

Specifically, consumption is determined as a fixed share ψ of expected disposable income, net of VAT (τ^{VAT}):

$$C_h^{\mathrm{d}}(t) = \frac{\psi Y_h^{\mathrm{e}}(t)}{1+\tau^{\mathrm{VAT}}}, \quad (2)$$

Consumers then allocate their consumption budget to purchase different goods from firms. The consumption budget of household h devoted to good g is

$$C_{hg}^{d}(t) = \frac{b_g^{HH}\,\bar{P}_g(t-1)}{\bar{P}^{HH}(t-1)}\,C_h^{d}(t), \quad (3)$$

where b_g^{HH} denotes the share of total consumption allocated to good g. $\overline{P}_g(t)$ denotes the average producer price index for good g, computed as the output-weighted average of individual firm prices within the sector producing that good.

Households also invest in dwellings. The household investment is determined as a fixed share ψ_H of expected disposable income, net of taxes on investment goods (τ^{CF}).

$$I_h^{\mathrm{d}}(t) = \frac{\psi_H\, Y_h^{\mathrm{e}}(t)}{1+\tau^{\mathrm{CF}}}, \quad (4)$$

Investment demand by household h for product g is then determined by fixed weights b_{CFH}

$$I_{hg}^{\mathrm{d}}(t) = \frac{b_g^{\mathrm{CFH}}\,\bar{P}_g(t-1)}{\sum_g b_g^{\mathrm{CFH}}\,\bar{P}_g(t-1)}\,I_h^{\mathrm{d}}(t). \quad (5)$$

The calibration of ψ, ψ_H, and the expenditure shares b_g^{HH} and b_g^{CFH} ensures consistency with the empirical Italian input–output structure used in the model. In particular, it reproduces aggregate consumption levels and the observed composition between nondurable and durable goods.

Matching and transaction prices convert nominal budgets into real quantities.

4.2. Firms

Firms operate within industries, producing goods and services using labor, intermediate goods, and capital. They form expectations about future demand and adjust their production and investment accordingly.

Firms anticipate future demand $Q_i^s(t)$ based on past observations and macroeconomic growth expectations:

$$Q_i^{\mathrm{s}}(t) = Q_i^{\mathrm{d}}(t-1)(1+\gamma^{\mathrm{e}}(t)). \quad (6)$$

Firms employ a Leontief production function, reflecting fixed proportions among inputs:

$$Y_i(t) = \min\left(Q_i^{\mathrm{s}}(t), \alpha_i N_i(t), \beta_i M_i(t-1), \kappa_i K_i(t-1)\right), \quad (7)$$

where α_i, β_i, and κ_i represent productivity coefficients for labor ($N_i(t)$), intermediate goods ($M_i(t-1)$), and capital ($K_i(t-1)$), respectively.

Desired purchases of intermediates are real quantities tied to the planned scale:

$$\Delta M_i^{\mathrm{d}}(t) = \frac{\min\left(Q_i^{\mathrm{s}}(t),\ \kappa_i K_i(t-1)\right)}{\beta_i}, \quad (8)$$

The composition of intermediates across goods follows fixed input–output coefficients:

$$\Delta M_{ig}^{\mathrm{d}}(t) = a_{sg}\,\Delta M_i^{\mathrm{d}}(t) \quad (9)$$

[7] The full dataset and the code necessary to replicate the original model simulations are available at: https://zenodo.org/records/7271552.

[8] The data and programs required to reproduce the results reported in this article have been provided to *Energy Economics* as an online supplementary replication package. The replication package includes the simulation code, calibration files, scenario inputs, parameter files, post-processing routines, and benchmark outputs used to generate data and figures in the paper. Part of the computational implementation adapts the supplementary software of Poledna et al. (2023), originally released under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License. The adapted code is included in the replication package for journal replication, audit, review and publication purposes with permission from the original authors. Further redistribution or reuse of third-party-derived components is subject to the terms of the original license and to any permission required from the original rights holders.

where a_{sg} denotes the share of good g in the intermediate consumption bundle of sector s.

Firms invest in new capital to maintain production capacity. The desired investment $I_i^{\mathrm{d}}(t)$ is given by:

$$I_i^{\mathrm{d}}(t) = \frac{\delta_i}{\kappa_i} \min\left(Q_i^{\mathrm{s}}(t), \kappa_i K_i(t-1)\right), \tag{10}$$

where δ_i is the depreciation rate. Desired investment $I_i^{\mathrm{d}}(t)$ (define in real terms) is allocated across goods with fixed *real* shares:

$$I_{ig}^{\mathrm{d}}(t) = b_g^{\mathrm{CF}}\, I_i^{\mathrm{d}}(t) \tag{11}$$

where b_g^{CF} denotes the share of total investment allocated to good g. The evolution of the capital stock follows:

$$K_i(t) = K_i(t-1) - \frac{\delta_i}{\kappa_i} Y_i(t) + I_i(t). \tag{12}$$

Firms determine intermediate input demand and investment quantities in real terms, as implied by the Leontief production technology and the input–output structure. At this stage, decisions concern physical quantities required to sustain the planned scale of production, independently of current prices. Nominal expenditures are computed only after the search and matching process, once transactions occur and prices are realized.

4.2.1. External finance

Firms finance production and investment through internal funds and, when necessary, by borrowing from banks. Each firm i forms expectations about its future cash flow, defined as the expected variation in deposits:

$$\begin{aligned} \Delta D_i^{\mathrm{e}}(t) = {} & \underbrace{\Pi_i^{\mathrm{e}}(t)}_{\text{expected profits}} - \underbrace{\theta\, L_i(t-1)}_{\text{debt repayment}} - \underbrace{\tau^{\mathrm{FIRM}} \max[0, \Pi_i^{\mathrm{e}}(t)]}_{\text{corporate taxes}} \\ & - \underbrace{\theta^{\mathrm{DIV}}(1-\tau^{\mathrm{FIRM}}) \max[0, \Pi_i^{\mathrm{e}}(t)]}_{\text{dividend distribution}}. \end{aligned} \tag{13}$$

Expected profits are extrapolated from the previous period as

$$\Pi_i^{\mathrm{e}}(t) = \Pi_i(t-1)\,[1+\gamma^{\mathrm{e}}(t)]\,[1+\pi^{\mathrm{e}}(t)], \tag{14}$$

where $\gamma^{\mathrm{e}}(t)$ and $\pi^{\mathrm{e}}(t)$ denote expected real growth and inflation, respectively. If expected liquidity is negative, firms resort to external finance by requesting new credit:

$$\Delta L_i^{\mathrm{d}}(t) = \max\left\{0, -\Delta D_i^{\mathrm{e}}(t) - D_i(t-1)\right\}, \tag{15}$$

where $D_i(t-1)$ represents the firm's deposits at the beginning of the period. Thus, the desired credit $\Delta L_i^{\mathrm{d}}(t)$ equals the gap between required funds and internal resources.

Firm i's net cash flow $\Delta D_i(t)$ measures the change in its deposit account, reflecting all incoming and outgoing monetary flows within the period:

$$\begin{aligned} \Delta D_i(t) = {} & \underbrace{P_i(t) Q_i(t)}_{\text{Sales}} - \underbrace{(1+\tau^{\mathrm{SIF}}) w_i(t) N_i(t) \bar{P}^{\mathrm{HH}}(t)}_{\text{Labor costs}} - \underbrace{\bar{P}_i(t)\, \Delta M_i(t)}_{\text{Material costs}} \\ & - \underbrace{(\tau_i^{\mathrm{Y}} + \tau_i^{\mathrm{K}}) P_i(t) Y_i(t)}_{\text{Net taxes/subsidies on products and production}} - \underbrace{\tau^{\mathrm{FIRM}} \max[0, \Pi_i(t)]}_{\text{Corporate tax payments}} \\ & - \underbrace{\theta^{\mathrm{DIV}}(1-\tau^{\mathrm{FIRM}}) \max[0, \Pi_i(t)]}_{\text{Dividend payments}} \\ & - \underbrace{r(t)\left[L_i(t-1) + \max(0, -D_i(t-1))\right]}_{\text{Interest payments}} + \underbrace{\bar{r}(t) \max(0, D_i(t-1))}_{\text{Interest received}} \\ & - \underbrace{P_i^{\mathrm{CF}}(t) I_i(t)}_{\text{Investment costs}} + \underbrace{\Delta L_i(t)}_{\text{New credit}} - \underbrace{\theta\, L_i(t-1)}_{\text{Debt repayment}}. \end{aligned} \tag{16}$$

The first term represents total sales revenue, followed by outflows for wages and social-insurance contributions, intermediate inputs, indirect taxes, and interest or dividend payments. Positive profits lead to corporate tax payments and dividends, while firms with outstanding debt repay a fraction θ of past loans. When existing liquidity is insufficient, new loans $\Delta L_i(t)$ expand the firm's deposits, effectively injecting purchasing power into the economy. Deposits then evolve according to

$$D_i(t) = D_i(t-1) + \Delta D_i(t), \tag{17}$$

and total debt follows

$$L_i(t) = (1-\theta) L_i(t-1) + \Delta L_i(t). \tag{18}$$

4.3. Government

The government collects taxes and redistributes income through social benefits and consumption. Its behavior is modeled as exogenous but influenced by economic conditions. The growth rate of government consumption $\Delta_{\%} C_G(t)$ evolves according to:

$$\Delta_{\%} C_G(t) = \alpha_G \Delta_{\%} C_G(t-1) + \beta_G + \epsilon_G(t), \tag{19}$$

where $\epsilon_G(t)$ represents stochastic shocks and α_G and β_G are the parameters of the autoregressive model capturing the constant and the trend, respectively.

The nominal budget per government entity j is

$$C_j^{\mathrm{d}}(t) = \frac{C_G(t)}{\sum_g c_g^G\, \bar{P}_g(t-1)\,(1+\pi^{\mathrm{e}}(t))} \Big/ J, \tag{20}$$

where J indicates the number of government entities that execute public spending. Public spending is allocated across goods as

$$C_{jg}^{\mathrm{d}}(t) = \frac{c_g^G\, \bar{P}_g(t-1)}{\sum_g c_g^G\, \bar{P}_g(t-1)}\, C_j^{\mathrm{d}}(t). \tag{21}$$

where c_g^G denotes the share of total government consumption directed toward good g. Matching and transaction prices convert nominal budgets into real quantities.

The government's budget balance $\Pi_G(t)$ is:

$$\Pi_G(t) = Y_G(t) - \left(C_G(t) + B_G(t) + r_G L_G(t-1)\right), \tag{22}$$

where $Y_G(t)$ is tax revenue (see Eq. (33)), $B_G(t)$ is social benefit spending, and $r_G L_G(t-1)$ denotes interest payments. Public debt accumulates simply as:

$$L_G(t) = L_G(t-1) - \Pi_G(t). \tag{23}$$

4.4. Rest of the world

Trade dynamics are represented through imports and exports, capturing the interaction between domestic and foreign economies. Real imports $Y^{\mathrm{I}}(t)$ and exports $C^E(t)$ follow autoregressive processes on the growth rates:

$$\Delta_{\%} Y^{\mathrm{I}}(t) = \alpha^{\mathrm{I}} \Delta_{\%} Y^{\mathrm{I}}(t-1) + \beta^{\mathrm{I}} + \epsilon^{\mathrm{I}}(t), \tag{24}$$

$$\Delta_{\%} C^E(t) = \alpha^E \Delta_{\%} C^E(t-1) + \beta^E + \epsilon^E(t). \tag{25}$$

where ϵ represents stochastic shocks and α and β are the parameters of the autoregressive model capturing the constant and the trend, respectively. This formulation abstracts from explicit price and competitiveness effects, as imports and exports evolve independently of relative prices or exchange rates. While this simplification allows the results to be determined independently of domestic and foreign prices, future extensions could introduce price-dependent trade dynamics to capture real competitiveness channels more explicitly.

Total export demand $C^E(t)$ is split across L foreign consumers:

$$C_l^{\mathrm{d}}(t) = \frac{C^E(t)}{\sum_g c_g^E\, \bar{P}_g(t-1)\,(1+\pi^{\mathrm{e}}(t))} \Big/ L \tag{26}$$

and across goods:

$$C_{lg}^{\mathrm{d}}(t) = \frac{c_g^E\, \bar{P}_g(t-1)}{\sum_g c_g^E\, \bar{P}_g(t-1)}\, C_l^{\mathrm{d}}(t). \tag{27}$$

where c_g^E denotes the share of total export directed toward good g. Matching and transaction prices convert the nominal export budgets into real quantities.

A representative foreign firm m supplies quantity to import

$$Y_m(t) = c_g^I\, Y^I(t) \tag{28}$$

where c_g^I denotes the share of import directed toward good g.

4.5. Banking sector and central bank

The banking sector provides credit to firms and households, while the central bank sets the policy rate to stabilize inflation and growth. The policy interest rate $\bar{r}(t)$ follows a Taylor rule:

$$\bar{r}(t) = \max\left(0, \rho\bar{r}(t-1) + (1-\rho)\left(r^* + \pi^* + \xi^{\pi}(\pi^{\mathrm{EA}}(t) - \pi^*) + \xi^{\gamma}\gamma^{\mathrm{EA}}(t)\right)\right). \tag{29}$$

where ρ denotes the speed of adjustment of the policy rate, r^* is the real equilibrium interest rate, and π^* the central bank's inflation target. The parameters ξ^{π} and ξ^{y} represent the relative weights the central bank assigns to inflation stabilization and output growth, respectively. $\pi^{EA}(t)$ and $\gamma^{EA}(t)$ are the inflation and the economic growth of the monetary union which are assumed to follow an AR(1) process.

5. Model calibration and amendments

The model reproduces the structure of the Italian economy using a 1:1000 scaling ratio, which guarantees computational efficiency while preserving sufficient heterogeneity within sectors. Smaller scales, such as 1:100,000, would result in several industries containing fewer than one firm on average, preventing any representation of intra-sectoral dynamics. At the chosen scale, the simulated economy comprises roughly 25,900 economically active and 33,400 inactive households, about 1200 government entities, and 2500 foreign consumers. The production side is represented by 4,933 firms distributed across 62 sectors defined according to the NACE 2-digit classification, capturing the dynamic and interconnected nature of economic activity across industries.[9] Each industry retains a sufficient number of producers to generate sector-specific heterogeneity in productivity, investment, and pricing behavior. This scaling procedure preserves the relative composition of the Italian economy while keeping computational costs within feasible limits. A comprehensive summary of all calibrated parameters and population aggregates for the Italian economy in 2019 is reported in Table A.7.

Households are differentiated according to their labor-market status and income composition, following the structure detailed in Section 4.1. They can be (i) *employed*, earning a gross nominal wage $w_h(t)$; (ii) *unemployed*, receiving benefits at the replacement rate θ^{UB}; or (iii) *inactive*, such as retirees and students, receiving social transfers $sb^{\mathrm{inact}}(t)$. All households may also receive other lump-sum transfers $sb^{\mathrm{other}}(t)$, and some additionally act as *capitalists*, earning dividends from firm or bank profits. Specifically, one capitalist household is associated with each firm and each bank, receiving dividends at payout ratio θ^{DIV}, net of the income and corporate tax rates (τ^{INC}, τ^{FIRM}). Disposable income is therefore heterogeneous across households and evolves endogenously with employment status, fiscal policy, and expected inflation $\pi^{\mathrm{e}}(t)$ (see Eq. (1)). Through this structure, the model captures income differentiation between wage earners, transfer recipients, and capital owners, thereby allowing for distinct consumption and saving responses to economic shocks.

The simulation covers the period from 2020 to 2050, with each time step corresponding to one quarter. Population and labor productivity are treated as exogenous variables: the population of households and firms in the model reproduces the Italian economy at a 1-to-1000 scale and is held constant at its 2019 level, based on census data used for calibration, whereas productivity evolves according to scenario-specific assumptions. Carbon taxes are also exogenous, while green incentives are determined endogenously within the simulations, reflecting the interaction between fiscal policy, investment decisions, and the credit market.

5.1. Energy sector decomposition

We model the green transition as driven by two distinct dynamics: (i) Electrification, which refers to the growing share of electricity within the overall energy mix. In this process, both firms and households gradually substitute fossil fuel consumption with electricity, thereby lowering their emission intensity; (ii) Decarbonization of electricity generation, characterized by a progressive shift from brown (fossil-based) electricity producers to green (renewable-based) electricity producers, increasing the share of clean energy in total electricity supply.

