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Essays on Ecological Transition, Finance and Inequalities

TITOLO DELLA TESI

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Essays on Ecological Transition, Finance and Inequalities

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Introduction

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy (PhD) programme in Economics (XXXVIII Cycle) at the Department of Economics, Roma Tre University. It comprises three original and stand-alone papers that combine theoretical analysis, macroeconomic modelling and empirical methods, unified by an investigation of the macro-financial implications of the low-carbon transition on distributive outcomes.

The central concept guiding the research conducted between January 2024 and December 2025 is that of a "just" transition: the need to align the ecological transition with sustainable policy interventions that safeguard the income distribution of workers and lower-income groups, uphold social responsibility for environmental degradation and promote high and stable levels of employment, the wage share, and overall wellbeing. A fair societal transition requires policies that minimise distributional asymmetries rather than exacerbate them in the pursuit of decarbonisation. This challenging theme underscores the importance of coherent and coordinated policy design, particularly in light of the significant role of the financial sector in propagating both risks and benefits during the transition. These issues are examined across the three papers that follow, each of which seeks to offer a modest, yet meaningful, contribution to the contemporary literature.

The first paper examines how macro-financial transition risks affect income distribution and, more broadly, macroeconomic dynamics. It reviews the non-equilibrium modelling literature on the low-carbon energy transition by applying a meta-model to identify its fundamental features and to assess the extent to which existing frameworks incorporate planetary boundaries, climate, and energy modules. More specifically, it analyses and systematises the drivers, transmission channels, and macroeconomic and distributive impacts of low-carbon structural change. The overarching objective is to shed light on the complexity of the transition, highlighting the central role of policy intervention in addressing the associated social and environmental challenges.

The second paper is a modelling contribution. It extends an agent-based stock–flow consistent (AB-SFC) model by introducing a housing module calibrated on EUROSTAT data and incorporating firms' low-carbon investment decisions alongside households' demand for green loans to finance residential retrofits. The analysis is situated within a

modern, financialised economy in which securitisation enables investors to access complex financial instruments, such as asset-backed securities (ABSs). The paper evaluates the macro-financial implications of a green retrofit scenario, with particular emphasis on the role of fiscal, redistributive, and financial policies in easing access to green credit, fostering energy-efficient refurbishment, and mitigating distributional inequalities.

The final paper provides an empirical assessment of the theoretical and modelling frameworks developed in the preceding contributions. It investigates the distributive effects of climate-change mitigation policies across a panel of 29 OECD countries over the period 1990–2020. Using an instrumental-variables local projections (IV-LPs) framework, it estimates the dynamic impact of shocks to the OECD Environmental Policy Stringency (EPS) Index on multiple income-inequality indicators drawn from the World Income Inequality Database. To address potential endogeneity in policy adoption, the paper introduces a novel instrument based on climate-related central-bank communication and country-specific institutional characteristics, thereby addressing an important gap in the existing literature.

Some meaningful, although preliminary, results are summarised in the general Conclusions section at the end of the essays.