Therefore, the energy sector, classified under CPA_D (NACE classification), divides into three subsectors based on the EXIOBASE database: green electricity production, brown electricity production and non-electricity production. The green electric sector includes renewable sources such as wind, solar and hydro, aiming to reduce emissions, while the brown electric sector encompasses fossil fuel-based electricity generation (gas, oil, coal). Finally, the non-electric sector covers energy production and use outside electricity, including transportation fuels, heating, and industrial processes. To achieve this distinction, the input–output table expands from the 62×62 format, as used by Di Domenico et al. (2025), to a 64×64 matrix. This require specifying the production functions for the three subsectors — green electric, brown electric, and non-electric — alongside detailing the production relationships between all industries and these subsectors. Furthermore, we disaggregate the demand (households and government consumption, investments, exports and imports, and intermediate consumption of firms) to specifically allocate it across the three energy subsectors, distinguishing the shares directed toward each of them.

To disaggregate the energy sector classified under NACE D35 into the three distinct subsectors, the process integrates data from EXIOBASE and NACE. This integration was necessary because Eurostat (based on NACE 2-digit) lacks a breakdown of green and brown energy production. EXIOBASE provides detailed input–output data, final demand, and production factors, specifically highlighting climate-related aspects.

First, we identify the EXIOBASE sectors that correspond to the disaggregated D35 NACE sector from Eurostat, according to our taxonomy, which groups them into the three subsectors. We report the mapping in Table 1.

To ensure consistency and maintain the balance between flows and stocks at the aggregate level, the values obtained from Eurostat (e.g. consumption, surplus, wages, taxes and so on) are allocated using

[9] Products are classified according to the Classification of Products by Activity (CPA), fully aligned with NACE, with a breakdown of 64 activities. However, entries for "Services provided by extraterritorial organizations and bodies" (CPA U) contain only zeros and are excluded. Similarly, entries for "Services of households as employers, undifferentiated goods and services produced by households for own use" (CPA T) are insignificant (less than 1% of the total labor factor) and are also excluded.

Table 1
Mapping D35 NACE sector (energy) into EXIOBASE sectors.

	NACE Sub Sectors	EXIOBASE Mapping
Brown	D35.1: Electric power generation, transmission and distribution	Distribution and trade of electricity Transmission of electricity Production of electricity by coal Production of electricity by gas Production of electricity by nuclear Production of electricity by petroleum and other oil derivatives
Green	D35.1: Electric power generation, transmission and distribution	Distribution and trade of electricity Transmission of electricity Production of electricity by hydro Production of electricity by wind Production of electricity by biomass and waste Production of electricity by solar photovoltaic Production of electricity by solar thermal Production of electricity by tide, wave, ocean Production of electricity by Geothermal Production of electricity nec
Non-electric	D35.2: Manufacture of gas, distribution of gaseous fuels through mains	Manufacture_of_gas, distribution of gaseous fuels through mains
	D35.3: Steam and air conditioning supply	Steam and hot water supply

Table 2
Allocation shares summary.

Ratios	Brown	Green	Not Electric
Capital Consumption	0.355	0.528	0.117
Capital Stock	0.355	0.528	0.117
Capital Formation	0.611	0.105	0.284
Household Consumption	0.751	0.246	0.002
Government Consumption	0.602	0.135	0.263
Export	0.620	0.099	0.281
Import	0.571	0.084	0.345
Inventories	0.623	0.095	0.282
Operating Surplus	0.356	0.496	0.148
Compensation Employees	0.322	0.076	0.602
Wages	0.322	0.076	0.602
Taxes Production	0.409	0.107	0.483
Taxes Products	0.506	0.412	0.082
Employment	0.322	0.076	0.602
Firms	0.440	0.440	0.121
Emissions	0.548	0.079	0.373

Table 3
Intermediate consumption disaggregation.

Intermediate Consumption Row Split			
Brown	0.479		
Green	0.160		
Not electric	0.361		
Intermediate Consumption Column Split			
	Brown	Green	Not Electric
B	0.745	0.248	0.006
C19	0.294	0.085	0.620
D	0.650	0.335	0.015
H49	0.281	0.102	0.616
...	0.333	0.333	0.333

proportional shares derived from the detailed sectoral breakdown available in the Exiobase dataset. For example, we calculate with Exiobase the share of capital consumption or operating surplus attributable to the green subsector in relation to the combined green, brown, and non-electric sectors. These calculated percentages were then applied to the total capital consumption or operating surplus reported by Eurostat for NACE D35, allowing for a consistent allocation of values across subsectors. The disaggregation is reported in Table 2.

Due to the lack of precise data on capital stock, we assume that the distribution among the three subsectors is proportional to the pattern observed in capital consumption. In addition, in the absence of detailed data on companies, we assume that their shares follow the same distribution as employment.

Intermediate consumption requires a separate discussion. To determine how other sectors source their inputs from the three energy subsectors, we use the contribution shares of these subsectors at the macro level as allocation keys (see Table 3). To disaggregate the intermediate consumption absorbed by the energy sector (D35) into its three subsectors, detailed data mapping the flows from all sectors to the three subsectors would ideally be required. However, this is not feasible due to the complexity of mapping 163 Exiobase sectors to the 64 NACE classifications. Consequently, we focus on the four most significant suppliers to the energy sector (within the NACE framework), which appear to be largely the most relevant. For these suppliers, we successfully map the data between EXIOBASE and Eurostat-NACE frameworks. For all other sectors, intermediate goods are divided equally into one-third for each of the energy subsectors. Below is a summary table of the contributive shares within the context of intermediate consumption:

Sectoral emissions data are calibrated based on the NACE Rev. 2 classification, provided by ISTAT within the framework of the Environmental Accounts, as shown in Fig. 1. In addition, to allocate emissions to green and brown electricity sectors, greenhouse gas emissions from EXIOBASE are used (Table 2).

5.2. Exogenous trends and endogenous propagation

The model integrates key NGFS scenario parameters, including carbon pricing, electrification rates, and carbon capture technologies.

Carbon taxes are applied across all sectors with values reported in Fig. 2 panel (a).

Electrification is modeled as an exogenous trend, reported in Fig. 2 panel (d). Indeed, the share of energy demand allocated to the two

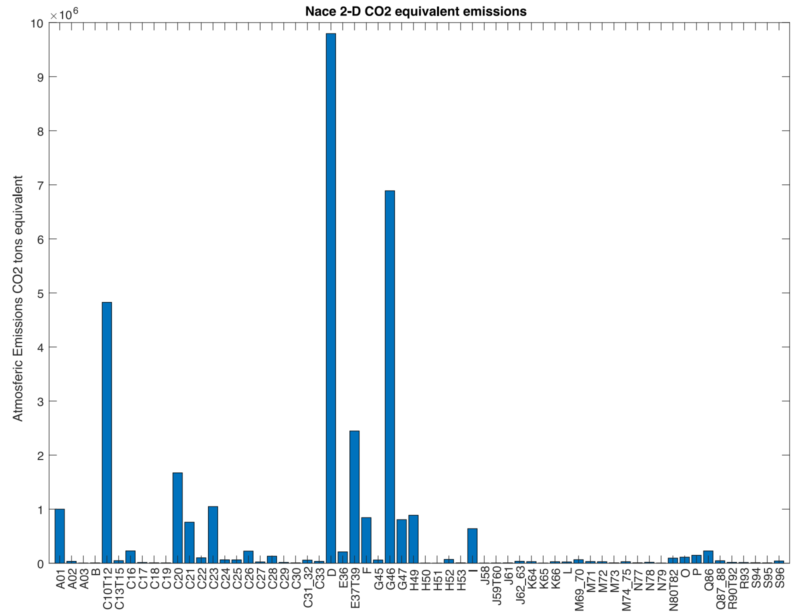

Fig. 1. The sectoral emissions data according to the NACE64 year 2020.
Source: ISTAT, Environmental Accounts and Atmospheric Emissions (NAMEA).

electricity sub-sectors increases at the rate of electrification growth projected in the corresponding NGFS scenarios, at the expense of the energy share of the non-electric sub-sector.

The amount of carbon capture and storage is shown in Fig. 2 panel (c) and is used for the reduction of total emissions.

To incorporate the effects of labor productivity growth and climate-related damages from temperature change, we also draw on labor productivity trends provided by the NGFS across different scenarios (Fig. 2 panel (b)), which show that higher emissions reduce labor productivity. However, physical climate damages are also expected to impact the stock of productive capital, a dynamic we acknowledge but leave for further exploration in future refinements of the model.

Labor productivity growth, and carbon capture are treated as exogenous factors, not driven by related endogenous investments in capital or research and development. Future developments of the model should take these aspects into account.

Although key transition drivers are introduced exogenously in order to ensure consistency with NGFS scenario trajectories, the macroeconomic and sectoral outcomes are not mechanically determined by these inputs. The model endogenously generates heterogeneous firm-level cost structures, profit rate differentials, credit constraints, and investment reallocations across sectors. Carbon pricing shocks propagate through the input–output production network via cost structures that reflect fixed technological coefficients and sector-specific emission intensities. As a result, the interaction between carbon pricing and sectoral production dynamics produces non-linear adjustment paths that depend on relative profitability, and network propagation effects. This framework therefore allows us to evaluate whether NGFS-consistent transition paths remain feasible once embedded into a decentralized, heterogeneous, and non-equilibrium production system.

5.3. Institutional interpretation of carbon pricing

The carbon price can be interpreted as a reduced-form shadow price associated with progressively tightening emissions caps, rather than as an additional tax layered on top of the EU Emissions Trading System — ETS (alternatively, it may be conceptualized as a tax-equivalent instrument that substitutes for the ETS altogether). This interpretation avoids any potential double-counting of regulatory costs. The model therefore captures the allocative effects of carbon pricing, while abstracting from the institutional microstructure of EU allowance trading. As the emissions cap declines over time, the resulting scarcity of allowances is expected to generate an increasing shadow price of carbon, reinforcing incentives for emissions reduction. This interpretation aligns with standard approaches in environmental and energy economics. Indeed, in empirical and theoretical analyses, the use of the carbon price as a proxy for the ETS mechanism is widespread. This approach captures the marginal cost of emissions embedded in the trading system without explicitly modeling its institutional complexity. Nordhaus (2019), who emphasizes carbon pricing as the central policy instrument for climate mitigation, in his speech upon receiving the Nobel Prize, clarifies that "Prices can be raised by putting a regulatory limit on the amount of allowable emissions and allowing trading ("cap-and-trade"), or by levying a tax on carbon emissions (a "carbon tax")". Weisbach and Metcalf (2009) explains that "a detailed consideration of how to implement a carbon tax can inform the discussion of how best to implement a cap-and-trade system should a cap-and-trade system end up being chosen as the carbon pricing mechanism". Notable contributions adopting this framework include (Stern, 2007), who highlights the role of carbon prices in guiding long-term investment decisions. Even though the use of carbon prices as a reduced-form representation of emissions trading systems is common in the literature, some studies, such as (Stern, 2008), Stavins (2019) and Chen et al. (2020), highlight the similarities and differences between these two approaches. Stern (2008) points out that "if taxation and carbon trading overlap, there are likely to be problems in establishing a clear and uniform price for carbon, leading to confused signals and inefficiency". However, if well-designed, they can coexist: (Cao et al., 2019) study the effect of a hybrid system with ETS and a carbon tax for non-ETS sectors. In practice, the regulatory system can become very complex. For instance, the European climate policy framework includes a set of coordinated regulatory and market-based

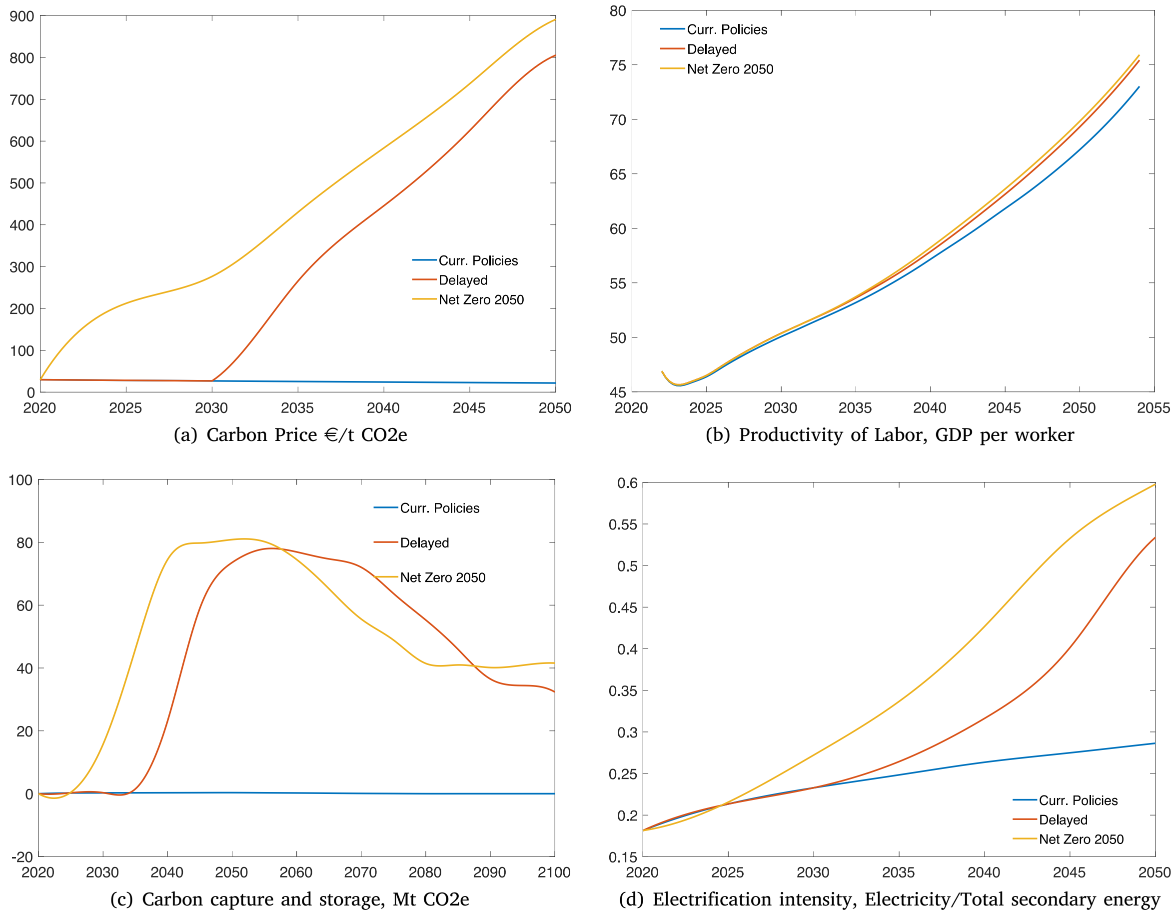

Fig. 2. NGFS IAM variables inputted into the ABM macro-model as exogenous trends.

instruments.[10] Taken together, these instruments define a coordinated cap-consistent framework in which the carbon price reflects the shadow value of progressively tightening emission constraints.

5.4. Model amendments

The key amendments needed to adapt the baseline model in order to perform the intended analysis are presented below. First of all, firms modify their pricing equation:

$$P_i(t) = P_i(t-1) \cdot \underbrace{(1+\pi_e)}_{\text{Expected inflation}} \cdot \underbrace{(1+\pi_i^c)}_{\text{Cost-push inflation}} \tag{30}$$

[10] Beside the EU Emissions Trading System, established by Directive 2003/87/EC and subsequently revised under the "Fit for 55" package, the Effort Sharing Regulation (Regulation (EU) 2018/842) sets binding national emission reduction targets for non-ETS sectors, effectively extending carbon constraints beyond the ETS coverage. The Carbon Border Adjustment Mechanism (Regulation (EU) 2023/956) introduces a carbon price adjustment on selected imports to mitigate leakage and preserve competitiveness under tightening EU carbon constraints. The "Fit for 55" legislative package (European Commission, 2021) revises ETS caps, expands sectoral coverage (including maritime and buildings), and accelerates renewable deployment. REPowerEU (European Commission, 2022) complements decarbonization objectives with accelerated electrification and renewable energy targets in response to energy security concerns. Finally, the Market Stability Reserve (MSR) adjusts the supply of emission allowances in the ETS in response to allowance surpluses, stabilizing the carbon price path.

by adding the carbon tax (in red) and subtracting the green production incentive (in green) in the cost-push formulation

$$\begin{aligned}\pi_i^c(t) = {} & \underbrace{\frac{(1+\tau^{\mathrm{SIF}})\bar{w}_i}{\bar{\alpha}_i}\left(\frac{\bar{P}^{\mathrm{HH}}(t-1)}{P_i(t-1)}-1\right)}_{\text{Increase of unit labor costs}} + \underbrace{\frac{1}{\beta_i}\sum_g a_{sg}\left(\frac{\bar{P}_g(t-1)}{P_i(t-1)}-1\right)}_{\text{Increase of unit Material costs}} \\ & + \underbrace{\frac{\delta_i}{\kappa_i}\left(\frac{\bar{P}^{\mathrm{CF}}(t-1)}{P_i(t-1)}-1\right)}_{\text{Increase of unit capital costs}} + \underbrace{\mu_i^e\left(\frac{CP(t-1)}{P_i(t-1)}-1\right)}_{\text{Increase of carbon unitary cost}} \\ & - \underbrace{\left(\frac{inc_{gr}(t-1)}{P_i(t-1)}-1\right)}_{\text{Increase of green incentives}} \qquad \forall i \in I_s\end{aligned} \tag{31}$$

. Here, $\bar{\alpha}_i$ represents the average labor productivity, while $\bar{w}_i$ denotes the average gross wage adjusted by the household consumer price index $\bar{P}^{\mathrm{HH}}(t)$, and includes the employer's contribution to social insurance at rate τ^{SIF}. $\frac{1}{\beta_i}\sum_g a_{sg}$ are the unit costs (in real terms) of intermediate inputs used by sector s for good g, weighted by $\bar{P}_g(t)$ of good g.

Capital costs per unit of output are determined by the depreciation rate δ_i and the capital productivity coefficient ϕ_i. Finally, $\bar{P}^{\mathrm{CF}}(t)$ denotes the average price of capital goods.

$\mu_i^e = \frac{E_i}{Y_i}$ denotes the emission intensity of firm i, defined as the ratio between emissions E_i and output Y_i. We assume a full pass-through of the carbon price to the final price of energy and goods. This is consistent with empirical findings, as shown by Lafrogne-Joussier et al. (2023) in the context of the recent energy crisis triggered by

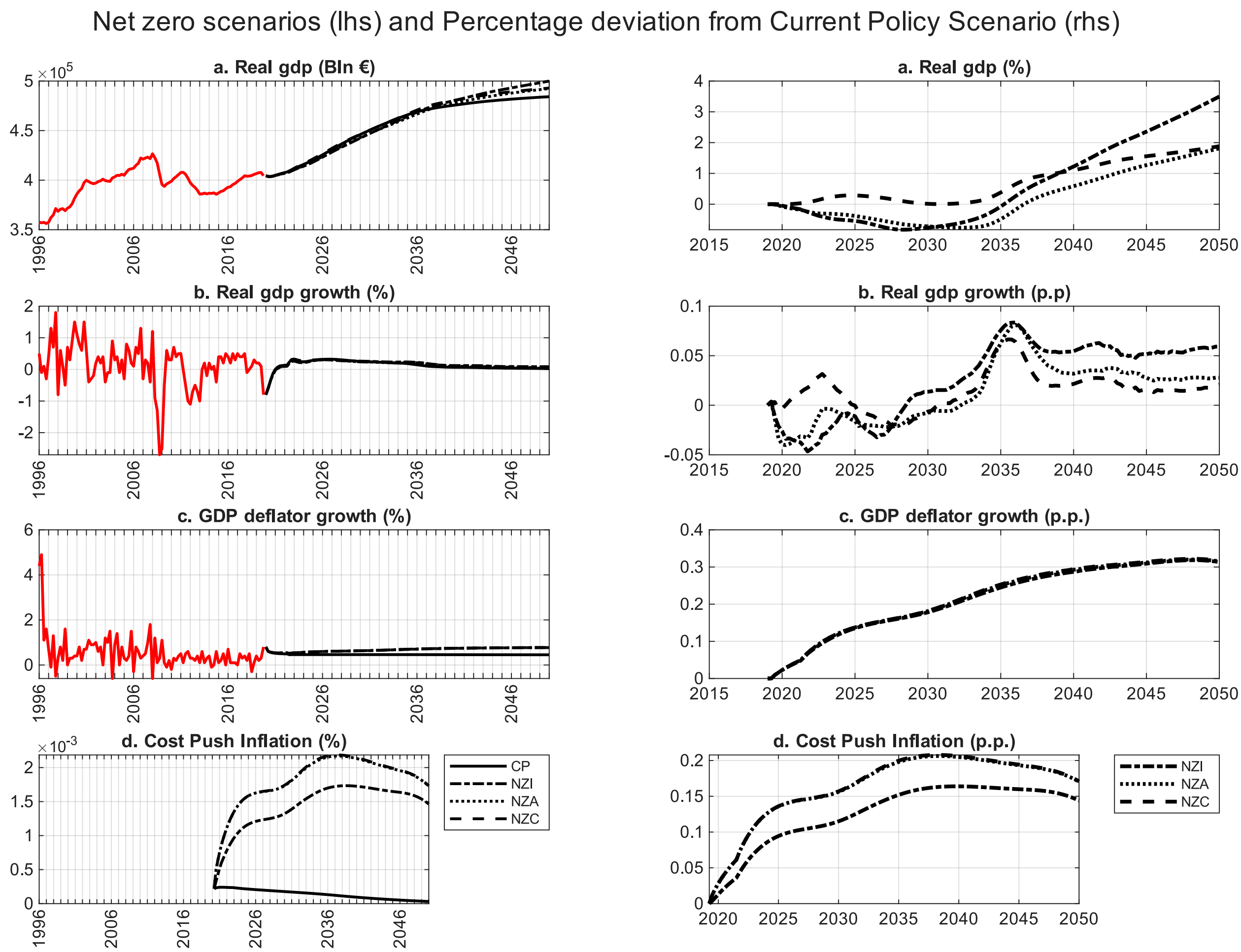

Fig. 3. Impact of carbon pricing policy. Net-zero scenario, absolute values (left panels), percentage deviation from Current policy (right panels).

the Russian invasion of Ukraine, as well as with similar modeling frameworks, such as (Reissl et al., 2025).

inc_gr is the green incentive per unit of product, computed as the total amount of carbon tax revenues collected by the government divided by the total output of green energy production. This makes the incentive endogenously determined within the simulation, since both the tax revenues and the output of the green electricity sector evolve according to the model's internal dynamics. This incentive applies exclusively to the green electricity production sector.

As a second modification, we revised the firms' profit equation to incorporate both the carbon tax and the green incentive, highlighted in color, as follows:

$$\begin{aligned}\Pi_i(t) = {} & \underbrace{P_i(t)Q_i(t)}_{\text{Sales}} + \underbrace{P_i(t)\Delta S_i(t)}_{\text{Inventory change}} - \underbrace{(1+\tau^{\text{SIF}})w_i(t)N_i(t)\bar{P}^{\text{HH}}(t)}_{\text{Labor costs}} \\ & - \underbrace{\frac{1}{\beta_i}\bar{P}_i(t)Y_i(t)}_{\text{Material costs}} - \underbrace{\frac{\delta_i}{\kappa_i}P_i^{\text{CF}}(t)Y_i(t)}_{\text{Depreciation}} - \underbrace{\mu_i^e CP_i(t)Y_i(t)}_{\text{Carbon Price Taxation}} + \underbrace{inc_{gr}(t-1)Y_i(t)}_{\text{Green incentives}} \\ & - \underbrace{\tau_i^{\text{Y}} P_i(t)Y_i(t) - \tau_i^{\text{K}} P_i(t)Y_i(t)}_{\text{Net taxes/subsidies on products/production}} \underbrace{- r(t)(L_i(t-1) + \max(0, -D_i(t-1)))}_{\text{Interest payments}} \\ & + \underbrace{\bar{r}(t)\max(0, D_i(t-1))}_{\text{Interest received}}\end{aligned} \qquad (32)$$

As before, the green incentive applies exclusively to the firms operating in the green electricity production sector.

In line with the previous modification, the government's revenue equation is adjusted as follows:

$$\begin{aligned}Y^{\text{G}}(t) = {} & \underbrace{(\tau^{\text{SIF}} + \tau^{\text{SIW}})\bar{P}^{\text{HH}}(t)\sum_{h\in H^{\text{E}}(t)} w_h(t)}_{\text{Social security contributions}} + \underbrace{\tau^{\text{INC}}(1-\tau^{\text{SIW}})\bar{P}^{\text{HH}}(t)\sum_{h\in H^{\text{E}}(t)} w_h(t)}_{\text{Labor income taxes}} \\ & + \underbrace{\tau^{\text{VAT}}\sum_h C_h(t)}_{\text{Value added taxes}} + \underbrace{\tau^{\text{INC}}(1-\tau^{\text{FIRM}})\theta^{\text{DIV}}\left(\sum_i \max(0,\Pi_i(t)) + \max(0,\Pi_k(t))\right)}_{\text{Capital income taxes}} \\ & + \underbrace{\tau^{\text{FIRM}}\left(\sum_i \max(0,\Pi_i(t)) + \max(0,\Pi_k(t))\right)}_{\text{Corporate income taxes}} + \underbrace{\tau^{\text{CF}}\sum_h I_h(t)}_{\text{Taxes on capital formation}} \\ & + \underbrace{\sum_i \tau_i^{\text{Y}} P_i(t)Y_i(t)}_{\text{Net taxes/subsidies on products}} + \underbrace{\sum_i \tau_i^{\text{K}} P_i(t)Y_i(t)}_{\text{Net taxes/subsidies on production}} \\ & + \underbrace{\tau^{\text{EXPORT}}\sum_l C_l(t)}_{\text{Export taxes}} + \underbrace{CP(t)\sum_i E_i Y_i(t)}_{\text{Carbon taxation}} - \underbrace{inc_{gr}(t)\sum_i E_i Y_i(t)}_{\text{Carbon incentives}}\end{aligned} \qquad (33)$$

. Moreover, we modify firms' expectations and investment behavior. Specifically, for the D35.1 electricity production sector, we introduce an adjustment factor in the setting of desired production, denoted as

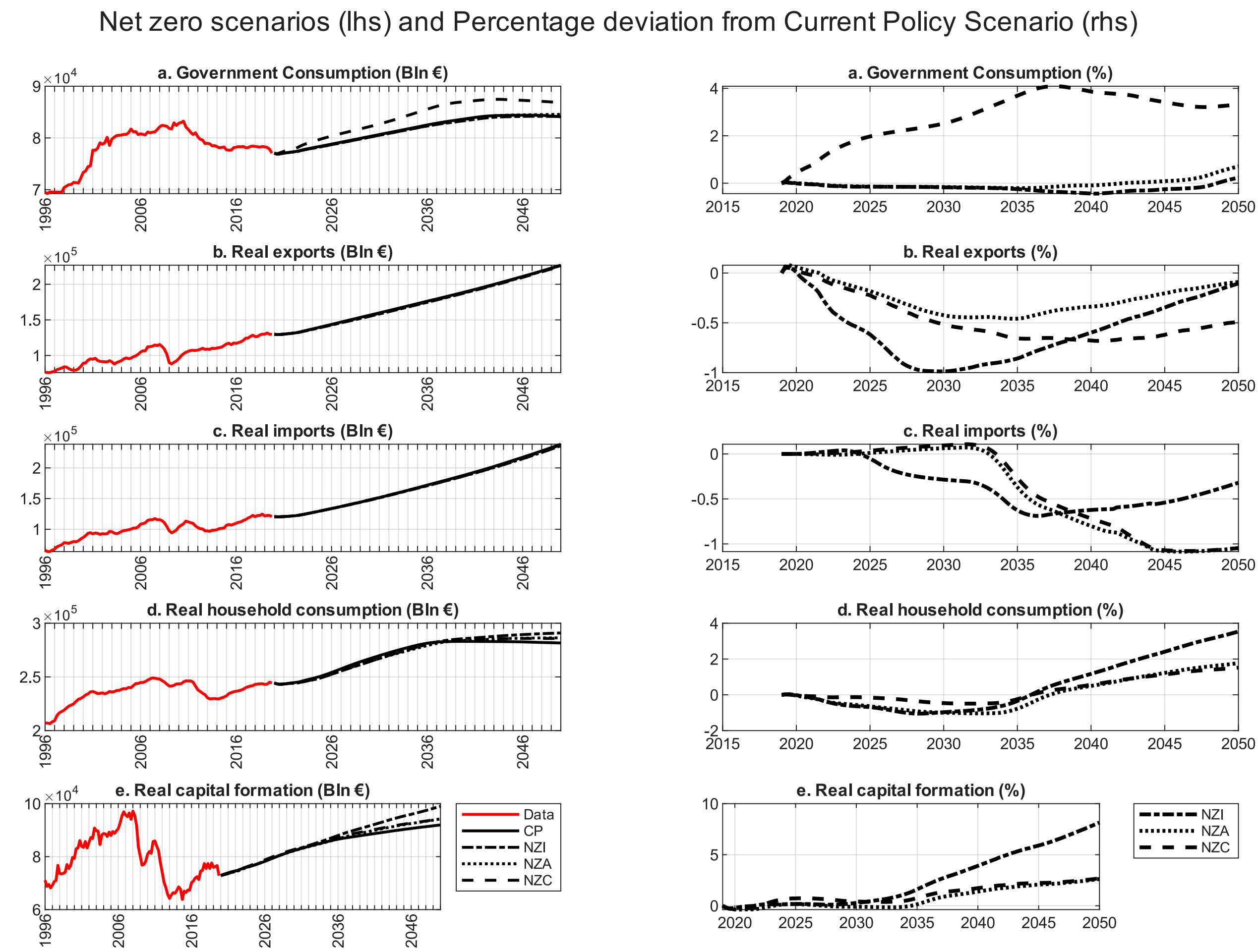

Fig. 4. Impact of carbon pricing policy. Net-zero scenario, absolute values (left panels), percentage deviation from Current policy (right panels).

$\phi(t)$

$$Q_i^s(t) = Q_i^d(t-1)(1+\gamma^e(t))(1+\phi(t)). \tag{34}$$

where ϕ is the gap between the profit rate of a firm (i) and the average profit rate of the corresponding industry (s). This amendment reflects relative profitability within the sector: if a firm performs above the industry average, it increases its investment; if it performs below average, it reduces it.

In addition, the original investment function for all firms used in Poledna et al. (2023)

$$I_i^d(t) = \frac{\delta_i}{\kappa_i} \min\left(Q_i^s(t), \kappa_i K_i(t-1)\right) \tag{35}$$

is amended to allow for positive net investment and to account for the need to replace machinery powered by non-electric energy with electrically powered alternatives, in line with the exogenous electrification trend (g_{elec}), determined from the NGFS scenario, as follows:

$$I_i^d(t) = g_{elec} \frac{\delta_i}{\kappa_i} Q_i^s(t) \tag{36}$$

The need for increased investment is consistent with the findings of Pettena and Raberto (2024), who highlight how the transition toward a low-carbon economy requires sustained investment efforts.

Finally, we amend the energy market matching. The non-electric market operates under the same search and matching protocol used across the rest of the economy, ensuring consistency with broader economic interactions. In contrast, the electricity market, comprising both green and brown sub-sectors, follows distinct dynamics. Market clearing ensures that, when available, supply fully meets demand, and a uniform selling price is determined by the marginal cost of the least efficient producer, effectively establishing a single price for all the firms across the two sub-sectors.

6. Results

The simulation covers the period from 2020 to 2050, with each time step corresponding to one quarter. In this section, we present the results of the computational experiments. We perform simulations for seven distinct cases, built upon three NGFS scenarios:

- Current Policy scenario (CP): Assumes no additional regulatory interventions beyond those already implemented, ultimately leading to a “hot house world” trajectory with persistently high emissions.
- Net Zero scenario (NZ): Represents a deep transition pathway aimed at achieving net-zero greenhouse gas emissions by 2050. It involves a major shift from fossil fuels to renewable energy sources, electrification of transport and industry, implementation of carbon pricing, and the deployment of carbon dioxide removal technologies.
- Delayed scenario (DS): Assumes that the implementation of climate policies consistent with the Net Zero scenario is postponed until after 2030.