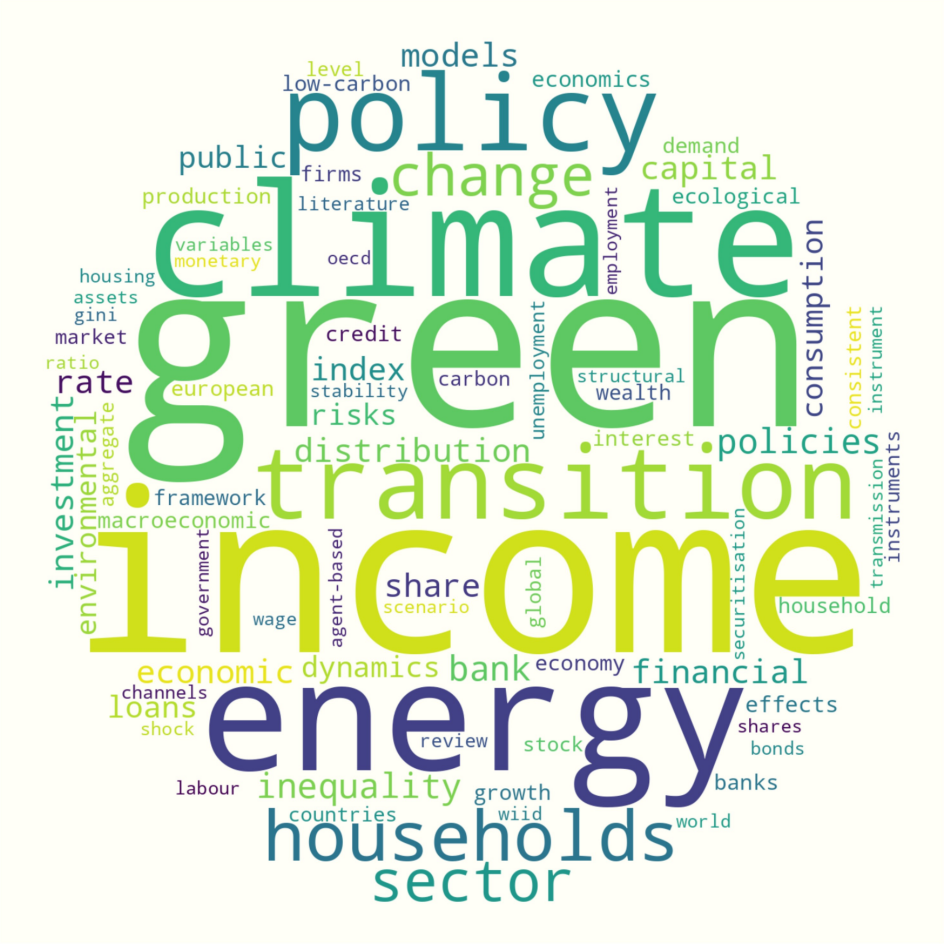


Figure 1: Word cloud of the most frequent terms and concepts used across the three papers of the thesis. Word size reflects the relative frequency of each term.

Macro-Financial Risks, Income Distribution and Socio-Ecological Transition in Climate-Energy Models

Mattia Leoni*

Abstract

Growing attention from academia and institutions has been devoted to understanding how to achieve a 'just' socio-ecological transition toward a lower-carbon economy. This paper reviews the economic modelling literature on the 'green' energy transition, with a particular focus on the macro-financial transitional risks and their implications on income distribution. We apply a meta-model aiming to identify specific peculiarities and the current state-of-the-art of non-equilibrium economic modelling. The study analyses drivers, transmission channels and impacts of low-carbon structural change on macroeconomic and distributive outcomes. The ultimate goal is to provide insights into the complexity of the transition, offering an in-depth analysis that underscores the central role of policy intervention in solving social and environmental dilemmas. We draw two main conclusions: from a methodological standpoint energy-related analysis is increasingly integrated into macro models, while in terms of policy implication, the possible negative drawbacks of such a shift in the energy transition can only be addressed by resorting to coordinated monetary, fiscal, and industrial policies in achieving an equitable decarbonisation, within a context of a narrowing window for climate action and growing disengagement from the world's governments.

Keywords: Ecological Macroeconomic Models; Energy-Economy Modelling; Low-Carbon Transition; Macro-Financial Risks; Income Distribution.
JEL codes: Q57, Q43, E44, C63, D31.

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1 Introduction

According to the latest IPCC report (Lee et al., 2023), emissions have increased since 2010 across all major sectors, with the energy sector playing the biggest role, responsible for approximately 34% of global net greenhouse gas emissions in 2019. Additionally, from 2015 to 2019, global final energy consumption grew by 6.6%, contributing further (Shukla et al., 2022). As of 2023, fossil fuels still account for around 80% of the worldwide energy mix (IEA, 2024). This ongoing trend is inconsistent with the goals outlined in the latest COP29 resolution -the United Nations Climate Change Conference held in Baku from November 11-22, 2024- which reaffirmed the ambitious Paris Agreement target set in Article 2: 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels' (UNFCCC, 2024). The effective achievement of this goal is increasingly at risk, as the World Meteorological Organisation has reported that the period from January to September 2024 was the hottest ever recorded, with an average temperature of 1.54°C (±0.13) above pre-industrial levels (WMO, 2024), signalling an extremely narrow window for effective climate action. It follows that any realistic climate policy that avoids the risk of green-washing must account for the central role of the energy sector in reducing the economy's impact on the ecosystem. This underscores the need for ambitious policies to steer the global economy toward more sustainable pathways.

At the same time, climate change poses risks to financial stability. As emphasised by Mark Carney, former Governor of the Bank of England, in his 2015 speech on "Breaking the Tragedy of the Horizon", one of the main channels through which climate change affects the financial system is via transition risks -i.e. the financial exposures and valuation losses that arise from the structural changes required for decarbonization (Carney, 2015). A growing body of research investigates the risks associated with low-carbon structural change (Campiglio et al., 2023; Daumas, 2024; Dunz et al., 2021; Semieniuk et al., 2021), raising concerns about which sectors and social groups are most likely to bear the highest costs. Furthermore, stricter climate policies and the widespread implementation of green technologies have been identified in the literature as key drivers of the so-called 'stranded assets' phenomenon, that is, the loss in the economic value of carbon-intensive enterprises resulting from the fossil-fuel phase-out and its associated macro-financial stability risks (Cahen-Fourot et al., 2021; Caldecott, 2017; Mercure et al., 2018; Semieniuk et al., 2021; Van der Ploeg & Rezai, 2020).