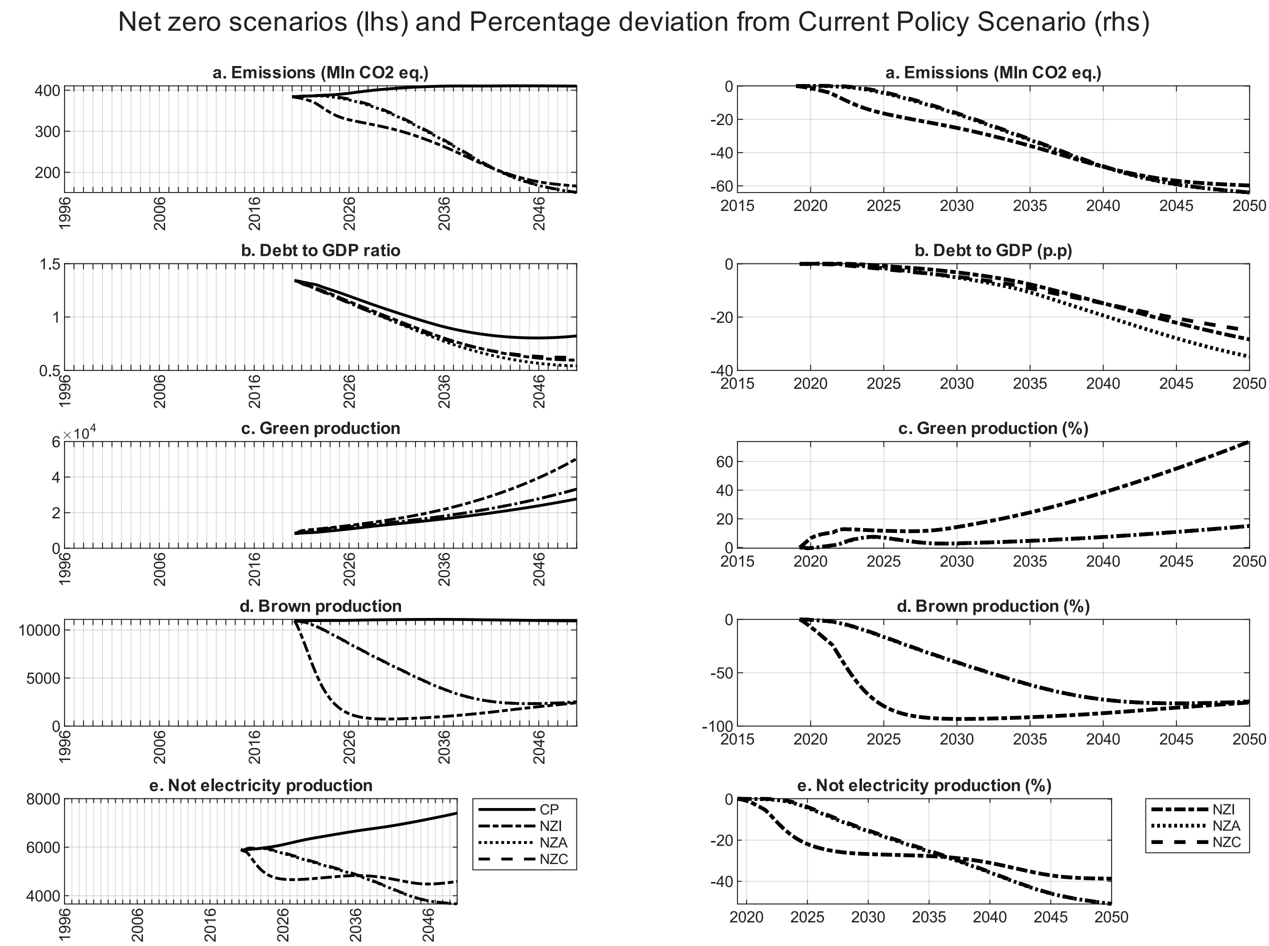

Fig. 5. Impact of carbon pricing policy. Net-zero scenario, absolute values (left panels), percentage deviation from Current policy (right panels).

For both the DS and NZ scenarios, we perform three experiments each:

- Debt Abatement (DSA and NZA): Carbon tax revenues are used to reduce government debt.
- Production Incentive (DSI and NZI): Carbon tax revenues are redirected to green electricity-producing firms to support investment and sectoral expansion.
- Government consumption (DSC and NZC): Carbon tax revenues are used to finance additional public consumption.

Figures from 3 to 8 show the simulation results and the deviations of the various DS and NZ scenarios from the current policy scenario, which serves as the baseline.

We start analyzing the NZ case presented in figures from 3 to 5. First, in Fig. 3 panel a–b, we note that the effects of a net zero strategy on GDP are modest: in the NZA and NZI scenarios GDP is about one percentage point below the CP case until the early 2030s, then growth becomes stronger than the CP case, and by 2050 GDP is higher than CP by about 2% for the NZA case and by more than 3% in the NZI case. The case with incentives concludes the simulation with the best performance mainly due to a higher level of investment (especially in green power generation), but also a higher level of household consumption driven by higher economic growth, as shown in Fig. 4 panel d. In addition, the small relative reduction in GDP recorded in the short to medium term can be avoided by using carbon tax revenues in state consumption. Indeed, the NZC case shows that there is never any reduction in GDP compared to the CP case. An increase in public spending in the short to medium run raises income, thereby mitigating the loss in household consumption and slightly increasing capital formation (Fig. 4, panels a, d and e). Moreover, in the long run, i.e. up to 2050, the NZC simulations result in a 2% increase in GDP, similar to the NZA case. These results are in line with much of the literature on the subject. Indeed, Reissl et al. (2025) report that "Empirical evidence regarding the macroeconomic effects of carbon pricing is somewhat mixed, with some studies finding no or even small positive effects on GDP (Metcalf, 2019; Metcalf and Stock, 2023) and others predicting negative impacts in the short run (Kanzig, 2023). Model-based analyses often predict that aggressive carbon pricing may reduce GDP and employment, but highlight that appropriate revenue recycling can mitigate these outcomes (Brenner et al. 2007; Conefrey et al. 2013; Allan et al. 2014; Rivera et al. 2016; Vermeulen et al. 2018; Allen et al. 2020; Wieners et al. 2024)".

Analyzing inflation (Fig. 3, panel c–d), we see that the carbon tax induces an increase in GDP deflator. Focusing on cost push inflation, that is essentially zero in the CP case, we observe a significant increase in the net zero scenarios because of the carbon tax (as already explained, we assume a full pass-through of the carbon price to the final price of energy and goods). However, the cost-push remains at low levels. Moreover the NZI scenario manages to slightly reduce cost-push inflation due to the increased substitution of energy from fossil

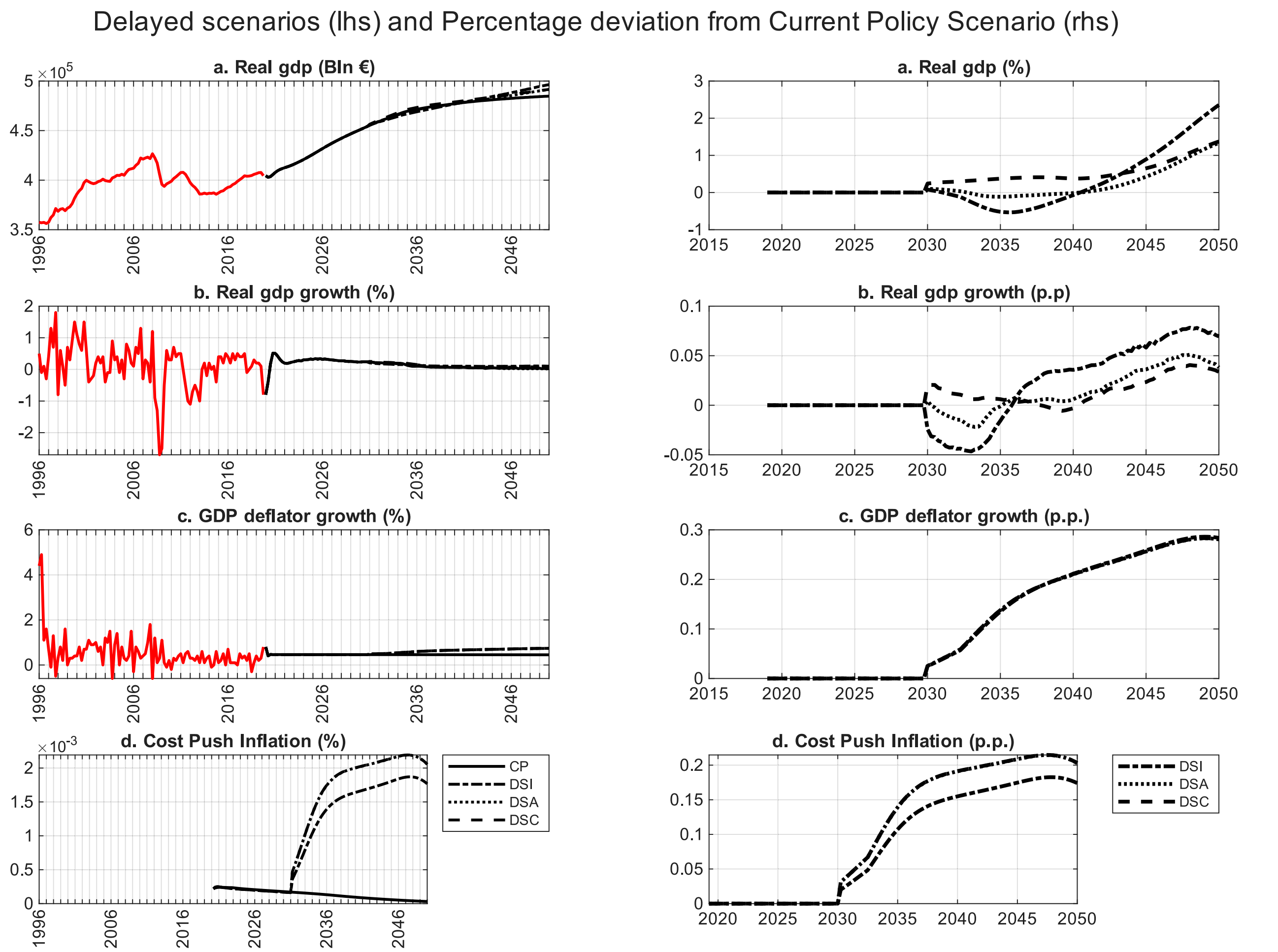

Fig. 6. Impact of carbon pricing policy. Delayed mitigation scenario, absolute values (left panels), percentage deviation from Current policy (right panels).

sources to renewable sources (Fig. 5 panel c–d), which, by eliminating producers with higher marginal costs, allows a reduction in the cost of energy.

The net zero scenario leads to a reduction in emissions of about 60 percent by 2050 (Fig. 5 panel a), thus not achieving zero emissions, but still having a very significant positive impact. We point out how the NZI scenario has a stronger impact in reducing emissions in the short run due to the greater substitution of renewable energy production at the expense of fossil energy production, although in the long run the reduction is smaller than in the case without incentives to renewable energy producing companies due to the higher long-term economic growth found in the NZI simulation.

Finally, we comment on the debt-to-GDP ratio (Fig. 5 panel b), which declines in all simulations, including the Current Policy scenario, as a result of the model calibration. However, in scenarios that involve significant carbon taxation, the model predicts a further reduction in public debt. This is obviously more pronounced in case the state uses carbon tax revenues to bring down debt. Still, the debt abatement remains strong even if the state spends the revenues from the carbon tax. Indeed, these simulations see nominal GDP growing, both because of real GDP growth and inflation growth, and this can add up to a smaller deficit due to higher tax revenues and a reduction in social spending linked to real GDP growth.

We also study the Delayed scenario. In this case, the simulations in the various settings are obviously the same until 2030. From 2030 onward, similar trends are found as in the NZ scenarios. In particular:

- GDP shows a marginal short-run decline in the DSI case compared to the CP scenario, but sees more growth in the long run driven by the investments in the renewable energy sector. In the DSC case, on the other hand, there is GDP growth even in the short term. Final GDP is slightly lower than that observed in the corresponding NZ scenarios.
- GDP deflator rises driven by cost push inflation due to carbon tax;
- CO_2 emissions are reduced, albeit by a smaller amount than in the NZ case.

The use of a disaggregated agent-based model allows for a detailed analysis of the economic performance of individual industries (for the list of industries see Table B.8). Sector-specific variations in performance can be significant, particularly for fossil fuel-related or energy-intensive sectors, which may face greater challenges. As illustrated in Fig. 9, certain sectors — such as agriculture (sector A) and mining (sector B) — appear to be more adversely affected by the short-term downturn associated with the carbon tax driven ecological transition, which also entails a restructuring of supply chains. In contrast, other sectors — including construction (sector F) and various service sectors (from M to S), such as education, healthcare, and public

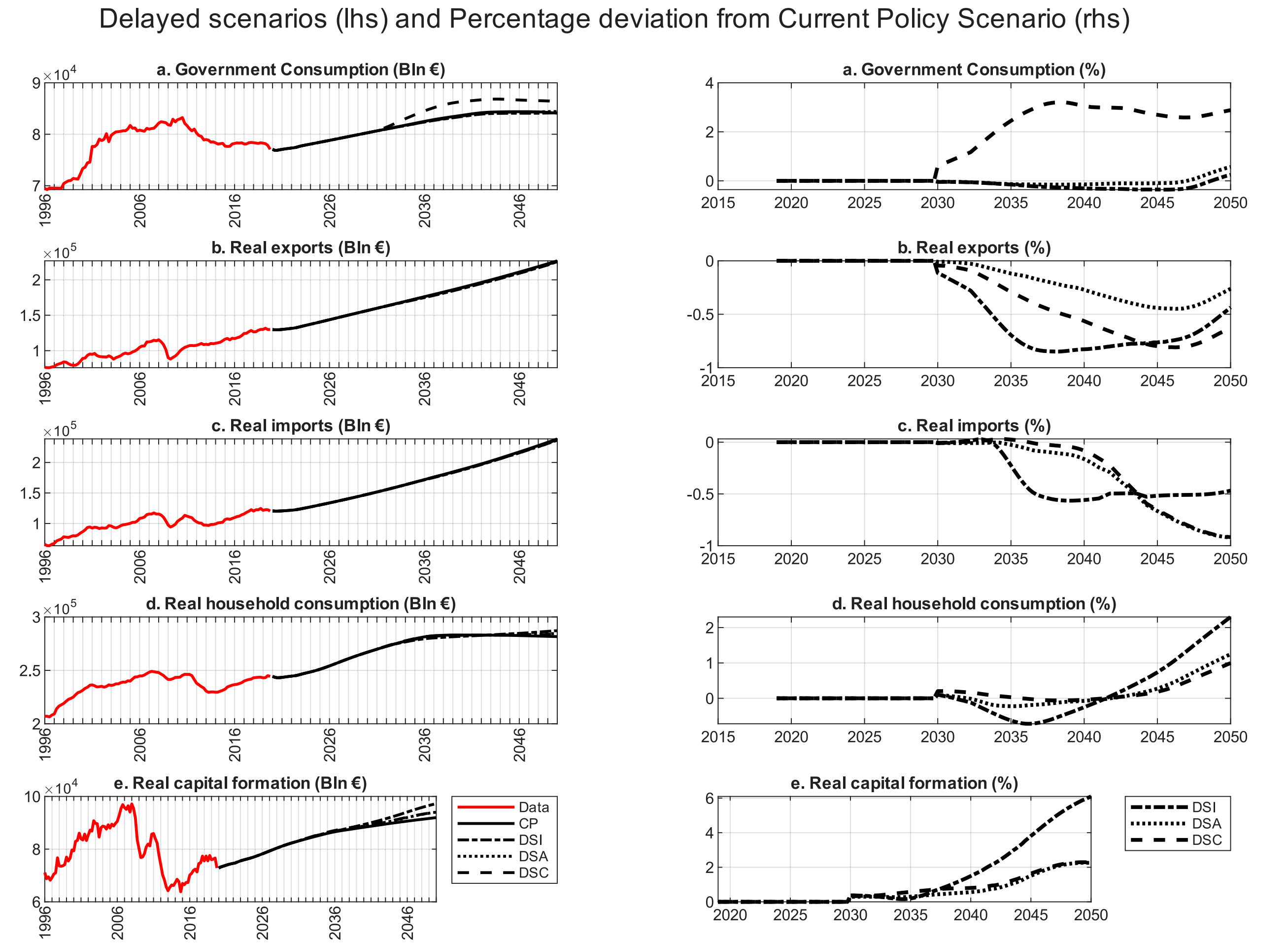

Fig. 7. Impact of carbon pricing policy. Delayed mitigation scenario, absolute values (left panels), percentage deviation from Current policy (right panels).

administration — experience relatively milder impacts. Moreover, the public spending rebate policy (NZC scenario) benefits the majority of sectors, and in particular sectors from O to R show a significant short term improvement. Finally, under the NZI scenario, the energy sector (D) exhibits a substantial long-term increase.

6.1. Robustness checks

As a robustness check, we perform 100 Monte Carlo simulations with yearly initialization from 2011Q1 to 2019Q1. The results for the Current Policy and the Net Zero with Debt Abatement scenarios are reported in Appendix C.1. Main results are confirmed.

As a further robustness check, we tested the system's response to different carbon tax levels (set at 150% and 200% of the level used in the previous simulation) within the net-zero scenario, where carbon tax revenues are used to reduce public debt. The results, reported in Appendix C.2, confirm the findings obtained so far. However, a larger reduction in GDP is observed in the short to medium term as the carbon tax increases (although the magnitude of the decline remains small), followed by a subsequent recovery. The same trend applies to government and household consumption, exports, imports, and real capital formation. The most significant deviation, albeit remaining at very modest absolute values, is in inflation, which rises as the carbon tax increases. Simulations show that increasing carbon pricing alone generates additional emission reductions but remains insufficient. In other words, under the behavioral and technological rigidities embedded in the Italian production network, NGFS-consistent carbon pricing and electrification trajectories appear insufficient to guarantee full net-zero convergence without stronger structural transformation mechanisms. Therefore, in Appendix C.3 we perform intensity tests by increasing both carbon price and electrification drivers beyond baseline levels to evaluate whether, and under which conditions, decentralized production dynamics can converge toward full net-zero emissions. We find that, a joint intensification of carbon pricing and electrification produces a non-linear acceleration in the substitution dynamics, allowing convergence toward net-zero emissions.

To address concerns related to structural breaks and geopolitical uncertainty, we conduct an additional set of stress-test simulations that introduce temporary but significant shocks to key structural parameters. Specifically, we consider an acute energy crisis (AEC), a broader geopolitical disruption (GD), and persistent trade fragmentation (PTF). These shocks are implemented independently of the NGFS transition drivers and are superimposed on the baseline Net Zero scenario described in Appendix C.3, with the aim of assessing the additional adjustments required to fully eliminate residual emissions. Detailed results are reported in Appendix C.4. All three stress scenarios lead to an immediate drop in real GDP compared with the Current Policies benchmark, accompanied by a higher path for the GDP deflator. Importantly, however, these disturbances do not alter the long-run direction of the transition: emissions reductions remain largely driven by policy measures. In the short run, emissions fall more sharply in the scenarios with external shocks, mainly due to the strong contraction in

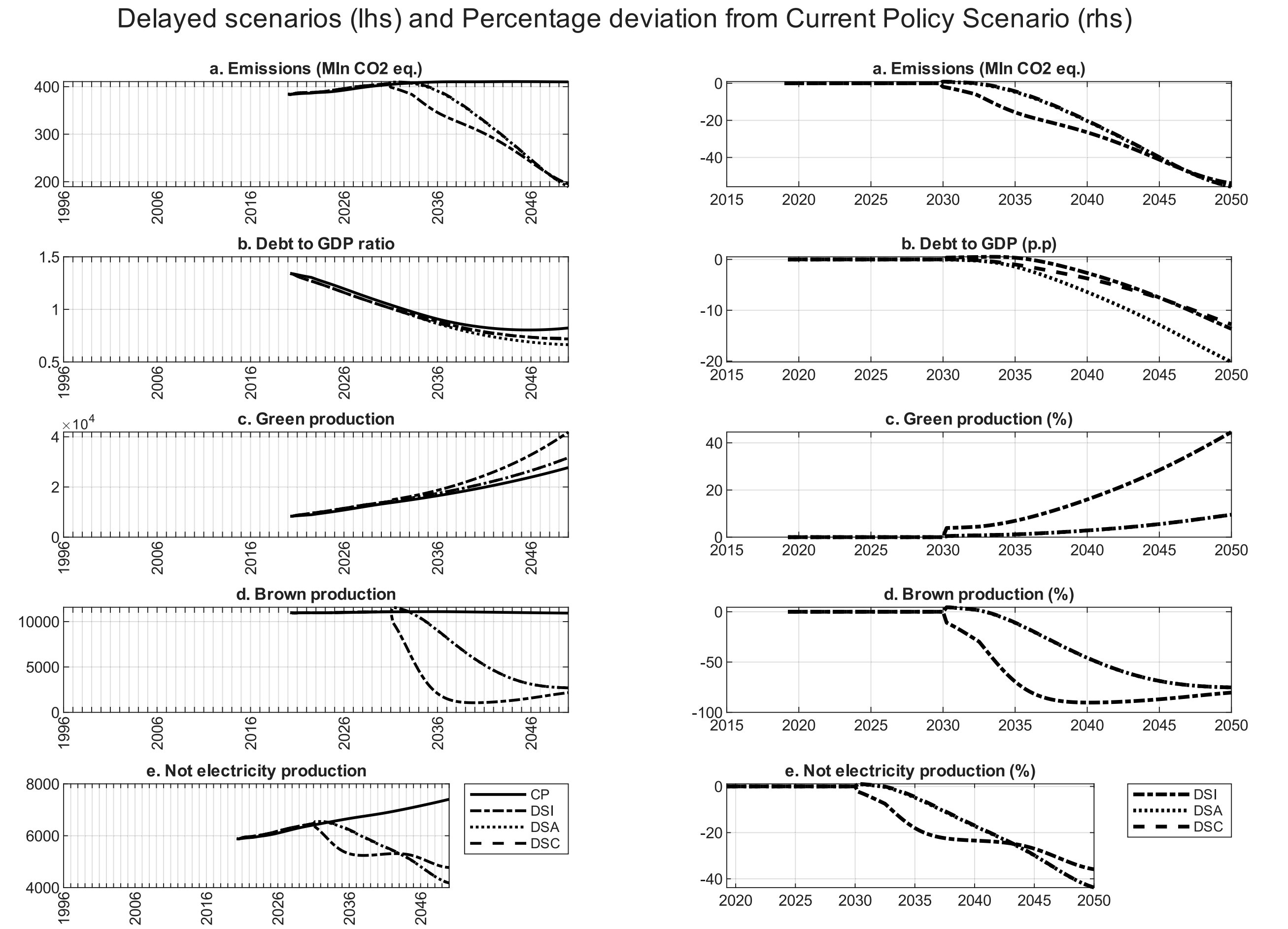

Fig. 8. Impact of carbon pricing policy. Delayed mitigation scenario, absolute values (left panels), percentage deviation from Current policy (right panels).

production. This result should be interpreted in light of the fact that the model does not include structural behavioral changes triggered by such shocks.

7. Conclusions and future developments

In this study, the application of an ABM calibrated for the Italian economy has enabled a detailed exploration of the macroeconomic effects of different NGFS climate scenarios, including Current Policy, Delayed and Net Zero scenarios. By integrating carbon-price paths and electrification trends into the framework, the model provides insights into sectoral and aggregate dynamics, offering a granular understanding of the trade-offs involved.

The simulation results reveal several important findings. First, emissions decline under both the Delayed (moderate reduction) and Net Zero (substantial reduction) scenarios, although in our decentralized economy setting the benchmark NGFS-consistent transition path remains insufficient to deliver literal net-zero emissions by 2050. Stronger carbon-price paths produce larger emission cuts, but also imply short-term costs for some sectors, especially fossil-fuel-dependent and energy-intensive activities such as Agriculture, Mining and Manufacturing. These further increases in the carbon tax alone are not sufficient to close the remaining emissions gap. By contrast, a joint intensification of carbon pricing and electrification enables convergence toward net-zero emissions.

Overall, GDP experiences only a modest short-term decline relative to the Current Policy scenario, while showing stronger long-run growth driven by investment in the renewable energy sector. Notably, when carbon-pricing revenues are coupled with higher government consumption, the negative short-run effects on GDP are fully offset.

The GDP deflator increases, reflecting cost-push inflation associated with carbon pricing. However, when carbon pricing is combined with green investment incentives, this inflationary pressure is partially mitigated.

These findings underscore the potential of well-designed policy mixes to reconcile environmental goals with sustained economic growth, while also showing that transition outcomes remain sensitive to the strength of the carbon-price path and to the broader macroeconomic environment.

While the model captures several important transmission channels and sector-specific dynamics, it also presents structural limitations and relies on simplifying assumptions.

Technological progress is not endogenously driven by investment or learning-by-doing, but is imposed exogenously across scenarios. Similarly, carbon removal and storage activities do not generate economic output, as they are not linked to any investment behavior within the model.

Production functions rely on fixed Leontief coefficients, with the exception of electrification, which is represented as an exogenous shift in the energy mix. The electrification process could be endogenized and, for example, linked to government incentives. Instead, on the consumption side, fixed spending shares are assumed; this approach can overestimate changes in preferences in response to relative price shifts, whereas this behavior could be more accurately captured using substitution elasticities between goods.

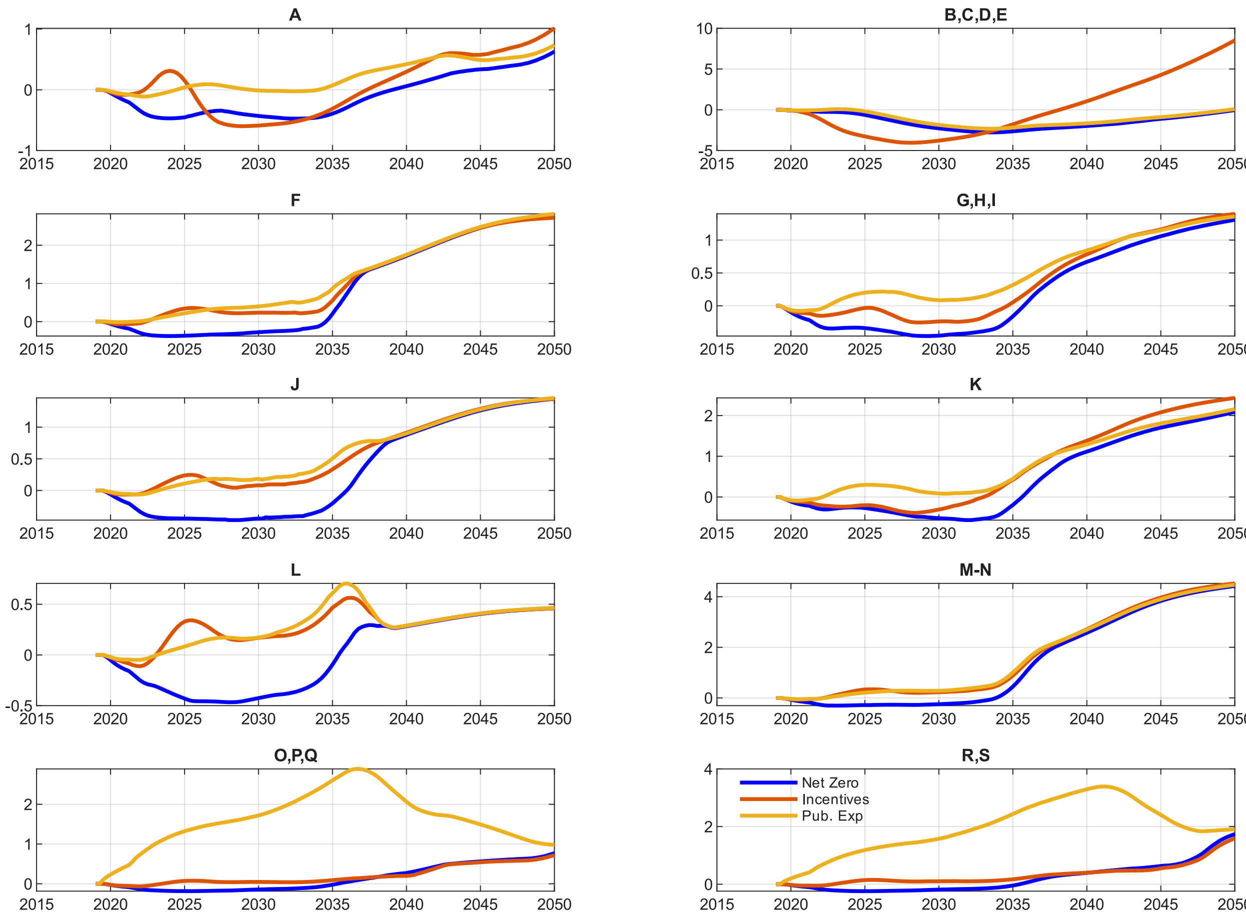

Fig. 9. Net Zero Gross Value-Added, percentage deviation level from Current Policies scenario.

Moreover, the SAM used to calibrate the model can be extended or adapted by using, for instance, Supply and Use Tables (SUT) in place of Input-Output Tables.

The model includes only a labor productivity-related channel for chronic physical risks. Acute physical risks (e.g., extreme weather events) and alternative damage channels, such as infrastructure loss or capital destruction, are not accounted for. These are some aspects of the model that could be improved in future developments of this research.

It should be noted, however, that some of these issues, such as the modeling of technological progress (but also political constraints or energy infrastructure issues), are common to all types of modeling approaches and are likely not fully solvable. For example, CGE models often rely on exogenous assumptions about technological progress, which limits their ability to capture the endogenous processes of innovation that are central to climate transitions (Aldy et al., 2010). Moreover they typically assume constant returns to scale and perfect competition, which may not fully reflect the complexities of real-world transitions to a low-carbon economy (Sato et al., 2011).

In conclusion, this study demonstrates the utility of ABMs as a robust tool for analyzing the complexities of climate transition policies. By leveraging their flexibility and detailed representation of agent behaviors, researchers and policymakers can uncover actionable insights to guide the global transition toward a sustainable future.

CRediT authorship contribution statement

Michele Catalano: Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jacopo Di Domenico:** Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luca Riccetti:** Writing – original draft, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table A.4
Indices used in the model.

Symbol	Definition
h	Household index
i	Firm index
s	Sector/industry index
g	Good index
t	Time index

Table A.5
Variables used in the model.

Symbol	Definition
$w_h(t)$	Gross nominal wage of household h (equals $w_i(t)$ of employing firm i)
$\bar{P}^{\mathrm{HH}}(t)$	Household consumption price index (CPI)
$\pi^{\mathrm{e}}(t)$	Expected inflation rate (AR(1) on CPI inflation)
$sb^{\mathrm{inact}}(t)$	Social benefits to inactive households (e.g., retirees, students)
$sb^{\mathrm{other}}(t)$	Other lump-sum transfers to households (child/means-tested, etc.)
$Y_h^{\mathrm{e}}(t)$	Expected disposable (net) nominal income of household h
$C_h^{\mathrm{d}}(t)$	Desired nominal consumption of household h
b^{HH}	Vector of household consumption budget shares across goods
$Q_i^{\mathrm{d}}(t)$, $Q_i^{\mathrm{s}}(t)$	Realized demand and desired supply for firm i
$\gamma^{\mathrm{e}}(t)$	Expected aggregate growth rate (AR(1))
$Y_i(t)$	Real output of firm i (production)
$N_i(t)$, $M_i(t)$, $K_i(t)$	Labor, intermediate inputs, and capital stock of firm i
$I_i^{\mathrm{d}}(t)$	Desired real investment of firm i
$P_i(t)$	Price of good produced by firm i
$\bar{P}_g(t)$	Average price index for good g
$\bar{P}^{\mathrm{CF}}(t)$	Capital goods price index
$\pi_i^{\mathrm{c}}(t)$	Firm i's cost-push term in pricing
$CP(t)$	Carbon price (euro per tCO_2e)
$inc_{gr}(t)$	Per-unit output incentive paid to *green electricity* firms
$\Pi_i(t)$	Nominal profit of firm i
$D_i(t)$, $L_i(t)$	Firm i's deposits (can be negative/overdraft) and loans stock
$r(t)$, $\bar{r}(t)$	Loan/deposit rates and policy rate (Taylor rule)
$\pi^{\mathrm{EA}}(t)$, $\gamma^{\mathrm{EA}}(t)$	Inflation and growth in the monetary union (AR(1))
$C_G(t)$, $B_G(t)$	Government consumption and social benefits
$Y^G(t)$, $\Pi_G(t)$	Government revenues and budget balance
$L_G(t)$	Public debt stock
α_G, β_G, $\epsilon_G(t)$	AR parameters and shock for C_G growth
$\Delta_{\%}X(t)$	Growth rate of variable X
g_{elec}	Exogenous electrification trend parameter (from NGFS)
$\phi(t)$	Profitability gap factor used in electricity production desired supply

Table A.6
Parameters used in the model.