While the literature provides extensive discussion of carbon-intensive sectors and the exposure of wealth to low-carbon structural changes, along with their implications for macro-financial stability, there has been relatively limited attention to the transitional risks posed by the new decarbonized economy itself (Semieniuk et al., 2021). Specifically, the impact on income distribution and the linkages with the financial sector remain under-explored, despite their established importance in climate-economy and energy-transition models. Although the number of reviews on this topic has grown, only a few studies have addressed income distribution in relation to the low-carbon transition (Balint et al., 2017; Castro et al., 2020; T. Jackson et al., 2014; Naumann-Woleske, 2023; Pollitt et al., 2010; Rezai & Stagl, 2016).

Our aim is to contribute to this gap by proposing a survey covering a wide range of non-equilibrium models, adopting the theoretical framework provided by Semieniuk et al. (2021). In this contribution, the authors develop a theoretical framework examining both low-carbon structural change, namely the decline of carbon-intensive industries ('sunset'), the rising share of low-carbon ones ('sunrise'), the threats to financial stability arising from the rise and fall of industries, and how these dynamics interact to shape aggregate demand and macro-financial outcomes. Their analysis identifies the main drivers and transmission channels, including the economic costs stemming from income losses and asset stranding for the non-financial sector, the impacts these costs may have on financial institutions and financial stability, in terms of non-performing loans, losses in portfolio values, and increased expenditures, and the broader macroeconomic repercussions potentially leading to a decline in aggregate demand and recession.

Our contribution covers Evolutionary, Complexity, Ecological and Post-Keynesian approaches, including both Agent-Based (MAB) and Stock-Flow Consistent (SFC) models. We also devote special attention to the recent

growth of hybrid and cross-fertilised modelling efforts, which combine key strengths such as heterogeneity in ABMs, monetary and financial linkages in SFC models, and sectoral interdependencies in Input–Output models, to capture the complexity inherent in the low-carbon transition.

The second strand of literature that we seek to connect with examines the socio-ecological transition. We take inspiration from the compelling call made by Oswald et al. (2021) to incorporate income distribution into energy system models and into energy and climate policies more broadly. This aligns with the notion of a 'just' transition (McCauley & Heffron, 2018), which aims to ensure a fair distribution of the economic benefits of the low-carbon transition (Vona, 2023), maintain a high and stable wage share and employment levels (García-García et al., 2020; Wang & Lo, 2021), protect vulnerable income groups, and uphold social and environmental responsibility in the allocation of costs (Galanis et al., 2025). A disorderly or delayed transition, together with concerns about social costs, could undermine public support for climate action and jeopardise the opportunities generated by the transition, including green job creation, sustainable growth and social inclusion.

The paper is organised as follows. Section 2 outlines the methodology adopted in the review. Section 3 introduces the modelling approaches, the contributions considered and those admitted to the formal analysis. Section 4 discusses the transmission channels examined in the literature, with a focus on the policy implications emerging from each framework. Section 5 concludes by summarising the key findings and outlining promising avenues for future research.

2 Methodology

Table 1: Meta-model structure

Topic	**Description**
First Step	
Production function	i) Cobb-Douglas, ii) Constant Elasticity of Substitution iii) Leontief iv) Other
Demand-led or Supply-led	i) Demand or Supply-led growth ii) How demand components are determined iii) Role of credit
Environmental representation and biophysical limits	i) Type of Environmental dimensions modelled ii) Biophysical Limits
Finance	i) Banking Sector ii) Financial Markets iii) Central Bank iv) Policy Rate v) Loan interest rate vi) Other information
Income Distribution	i) Functional ii) Mixed iii) Multiple iv) Personal v) Analysis performed
Energy sector	i) Absence ii) Presence iii) Fossil Fuel Sector iv) EROI v) Additional info
Climate module	i) Carbon cycle ii) GHGs Emissions iii) Damage function iv) No climate box
Second Step	
Energy Transition	Modelling of low-carbon energy structural change
Distribution Analysis	Relevance of income distribution in macroeconomic performance
Financial Sector	Active role of financial sector in spreading transition risks
Transmission channel	Description of drivers, channels and impacts

2.1 Model selection and review

This paper aims to: (i) survey macroeconomic models addressing climate-energy interactions, mapping research trends in non-equilibrium modelling; (ii) review the mechanisms through which the transition can generate macro-financial risks, shaping income distribution, employment, and broader economic outcomes; and (iii) summarise the main policy implications for an equitable socio-ecological decarbonisation.