Symbol	Definition
θ^{UB}	Unemployment benefit replacement rate
θ^{DIV}	Dividend payout ratio to households
τ^{INC}	Income tax rate on labor and capital income
τ^{SIW}, τ^{SIF}	Employee and employer social-insurance contribution rates
τ^{FIRM}	Corporate income tax rate
τ^{VAT}	Value-added tax rate
α_i, β_i, κ_i	Productivity/requirement coefficients for labor, materials, capital
δ_i	Depreciation rate
a_{sg}	Input coefficient of good g used by sector s
μ_i^e	Emission intensity of firm i (emissions per unit of output)
τ_i^{Y}, τ_i^{K}	Net taxes/subsidies on products and on production (sector i)
ρ, ξ^{π}, ξ^{γ}	Taylor-rule parameters
r^*, π^*	Real equilibrium interest rate and inflation target
r_G	Average nominal interest rate on public debt

Appendix A. Notation

See Tables A.4–A.7.

Appendix B. List of sectors

See Table B.8.

Table A.7
Calibration for the Italian economy (2019Q4 calibration).

Parameter	Description	Value
G/S	Number of products/industries	64
H^{act}	Economically active persons (thousands)	25 895
H^{inact}	Economically inactive persons (thousands)	33 448
J	Number of government entities (thousands)	1233
L	Number of foreign consumers (thousands)	2467
I	Number of firms allocated to different sectors (thousands)	4933
τ^{INC}	Income tax rate	0.2353
τ^{FIRM}	Corporate tax rate	0.0443
τ^{VAT}	Value-added tax rate	0.1491
τ^{SIF}	Social insurance (employers' contrib.)	0.3860
τ^{SIW}	Social insurance (employees' contrib.)	0.1517
τ^{EXPORT}	Export tax rate	0.0011
τ^{CF}	Tax rate on capital formation	0.1737
τ^{G}	Tax rate on government consumption	0.0026
r^{G}	Interest rate on government bonds	0.0066
μ	Risk premium on policy rate	0.0100
ψ	Fraction of income to consumption	0.9160
ψ^{H}	Fraction of income to housing investment	0.0921
θ^{DIV}	Dividend payout ratio	0.7864
θ^{UB}	Unemployment benefit replacement rate	0.3568
θ	Debt installment rate	0.0500
ζ	Banks' capital ratio	0.0300
ζ^{LTV}	Loan-to-value (LTV) ratio	0.6000
ζ^{b}	Loan-to-capital ratio (new firms post-bankruptcy)	0.5000
π^{*}	Monetary authority inflation target	0.0050
α^{G}	AR coefficient for government consumption	0.9573
β^{G}	Constant for government consumption	0.4823
σ^{G}	Std. dev. of government consumption	0.0070
α^{E}	AR coefficient for exports	0.9804
β^{E}	Constant for exports	0.2306
α^{I}	AR coefficient for imports	0.9504
β^{I}	Constant for imports	0.5584
$\alpha^{\gamma^{EA}}$	AR coefficient for EA growth	0.9832
$\beta^{\gamma^{EA}}$	Constant for EA GDP	0.2502
$\alpha^{\pi^{EA}}$	AR coefficient for EA inflation	0.3988
$\beta^{\pi^{EA}}$	Constant for EA inflation	0.0023
$\sigma^{\pi^{EA}}$	Std. dev. of EA inflation	0.0021
ρ	Policy rate adjustment coefficient	0.9595
r^{*}	Real equilibrium interest rate	−0.0086
ξ^{π}	Weight on inflation gap (Taylor rule)	−0.7384
ξ^{γ}	Weight on growth (Taylor rule)	1.9581

Appendix C. Robustness

C.1. Initial conditions and Monte Carlo simulations

See Figs. C.10 and C.11.

C.2. Carbon price severity

The panels on the left show the current policy (CP) simulation and the three net zero scenarios, with carbon prices at 100% (NZ1), 150% (NZ1.5), and 200% (NZ2), while the panels on the right show the percentage deviations of the three net zero scenarios from the current policy one (see Figs. C.12 and C.13).

C.3. Net zero implementation

This appendix performs intensity tests by increasing individual NGFS drivers beyond their baseline levels in order to assess under which conditions production can converge toward full net-zero emissions.

The analysis conducted in Appendix C.2 shows that increasing the carbon price beyond certain thresholds becomes ineffective. Therefore, achieving the targeted outcome requires a joint adjustment of policy drivers, rather than relying on a single instrument.

In particular, our results indicate that combining a higher carbon price with a stronger electrification process is necessary. When the carbon price severity is set at 150% of the baseline level, net-zero emissions can be achieved with an increase in electrification equal to 140% of its baseline level.

The corresponding simulation results are reported in Figs. C.14 and C.15.

Table B.8
List of the 62 sectors.

No.	Sector_ID	Description
1	A01	Products of agriculture, hunting and related services
2	A02	Products of forestry, logging and related services
3	A03	Fish and other fishing products; aquaculture products; support services to fishing
4	B	Mining and quarrying
5	C10-12	Food, beverages and tobacco products
6	C13-15	Textiles, wearing apparel, leather and related products
7	C16	Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials
8	C17	Paper and paper products
9	C18	Printing and recording services
10	C19	Coke and refined petroleum products
11	C20	Chemicals and chemical products
12	C21	Basic pharmaceutical products and pharmaceutical preparations
13	C22	Rubber and plastic products
14	C23	Other non-metallic mineral products
15	C24	Basic metals
16	C25	Fabricated metal products, except machinery and equipment
17	C26	Computer, electronic and optical products
18	C27	Electrical equipment
19	C28	Machinery and equipment n.e.c.
20	C29	Motor vehicles, trailers and semi-trailers
21	C30	Other transport equipment
22	C31-32	Furniture and other manufactured goods
23	C33	Repair and installation services of machinery and equipment
24	D	Electricity, gas, steam and air conditioning
25	E36	Natural water; water treatment and supply services
26	E37-39	Sewerage services; sewage sludge; waste collection, treatment and disposal services; materials recovery services; remediation services
27	F	Constructions and construction works
28	G45	Wholesale and retail trade and repair services of motor vehicles and motorcycles
29	G46	Wholesale trade services, except of motor vehicles and motorcycles
30	G47	Retail trade services, except of motor vehicles and motorcycles
31	H49	Land transport services and transport services via pipelines
32	H50	Water transport services
33	H51	Air transport services
34	H52	Warehousing and support services for transportation
35	H53	Postal and courier services
36	I	Accommodation and food services
37	J58	Publishing services
38	J59-60	Motion picture, video and television programme production services, sound recording and music publishing; programming and broadcasting
39	J61	Telecommunications services
40	J62-63	Computer programming, consultancy and related services; Information services
41	K64	Financial services, except insurance and pension funding
42	K65	Insurance, reinsurance and pension funding services, except compulsory social security
43	K66	Services auxiliary to financial services and insurance services
44	L68A	Real estate services
45	M69-70	Legal and accounting services; services of head offices; management consultancy services
46	M71	Architectural and engineering services; technical testing and analysis services
47	M72	Scientific research and development services
48	M73	Advertising and market research services
49	M74-75	Other professional, scientific and technical services and veterinary services
50	N77	Rental and leasing services
51	N78	Employment services
52	N79	Travel agency, tour operator and other reservation services and related services
53	N80-82	Security and investigation services; services to buildings and landscape; office administrative, office support and other business support
54	O	Public administration and defense services; compulsory social security services
55	P	Education services
56	Q86	Human health services
57	Q87-88	Residential care services; social work services without accommodation
58	R90-92	Creative, arts, entertainment, library, archive, museum, other cultural services; gambling and betting services
59	R93	Sporting services and amusement and recreation services
60	S94	Services furnished by membership organizations
61	S95	Repair services of computers and personal and household goods
62	S96	Other personal services

These findings suggest that NGFS-consistent carbon price paths may be macroeconomically insufficient when filtered through decentralized production networks, unless accompanied by stronger structural electrification dynamics. The interaction between carbon pricing and electrification exhibits complementarity rather than linear additivity, highlighting the importance of coordinated transition design.

C.4. Robustness to structural breaks: energy crises, geopolitical disruptions, and trade fragmentation

To assess the robustness of the transition path to adverse external environments, we augment the NZ1.5E1.4 experiment with three reduced-form structural-break stress tests: an acute energy crisis (AEC), a broader geopolitical disruption (GD), and persistent trade fragmentation (PTF). These exercises are not meant to reproduce specific historical events literally. Rather, they are designed as adverse external wedges around the

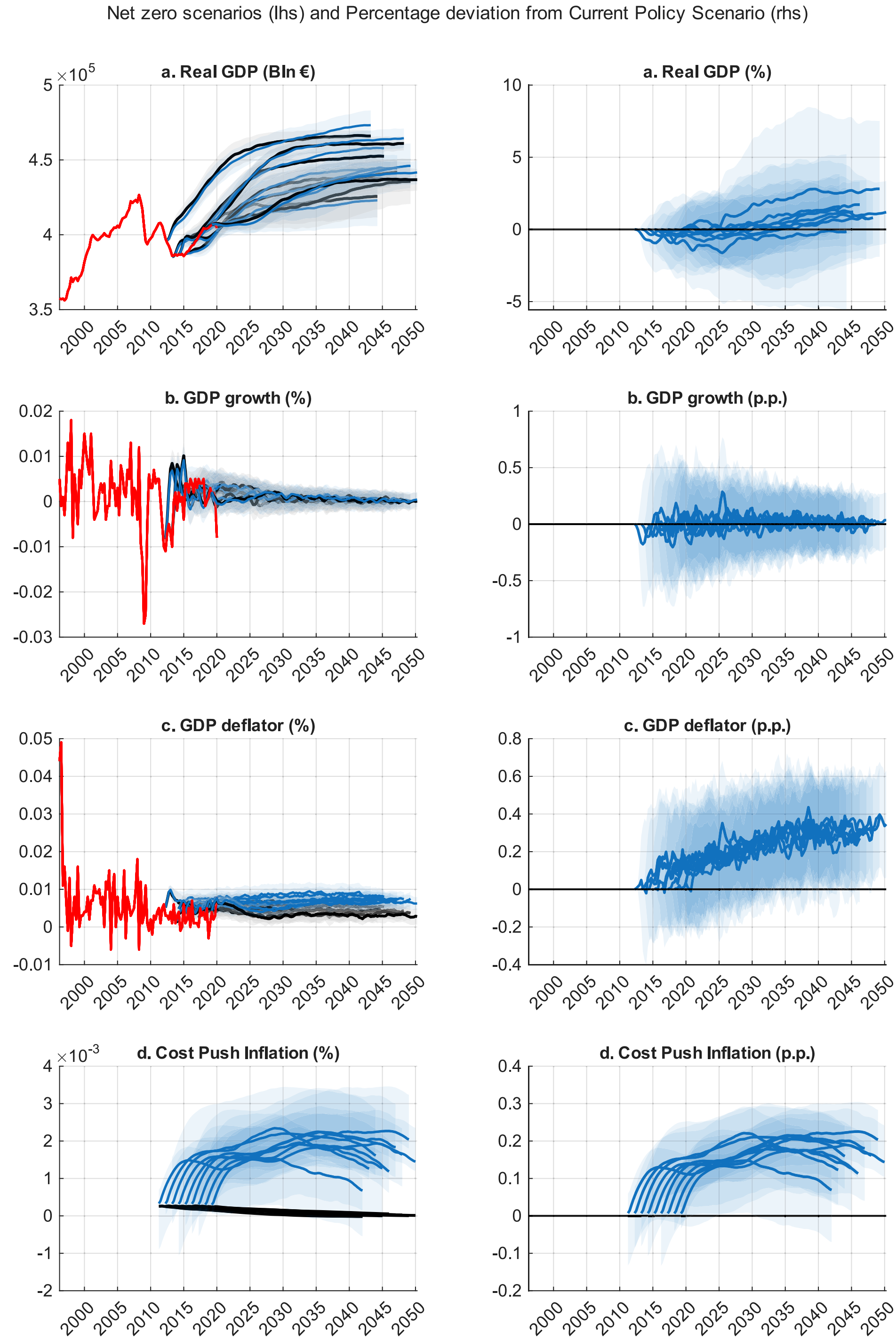


Fig. C.10. 100 Monte Carlo simulations are performed for each initial condition, fixed at the first quarter of each year between 2011 and 2019, for the current policy scenario (solid line) and the net zero scenario (blue line) with carbon tax used to reduce government debt. Blue Shaded Area: 80%-Confidence Intervals.

transition path, while keeping unchanged the long-run carbon-pricing and electrification trajectories as well as supply chains and the underlying social accounting structure. This allows us to isolate whether the main conclusions of the transition exercise remain robust when the economy is exposed to temporary external disruptions.

The stress tests only affect a limited set of macro drivers. In particular, we modify the expectation formation process for domestic growth rates ($\gamma^{e}(t)$) and inflation ($\pi^{e}(t)$), foreign growth rates ($\gamma^{EA}(t)$) and inflation ($\pi^{EA}(t)$), and import and export growth rates $\gamma^{E}(t)$ and $\gamma^{I}(t)$.

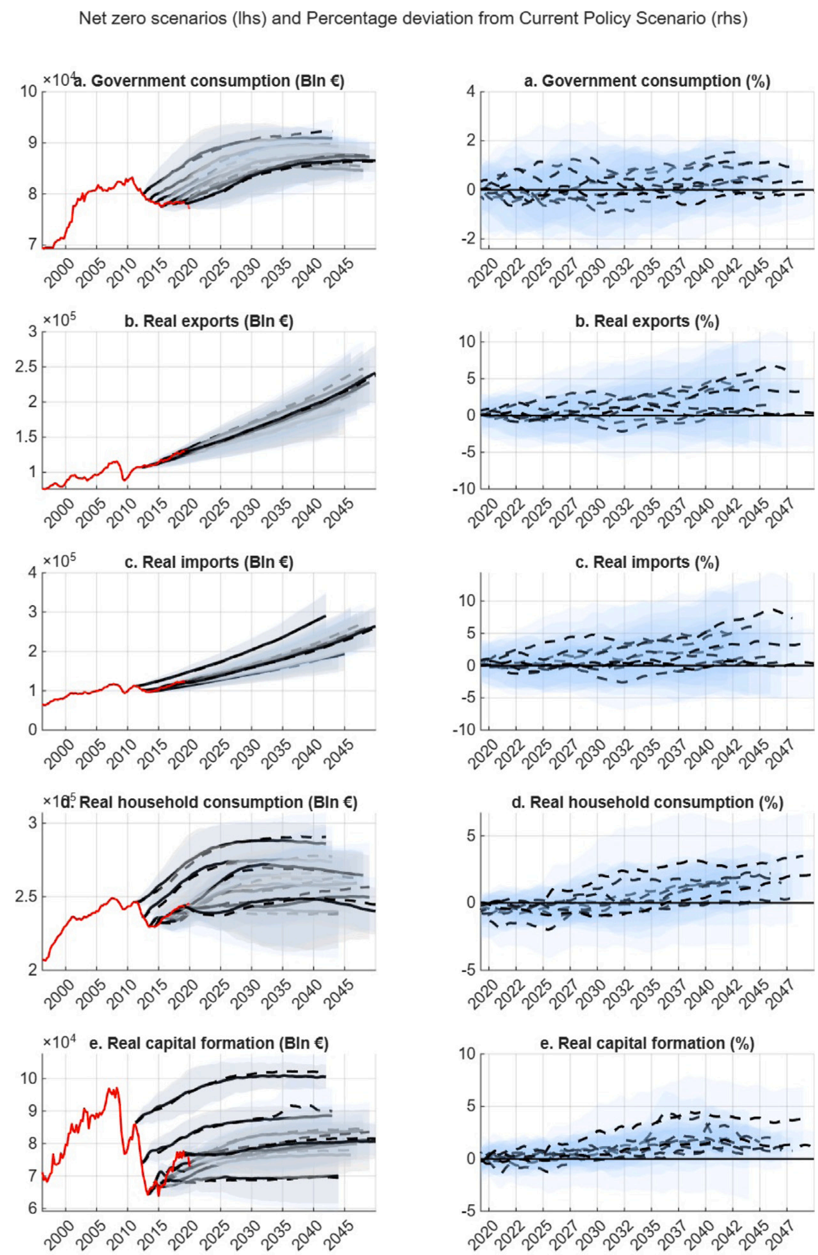


Fig. C.11. 100 Monte Carlo simulations are performed for each initial condition, fixed at the first quarter of each year between 2011 and 2019, for the current policy scenario (solid line) and the net zero scenario (dashed line) with carbon tax used to reduce government debt. Blue Shaded Area: 80%-Confidence Intervals.