We have considered, to the best of our knowledge, the most relevant macroeconomic models encompassing different theoretical approaches, including Ecological, Post-Keynesian, Evolutionary, and Complexity economics. The selected contributions are required to be published in peer-reviewed journals by the end of 2025.

In line with other surveys (Hafner et al., 2020; Hardt & O'Neill, 2017; Rezai & Stagl, 2016), we do not consider General Equilibrium and Neoclassical models in this work. This decision is motivated by the fact that these models rely on assumptions of perfect markets and forward-looking, utility-maximising behaviour (Farmer, 2025), whereby, according to the standard production function, the remuneration of productive factors equals their marginal productivity. This holds true for both environmental DSGE models (Annicchiarico & Di Dio, 2015; Annicchiarico et al., 2024; Diluiso et al., 2021; Ferrari & Landi, 2024) and heterogeneity-friendly HANK models (Auclert et al., 2023). We argue that standard Neoclassical models, which mainly rely on representative agents, rational expectations, and general equilibrium, struggle to capture the radical uncertainty and emergence of systemic risk inherent in a structural low-carbon change. For these reasons, we consider it appropriate to exclude them from our analysis, both on theoretical grounds and to sharpen the focus and purpose of this work.[1]

The selection process has been non-systematic and exploratory, combining manual search and iterative refinement rather than a systematic protocol. The resulting corpus was then classified into MABM and SFC subsets.

Step 1 - Identification All contributions were searched manually on Google Scholar using combinations of terms such as 'macro-model', 'agent-based', 'stock-flow consistent', 'climate', 'energy', 'transition', 'income distribution', and 'financial risk'. Whenever a relevant contribution was found, additional works were identified through its references and citations[2].

Contributions were considered if they: (i) adopted a macroeconomic framework identifiable as a a MABM or a SFC; (ii) addressed climate, energy, or environmental transitions; and (iii) employed a simulation or computational framework for scenario or policy analysis. As already mentioned, General Equilibrium, Neoclassical, and purely theoretical models were excluded.

Step 2 - Analysis & Eligibility The selected papers were grouped into two subsets (MABM and SFC) according to their dominant structure. In the first stage, we introduce and examine all models across several key dimensions, providing a broad overview of their theoretical background and extracting common structural features, following an approach similar to Hafner et al. (2020). Specifically, we consider the following core aspects:

i) Production structure

ii) Demand-led or supply-led dynamics

iii) Environmental representation and biophysical limit

iv) Presence and role of the financial sector

v) Treatment of income distribution

vi) Inclusion of an energy sector

vii) Interaction with climate dynamics

These dimensions have been chosen to inform the subsequent step, in which we assess whether each model is eligible for inclusion in the formal transmission-channel analysis. In particular, eligibility is evaluated with respect

[1] For a critical review of the theoretical assumptions underpinning this class of models and their main limitations, see Dafermos et al. (2024).

[2] For these reasons, the procedure implemented may not be fully replicable, however, we believe it ensured a broad coverage of the key contributions representing the MABM and SFC system-dynamics approaches to economic modelling.

to the model's ability to capture energy-transition dynamics, income-distribution mechanisms, and the role of the financial sector in propagating transition risks.

In this stage, we identify four essential qualitative features that, when incorporated into model environments, enable a meaningful assessment of the macro-financial transitional risks associated with the low-carbon shift (Campiglio et al., 2023; Daumas, 2024; Semieniuk et al., 2021). They are:

i) the inclusion of an energy sector and an explicit representation of the transition process;

ii) the presence of a household sector that explicitly accounts for income distribution;

iii) the integration of a financial sector interacting with the real economy;

iv) the modelling of transitional transmission channels that influence income distribution and broader macroeconomic outcomes.

A summary overview of these two phases are provided in Table 1.

Step 3 - Results: Transmission channels and Policy After completing the identification and eligibility assessment in Steps 1 and 2, we select the models that meet the required criteria and proceed to the final stage of the review. Here, we assess their transmission channels and discuss the associated policy implications.

3 Models

Macro Agent-Based (MAB) and Stock-Flow Consistent (SFC) models are non-equilibrium (disequilibrium) approaches to economic modelling that represent an attempt to respond to the limitations of standard neoclassical framework assumptions, namely its assumptions of rational expectations, complete markets, and marginal-productivity-based remuneration of production factors[3][4]. MABMs are an established computable macroeconomic models, viewing economic phenomena as 'complex evolving systems' arising from decentralised interactions (Delli Gatti et al., 2018). They represent a heterogeneity-friendly, micro-founded, and bottom-up approach in which agents exhibit bounded and procedural rationality rather than optimization underpinning neoclassical models. Their behaviours are calibrated based on 'heuristics' -simple rules of thumb- capable of matching and replicating a wide range of macro-stylized facts (Dosi, 2023; Haldane & Turrell, 2018). MABMs have been extensively used to simulate innovation and technological change (Dosi et al., 2015, 2013, 2010) in shaping macroeconomic outcomes, demonstrating characteristics of path-dependency, lock-in patterns, uncertainty, and unpredictable results. For these reasons, this class of models is widely acknowledged in the literature as a natural environment that ensures a satisfactory level of heterogeneity and granularity for simulating and assessing the asymmetric and distributional impacts of the transition toward the decarbonization (Balint et al., 2017; Farmer et al., 2015; Mercure et al., 2016, 2019; Pollitt et al., 2010; Wolf et al., 2016).

Stock-Flow Consistent Models (SFC) models are rooted in the Keynesian theory and rigorous accountant relationships. They integrate the real and financial sides of the economy, based on stocks and flows feedback in

[3] A recent strand of non-equilibrium models in the context of the low carbon transition and climate policy is represented by discrete-choice transition (DCT) setups, which model heterogeneous agents' probabilistic switching behaviour under alternative policy and behavioural scenarios. Contributions such as Cahen-Fourot et al., 2023 and Campiglio et al., 2024 emphasise the role of belief heterogeneity and policy credibility in generating carbon lock-in or credibility traps. Others incorporate environmental attitudes, social coordination, learning dynamics, and path dependence in the diffusion of clean technologies (Dávila-Fernández and Sordi, 2020; Zeppini, 2015; Zeppini and van den Bergh, 2020), while Galanis et al., 2023 extends the framework to an international political economy IAM with heterogeneous climate preferences. However, we must acknowledge that none of these models is able to satisfy all four points of Step Three simultaneously, particularly the requirement of a household sector explicitly accounting for income distribution (ii). For this reason, they are mentioned here but not included in the formal analysis.

[4] For related Agent-Based models that, however, do not operate in a fully macroeconomic setting, see Foramitti et al. (2021), Janssen and de Vries (1998), Konc et al. (2022), and Torren-Peraire et al. (2024).

determining the economic aggregate outcome, with an internal logical consistency that removes any 'black holes' (Godley & Lavoie, 2006). The sectors composing the economy interact by means of current and capital account relationships, ensuring four main principles (Caverzasi & Godin, 2015; Godley & Lavoie, 2006; Nikiforos & Zezza, 2018): i) Flow consistency, meaning that every single payment must come from an agent or sector and go to another ii) Stock consistency, stating that every financial asset must correspond to another financial liability iii) Stock-flow consistency, ensuring that every change in asset or liability flows must be reflected in a change of aggregated stocks among sectors iv) Quadruple entry, in which every single transaction involves four different entries: an outflow and a decrease in asset position for the purchaser, an inflow and an increase in asset position for the seller. A rising number of contributions in the literature couple SFC structures with input-output inter-industrial analysis as a consequent tool to assess the effects of structural changes in output composition in the context of a green energy transition, shifting away from carbon-intensive energy production methods (Hardt & O'Neill, 2017).

Table 2 compares a selection of core features of these two system-dynamics approaches, highlighting how each can contribute to modelling the climate–energy and socio-ecological transition. The choice between them reflects their underlying theoretical frameworks and involves trade-offs regarding the representation of agents and their behaviour, the research focus, and the type of policy experiments that can be simulated. As noted in the Conclusion, these choices also shape the resulting policy implications, from market-based and industrial strategies (for example carbon taxation, regulation, and incentives) to the macroeconomic effects of fiscal and monetary policies on aggregate demand and financial stability, including how growth is treated. Notably, MABMs often provide a natural environment for technology-innovation-led growth, where improvements in technology translate into higher capital-goods productivity, whereas in SFC models growth is usually treated as exogenous, driven by the autonomous components of aggregate demand.

3.1 Step I - Identification

Table 3 reports the set of macroeconomic models examined in the first step of our review. The sample comprises 21 contributions, of which eight belong to the macro-agent-based (MABM) strand and thirteen to the stock-flow consistent (SFC) tradition. For each model, the table summarises the main modelling approach, a short description of its structural features, the calibration strategy or geographical coverage, the simulated time horizon, and the sectors or class of agents represented. This overview provides a common basis for comparing the internal structure of the models and for assessing their suitability for the subsequent step of the analysis, where we evaluate their ability to capture the macro-financial, distributional, and socio-ecological transition dimensions of decarbonisation.
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Table 2: Comparison of non-equilibrium economic modelling approaches: macro agent-based (MABM) and stock-flow consistent (SFC) models