Formally, for each expectation variable $X_{j,t}$, we define:

$$X_{j,t} = \alpha_0 + \alpha_j \gamma_{j,t-1} + \lambda_j^{(s)} z_t \sigma_{\varepsilon,j}. \tag{C.1}$$

where $\alpha_{i,j}$ are the AR(1) processes estimated parameters, $\sigma_{\varepsilon,j}$ is the estimated standard deviation of the corresponding AR(1) process, $\lambda_j^{(s)}$ is a scenario-specific loading, and z_t is a common disruption factor describing the time profile of the stress episode.

Positive loadings are assigned to domestic and foreign inflation expectations, while negative loadings are assigned to the other variables. The three stress scenarios then superimpose different temporal and compositional profiles on the same baseline path. The acute energy crisis is designed to be sharp but temporary and loads more strongly on inflation. The geopolitical disruption scenario is broader, combining inflationary pressure with larger effects on overall economic activity and trade. Persistent trade fragmentation is instead modeled as a longer-lasting adverse shock with a stronger effect on trade and foreign demand, but a more moderate inflationary component. Table C.1 summarizes the shock design and parameterization used in the robustness analysis.

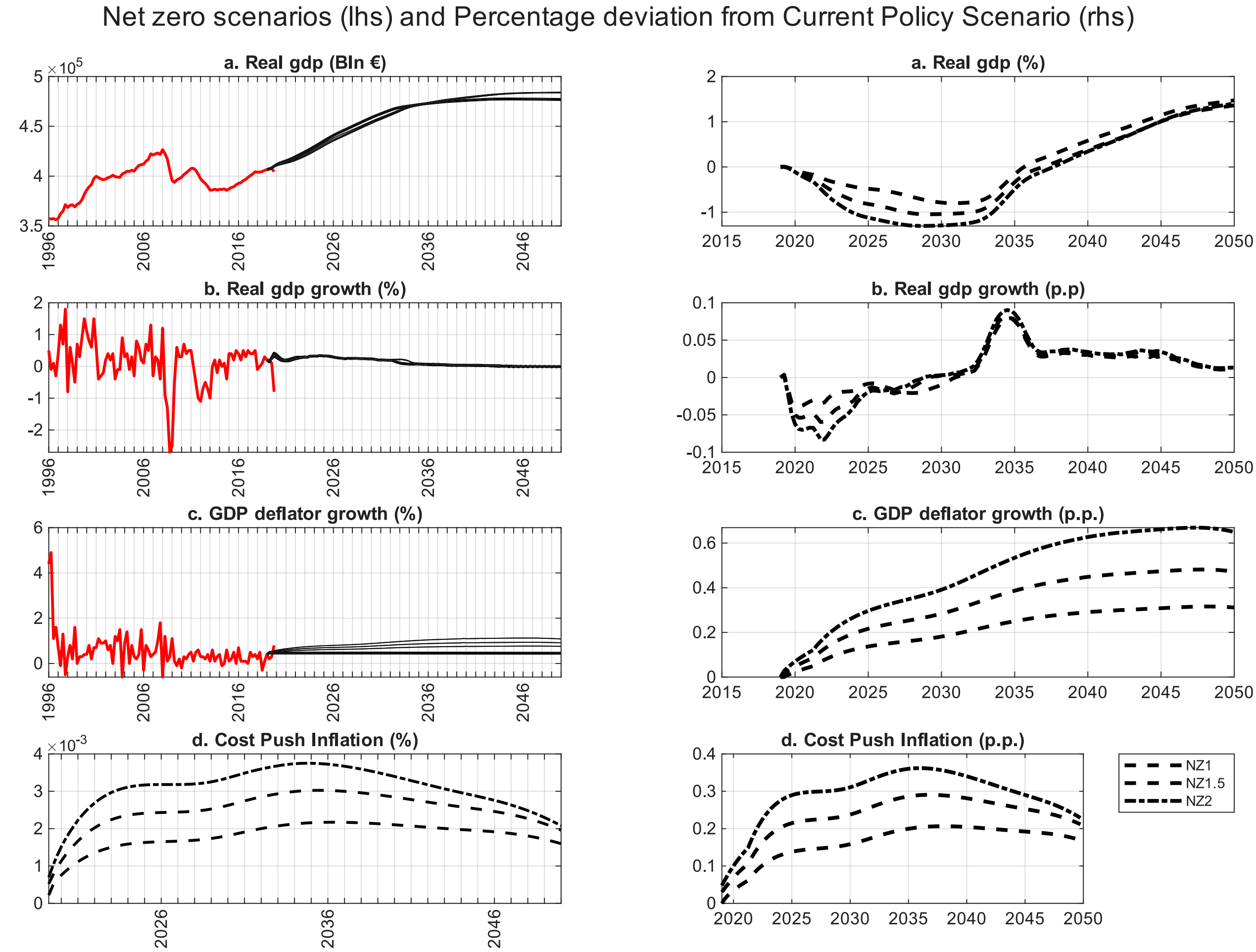
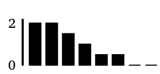
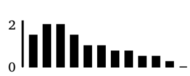


Fig. C.12. Carbon price severity (1, 1.5, 2).

Table C.1
Design and parameterization of structural-break stress tests.

Scenario	Horizon	Shock path z_t	λ_{γ^e}	λ_{π^e}	$\lambda_{\gamma^{EA}}$	$\lambda_{\pi^{EA}}$	λ_{γ^I}	λ_{γ^E}	Interpretation
NZ1.5E1.4	–	———	0	0	0	0	0	0	Baseline transition path with no additional external disruption.
AEC	8 quarters		−1.0	1.5	−0.8	1.5	−0.8	−0.8	Sharp and temporary energy-price shock, with strong inflationary pressure and moderate recessionary effects.
GD	12 quarters		−1.2	1.0	−1.3	1.0	−1.2	−1.2	Broader geopolitical disruption combining inflation, uncertainty, weaker external demand, and lower activity.
PTF	20 quarters		−0.6	0.5	−1.0	0.5	−1.3	−1.3	Persistent trade-fragmentation stress with stronger effects on trade and foreign demand and milder inflation effects.

Notes: λ_{γ^e} denotes the loading on the domestic growth rate, λ_{π^e} on domestic inflation, $\lambda_{\gamma^{EA}}$ on foreign growth rate, $\lambda_{\pi^{EA}}$ on foreign inflation, λ_{γ^I} and λ_{γ^E} on import and export growth rate.

Fig. C.16 shows that the NZ1.5E1.4 baseline implies only a modest output cost in the short run relative to Current Policies, with a limited GDP loss in the transition phase and a relatively positive small effect on GDP in the long run. By contrast, once external stress is superimposed on the same transition backbone, the short- and medium-run macroeconomic costs become substantially larger. All three stress scenarios generate an immediate decline in real GDP relative to Current Policies, together with a higher GDP-deflator path. The qualitative ranking is intuitive: more

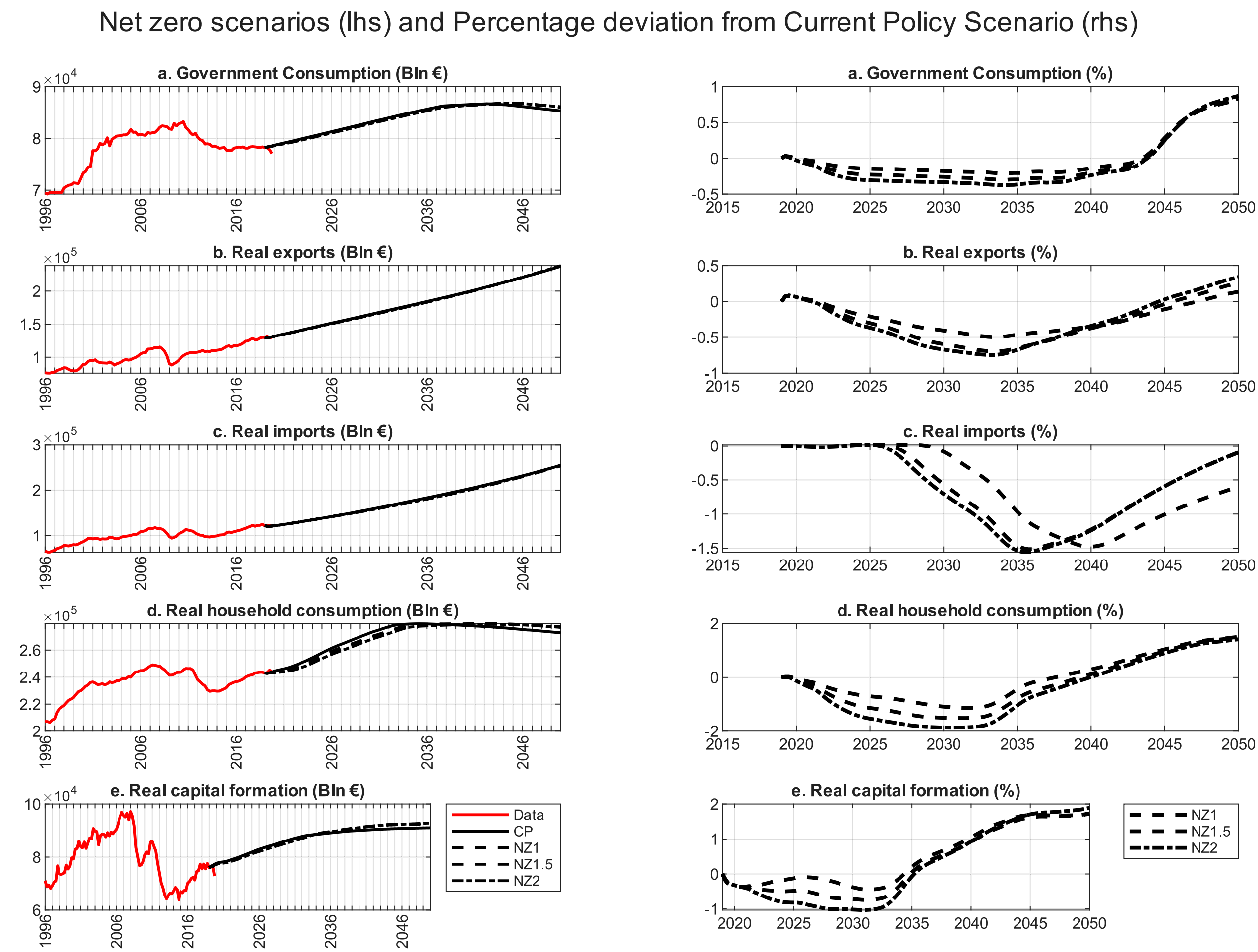


Fig. C.13. Carbon price severity (1, 1.5, 2).

persistent disruptions are associated with more prolonged output losses, whereas the acute energy shock generates a milder and less persistent deterioration in macroeconomic activity alongside a sharper short-run inflation surge. Importantly, however, none of these disturbances overturns the basic long-run direction of the transition; rather, they worsen the path followed to reach it.

Fig. C.17 shows that the emissions trajectory remains strongly downward-sloping in all net-zero variants relative to Current Policies. In the short term, the reduction in emissions resulting in the cases with external shocks appears much more pronounced than in the NZ1.5E1.4 scenario, due to the significant decline in production. However, in the long run, differences across the stressed scenarios appear small compared with the overall gap between Current Policies and the transition scenarios. In other words, the long-run emissions reduction remains primarily policy-driven, while the structural-break shocks mainly affect the macroeconomic cost of adjustment rather than the broad direction of decarbonization.

Fig. C.18 helps clarify the transmission channels. Government consumption is comparatively stable and, if anything, tends to move only modestly across scenarios. Exports and imports fall sharply under all adverse stress scenarios, with the most persistent losses arising under trade fragmentation. Household consumption also drops below the Current Policies benchmark, though it gradually recovers over time. Capital formation exhibits a similar short-run contraction, followed by a more gradual and delayed recovery.

Taken together, the results suggest a clear conclusion. The main transition logic of the model remains intact under structural-break stress tests: the carbon-price path and the electrification process continue to drive the long-run reallocation away from brown and non-electric activities and toward greener production. The transition therefore remains broadly unchanged and feasible, as it is primarily driven by explicit policy choices. This conclusion, however, reflects the fact that the model does not incorporate structural behavioral changes triggered by the occurrence of these shocks. A richer microfoundation could alter the quantitative outcomes. For instance, an energy crisis originating in the fossil fuel sector could accelerate the shift toward green technologies, while a macroeconomic downturn could instead depress investment in electrification and renewable energy. Exploring these behavioral feedbacks goes beyond the scope of this paper and is left for future research.

Appendix D. Supplementary data

The replication code is provided in the supplementary material accompanying this article, available online at https://doi.org/10.1016/j.eneco.2026.109489.

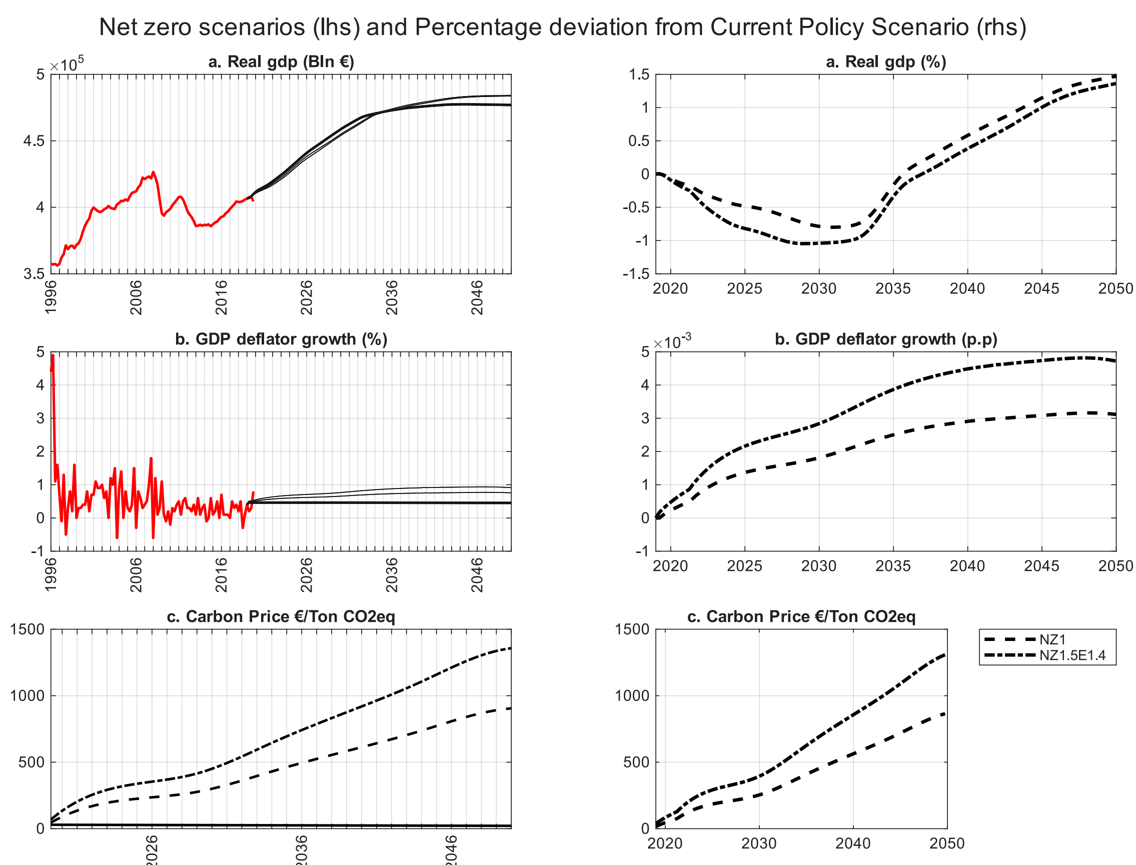


Fig. C.14. Baseline net zero simulation (NZ1, dashed line) vs Joined carbon price and electrification arise (NZ1.5E1.4, dash-dotted line).