Feature	MABM	SFC	Why it Matters
Core philosophy	Economy as a complex, evolving system driven by decentralised interactions.	Keynesian foundations and strict accounting consistency.	Rejection of equilibrium analysis in favour of studying emergent, path-dependent outcomes (MABM); provides a consistent accounting framework for analysing disequilibrium dynamics (SFC).
Foundational principles	Bottom-up emergence. Macro phenomena result from micro-level agent interactions.	Top-down consistency. The system is defined by accounting matrices that must balance.	Determines how policies propagate: micro-to-macro (MABM) vs sectoral balances (SFC).
Representation of agents	Individual, heterogeneous agents interacting through matching protocols.	Agents are typically grouped into institutional sectors.	Reflects different agent- and sector-specific attitudes towards the transition. This distinction is key to studying distributional and sectoral effects of climate policies: who loses, who adapts, and which financial actors are most exposed.
Agent behaviour	Bounded/procedural rationality; heuristic decision-making in the face of radical uncertainty.	Non-optimising, sector-specific rules (e.g., hand-to-mouth consumption).	Reflects realistic behaviour under radical uncertainty surrounding the climate–energy transition.
Key strength	Innovation, technological change, path dependence, emergent phenomena.	Integration of real and financial sectors with full accounting consistency.	Models technological lock-in and disruptive innovation dynamics, alongside potential financial contagion risks and stranded assets; transition and out-of-equilibrium analysis.
Handling of finance	Possible inclusion; typically stylised firm-bank relations.	Core focus. Complete mapping of stocks and flows.	Essential for assessing green credit markets and investment behaviour, and climate-related transition risks to financial stability.
Empirical foundation and policy use	Calibrated to reproduce key macro stylised facts.	Calibration or construction from national accounts.	Supports empirically grounded projections and transition scenarios.

[H]

Table 3: Overview and main features of first-step identified MAB and SFC models

Model	Type	Brief definition	Calibration	Time scale	Sectors
AB Models					
C&C	MABM	Macro-evolutionary agent-based model	The geographical coverage of the model is not explicit; it is an artificial one-country economy.	30 years	Households, Firms producing final consumption and capital goods, Banking, Public Sector
Reissl et al., 2025	MABM-IAM	Macroeconomic, evolutionary, integrated-assessment macro agent-based model	The spatial representation is a generic socio-ecological system interpreted as global, in line with the IAM literature.	2000-2100	Households, Consumption Firms, Capital Firms, Energy, Banking, Government, Central Bank
EURACE	MABM-SFC	Macroeconomic, multi-regional, bottom-up agent-based computable model	The model accounts for multiple regions and mimics Europe.	20 years	Households, Final-Good Firms, Capital-Good Firms, Energy Sector, Banking Sector, Public Sector
Lackner et al., 2025	OD-MABM	Opinion-dynamics macroeconomic agent-based model based on the DSK framework	Calibrated on European countries.	2020-2050	Households, Capital- and Consumption-Good Sectors, Banks, Fossil-Fuel and Energy Sectors, Government, Central Bank
MATRIX	MABM	Multi-agent model for transition risks endogenising an energy sector to investigate financial and distributional aspects	The model is calibrated on EU data.	2000-2050	Households, Consumption Firms, Capital Firms, Energy Firms, Banks, Fossil-Fuel Sector, Central Bank, Government

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Model	Modelling Approach	Brief Definition	Calibration	Time Horizon	Main Sectors/Agents
Ravaioli et al., 2025	MABM-IAM	Integrated-assessment agent-based model, extension of the DSK framework	Calibrated on a high-income economy.	2025-2050	Households, Consumption-Good Firms, Capital Firms, Fossil-Fuel Sector, Energy Sector, Banks, Government, Central Bank
S&B	MABM	Macro-evolutionary agent-based model	The geographical coverage is not explicit; however, the energy sector is calibrated on UK data.	1000 time steps	Households, Firms, Banking Sector, Energy Sector
Wieners et al., 2025	MABM	Macro-financial integrated-assessment agent-based model	Global	2022-2160	Households, Consumption-Good Firms, Capital-Good Firms, Energy Sector, Banking System, Government, Central Bank.
SFC Models					
Berg et al. (2015)	SFC-IO	Stock–flow, input–output macro-ecological model	Generic ecological-economic system	40 time spans	Households (consolidated), Multiple industries, Government/Banking (consolidated)
Bovari et al.	SFC	Continuous–time stock–flow macro-financial model	Global economy	2010-2100	Households, Firms, Banks, Public Sector
Carnevali et al. (2024)	SFC	Ecological SFC discrete-time dynamic macroeconomic model	Global economy	2020–2050	Households, Production Firms, Commercial Banks/Central Bank, Government
DEFINE	SFC	Stock–flow–fund ecological macroeconomic model	Global economy	2018-2100	Households, Firms, Banks, Government, Central Bank

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Model	Modelling Approach	Brief Definition	Calibration	Time Horizon	Main Sectors/Agents
Dunz et al. (2021)	SFC	Stock–flow consistent model with adaptive forecasting of banks' climate sentiments	Generic high-income one-region economy; calibrated on the EU	50 time steps	Households, Government, Central Bank, Consumption-Good Producer, Brown Capital-Good Producer, Green Capital-Good Producer
EIRIN	SFC-AB	Stock–flow, behavioural, open-economy model	Generic middle-/high-income country (EA), reliant on fossil fuels and raw materials for production and consumption	2020-2050	Households; Non-financial sectors (Energy, Consumer Goods and Services, Capital); Financial sectors (Commercial Banks, Central Bank); Government; Rest of the World
GEMMES	SFC	Disequilibrium model assessing climate–financial risks for a developing country	Empirically calibrated on Tunisia	2020-2050	Firms, Households, Banks, Government, Central Bank, Rest of the World. The firms sector is subdivided into Agriculture and Non-Financial Corporations (NFCs)
HARMONEY	SFC-IO	Post-Keynesian, biophysical, stock–flow consistent growth model	Not calibrated, but simulated data compared to long-term trends in US real data	0-300 time spans (interpreted as years)	Households, Resource Extraction, Capital/Goods, Banking
LowGrow	SFC	Post-Keynesian ecological macroeconomic stock–flow consistent model	Empirically calibrated on the Canadian economy	2017-2067	Firms, Households, Government, Commercial Banks, Central Bank, Foreign Sector
Naqvi and Stockhammer (2018)	SFC	Post-Keynesian ecological macroeconomic, demand-driven, multi-sector model with endogenous technological change	No explicit geographical coverage (global economy); calibrated in line with the literature	50 years	Households, Firms, Banks, Government

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Model	Modelling Approach	Brief Definition	Calibration	Time Horizon	Main Sectors/Agents
TEMPLE	SFC	Biophysical-based ecological stock–flow consistent model for the energy transition	Calibrated at global scale	2020-2060	Households, Energy and Capital-Good Firms, Bank, Government
TranSim	SFC-IO	Stock–flow energy-technology transition growth model with EROI analysis	No explicit geographical coverage; broadly akin to an advanced economy	2015–2070	Households, Banks, Energy Firms, Capital Firms, Other Firms (non-energy, non-capital)
Triode Pettena and Raberto, 2025	SFC-IO	Ecological macro-model with a post-Keynesian perspective	Globally calibrated	2020-2090	Worker Household, Capitalist Household, Bank, Government, Central Bank, 27 Industries

3.2 Step II - Analysis & Eligibility

The second step consists of two components. In the first component (Analysis), we scrutinize the models in greater depth along the dimensions outlined in Table 1. The individual topics are discussed in detail in Appendix .1–.7, where we explore their theoretical relevance and explain their importance for our analysis. The corresponding assessment for each model identified in Step 1 is presented in Tables A1–A7. This forms the foundation for the subsequent stage of the review.

In the second component (Eligibility), we assess whether each model meets the criteria required for inclusion in the final analysis, with a particular focus on its ability to capture energy-transition dynamics, income-distribution mechanisms, the role of the financial sector, and the propagation of transition risks. To this end, Table 4 indicates whether these four dimensions are explicitly addressed, thereby laying the groundwork for the final step, where we present the results.

Table 4: Dimensions Required for Evaluating Macro-Financial and Distributional Transmission Channels

Model	Energy Transition	Income distribution	Financial Sector	Transitional risks
MABM				
C&C (Rengs et al., 2020)	✗	✓	✗	✓
Reissl et al. (2025)	✓	✗	✓	✓
EURACE (Ponta et al., 2018)	✓	✗	✓	✓
Lackner et al. (2025)	✓	✗	✓	✓
MATRIX (Rizzati et al., 2025)	✓	✓	✓	✓
Ravaioli et al. (2025)	✓	✓	✓	✓
S&B (Safarzyńska & Van Den Bergh, 2017b)	✓	✓	✓	✓
Wieners et al. (2025)	✓	✗	✓	✓
SFC				
Berg et al. (2015)	✓	✗	✓	✓
Bovari et al.	✗	✓	✓	✓
Carnevali et al. (2024)	✗	✓	✓	✓
DEFINE (Dafermos & Nikolaidi, 2022)	✓	✓	✓	✓
Dunz et al. (2021)	✗	✗	✓	✓
EIRIN (Monasterolo et al., 2022)	✓	✓	✓	✓
GEMMES (Yilmaz et al., 2025)	✗	✗	✓	✗
HARMONEY (King, 2020)	✗	✓	✗	✓
LowGrow (T. Jackson & Victor, 2020)	✓	✓	✓	✓
Naqvi and Stockhammer (2018)	✗	✓	✓	✓
TEMPLE (Jacques et al., 2023)	✓	✓	✓	✓
TranSim (A. Jackson & Jackson, 2021)	✓	✓	✓	✓
Triode (Pettena & Raberto, 2025)	✓	✓	✗	✓

4 Results

After completing the two-step review, seven models are retained for the final stage of the analysis: three from the MABM tradition and five from the SFC paradigm. These models simultaneously incorporate fossil-to-low-carbon energy transition dynamics, transition risks, income-distribution mechanisms, and a functioning financial sector. This section first offers a concise introduction to each contribution, before turning to the transmission channels examined in the simulations and the associated policy implications.