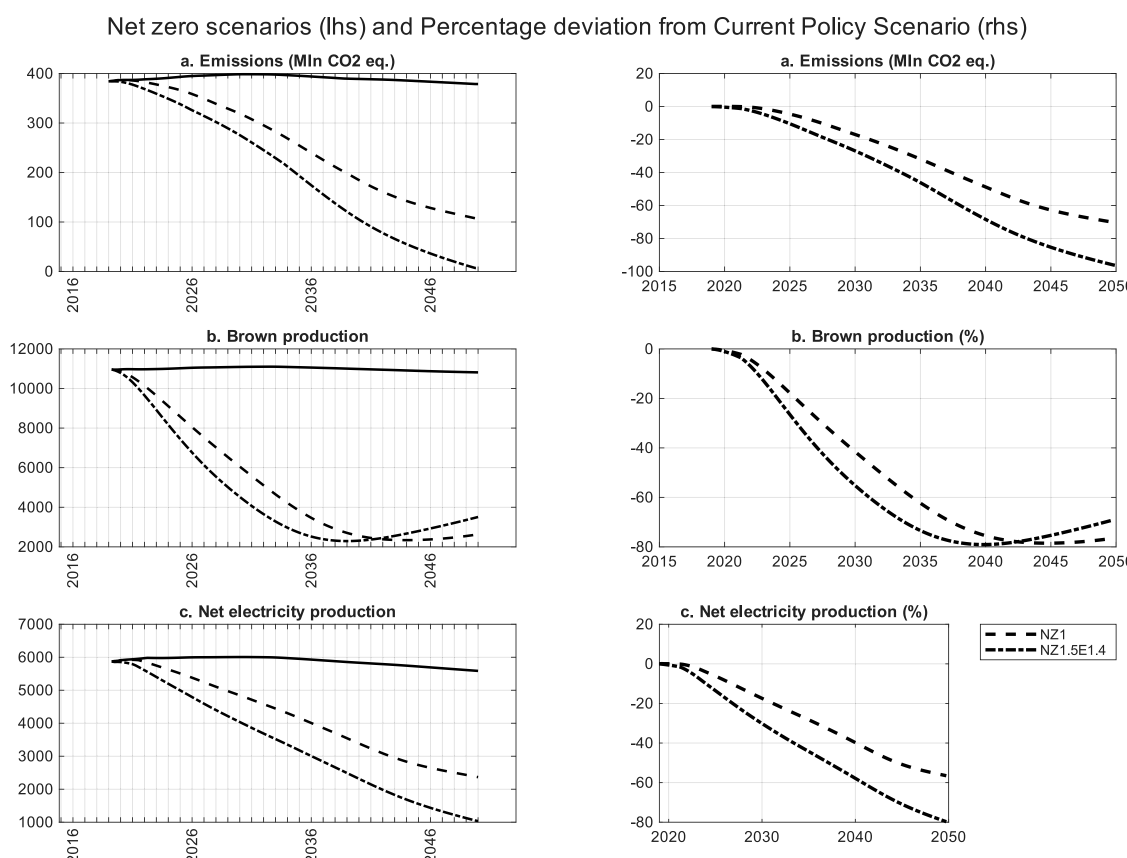


Fig. C.15. Current Policies (solid black line in the left panels), the Net Zero scenario (NZ1), and the joint carbon price and electrification rise scenario (NZ1.5E1.4).

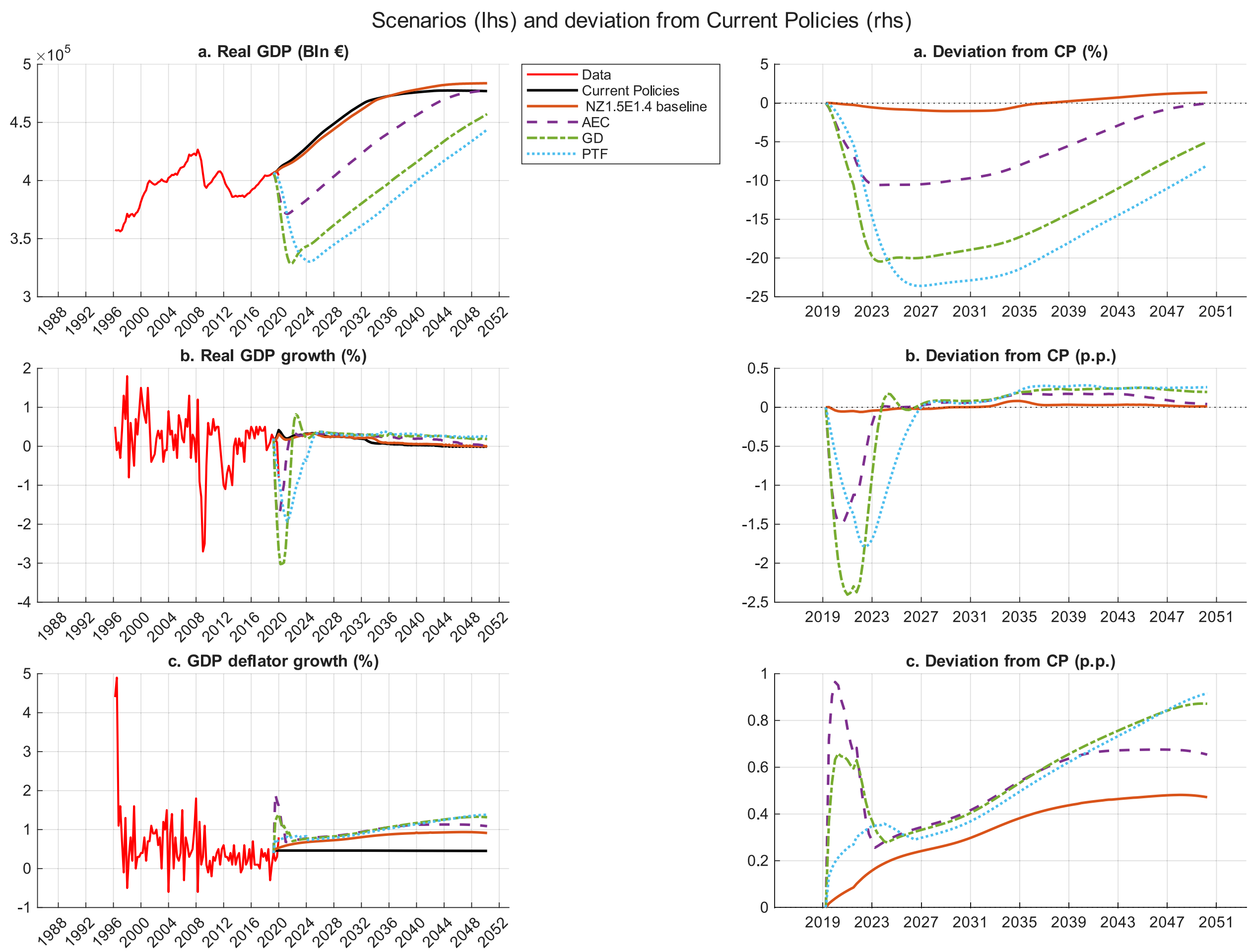


Fig. C.16. Macroeconomic dynamics under Current Policies, the NZ1.5 baseline, and the alternative structural-break stress tests. The left-hand-side panels report levels, while the right-hand-side panels report deviations from Current Policies.

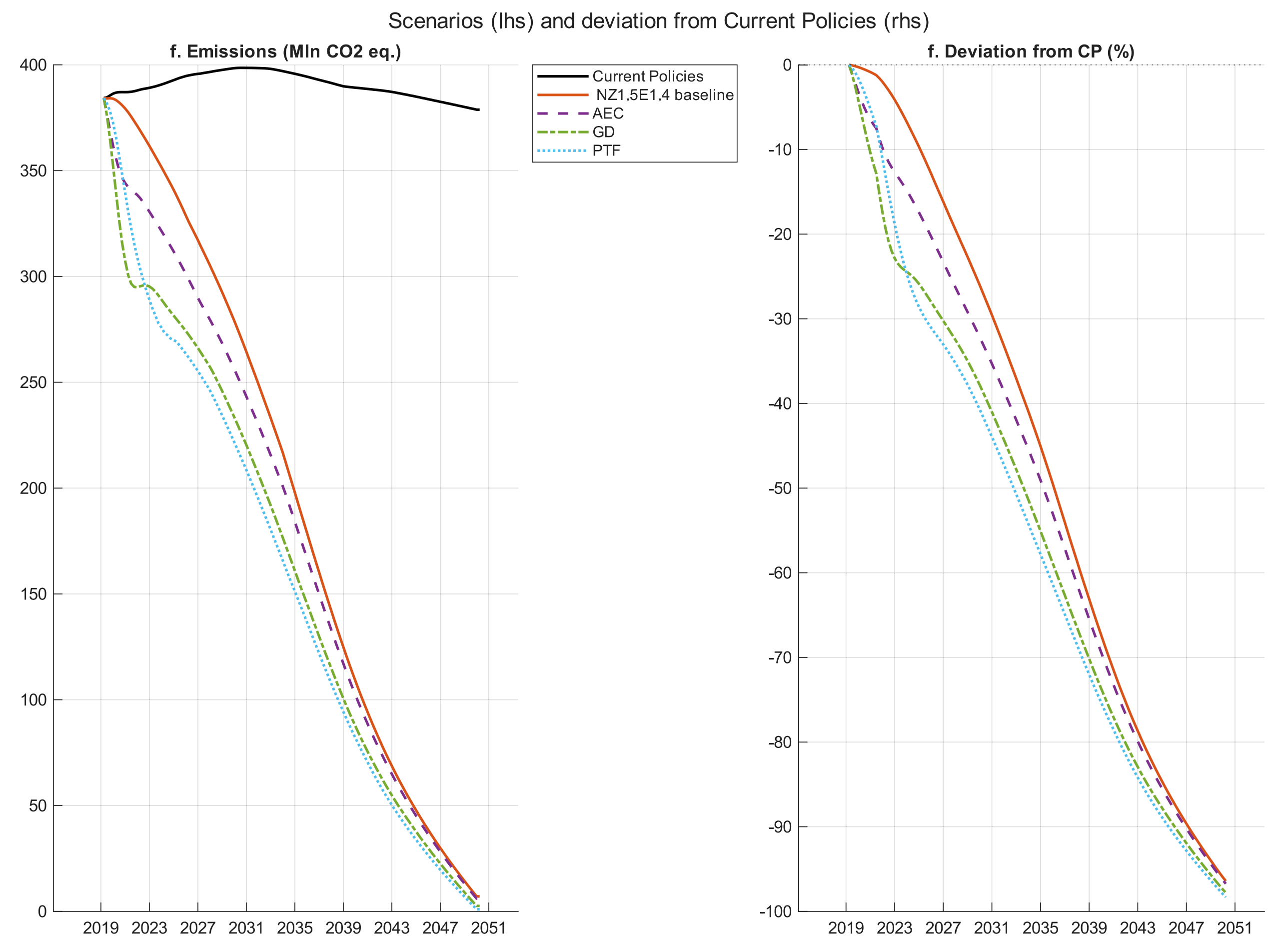


Fig. C.17. Emissions trajectories under Current Policies, the NZ1.5 baseline, and the alternative stress tests.

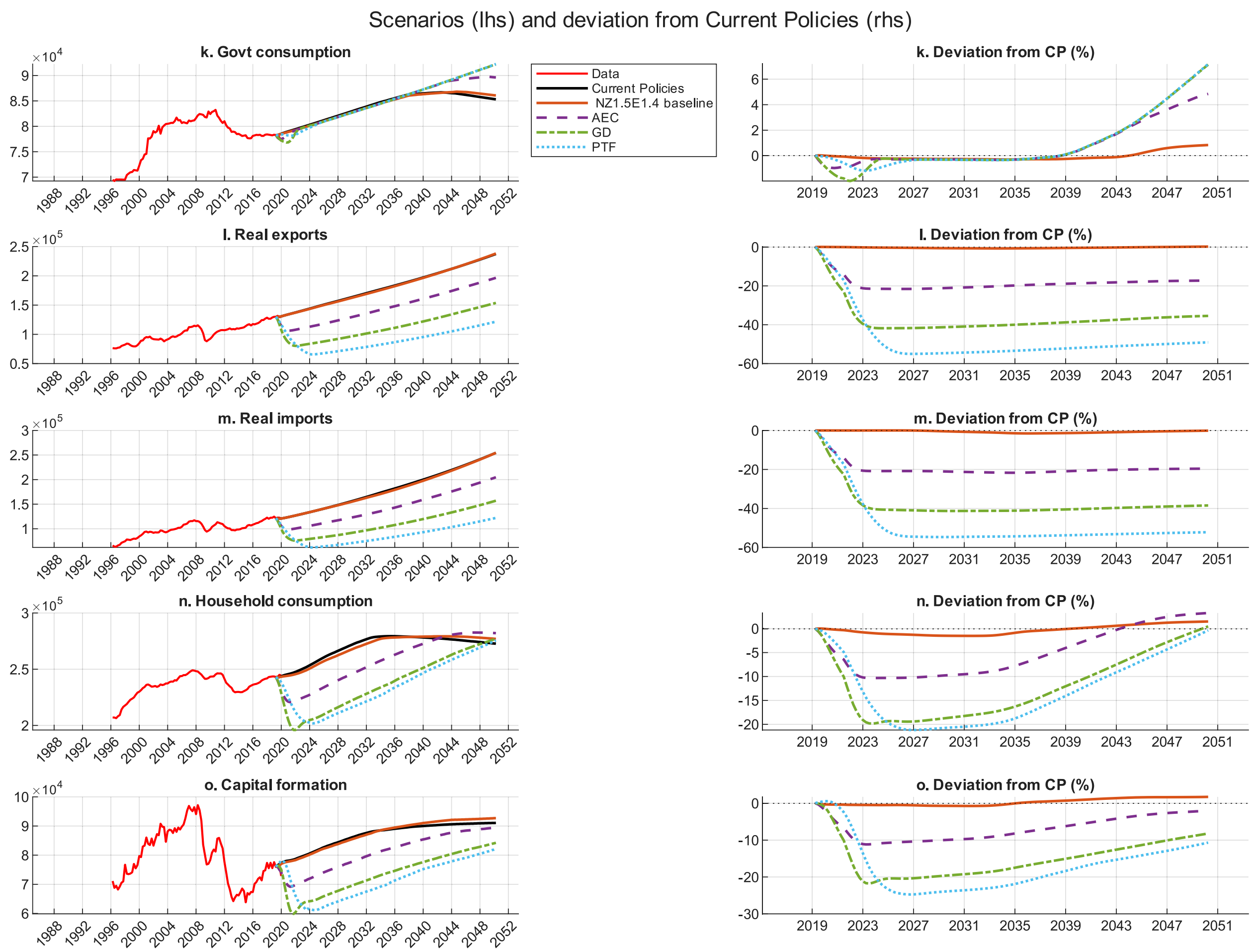


Fig. C.18. Demand-side transmission: government consumption, exports, imports, household consumption, and capital formation across scenarios.

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