4.1 Macro Agent-Based (MAB) Models

We identify in the literature three families of macro agent-based models[5], according to the second-step analysis summarised in Table 4.

The first contribution to be considered belongs to the MATRIX project, a recent multi-agent, multi-sector model developed within the FEEM-MET[6] research programme. The project was initiated in the wake of the 2021 energy crisis, initially to assess the heterogeneous distributive and economic impacts of rising energy prices and different energy shocks (Ciola et al., 2023), and subsequently to examine their implications for stabilisation policies (Turco et al., 2023). Bazzana et al. (2024) enhance the simulation environment by incorporating a carbon cycle and a damage function consistent with the IAM literature, enabling an assessment of climate change and mitigation policies in the euro area under alternative assumptions regarding the form of the damage function. The contribution by Rizzati et al. (2025) investigates the role of green preferences in achieving the low-carbon transition, with a focus on distributive and inequality issues. Two key insights emerge: (i) only extremely high levels of green preferences can deliver a net-zero transition without active policy; and (ii) subsidies, alongside a carbon tax, are crucial in mitigating adverse heterogeneous effects. In the most recent paper, Ciola et al. (2025) explore several energy-transition pathways and policy experiments to assess financial-stability risks arising from structural change in the energy system. They also simulate a range of policy scenarios involving monetary policy, green finance, and green industrial interventions, as well as potential policy coordination, to address emerging macro-financial risks.

The second contribution (Ravaioli et al., 2025) builds on the Dystopian Schumpeter meeting Keynes (DSK) framework,[7] an agent-based integrated assessment model extending the evolutionary Schumpeter meeting Keynes (K+S) family (Dosi et al., 2015, 2013, 2010) with a carbon cycle and a damage function to capture economy-ecosystem-climate feedbacks (Lamperti et al., 2018). The model was initially developed to examine how micro-climate extremes affect labour productivity, firms' energy efficiency, and the dynamics of capital stocks and inventories, as temperature spikes intensify with rising atmospheric GHG concentrations. Subsequent work incorporated financial transmission channels (Lamperti et al., 2019, 2021), explored the likelihood of low-carbon transition pathways under alternative climate-damage scenarios (Lamperti et al., 2020), and evaluated policy packages capable of reducing transition risks without undermining growth or employment (Lamperti et al., 2025; Wieners et al., 2025). The framework has also been extended with an opinion-dynamics module to account for public support for climate policy (Lackner et al., 2025). Within this broader family, the contribution included in our final assessment is Ravaioli et al. (2025), which expands the simulation set-up dividing households into three income-based classes with different labour, capital income, and demand for consumption and energy goods, to investigate how different policy mixes perform in navigating the growth-stability-emissions-distribution trade-offs inherent in the low-carbon transition.

The third and last MABM contribution included in our review is the model developed by Safarzyńska and Van den Bergh (Safarzyńska & Van Den Bergh, 2017a, 2017b) (hereafter S&B). This behavioural-evolutionary macroeconomic framework charts the complex feedback and network effects among heterogeneous consumers, producers, power plants, and banks in shaping both the technological trajectory of the energy transition and overall financial stability (Safarzyńska & Van Den Bergh, 2017b). On the sustainability-policy side, their results show that higher income inequality and rising energy prices significantly increase bankruptcy rates in the economy. In a related contribution, Safarzyńska and Van Den Bergh (2017a) identify a negative link between green-energy investment and banks' network connectivity, and derive an optimal fossil-renewable energy mix that minimises financial instability.

[5] Although they are grouped within the same group, we must acknowledge that there may be substantial differences in terms of the size of agent classes involved and the complexity of relations across and between agents, depending on the specific focal point of the economic dynamics under investigation.

[6] Fondazione Eni Enrico Mattei – Modelling the Energy Transition

[7] For a review see Lamperti and Roventini (2022); for the DSK-SFC version see Reissl et al. (2025).

4.2 Stock-Flow Consistent (SFC) Models

Moving from middle to bottom part of Table 4, the seminal contribution of Dafermos et al. (2017) represents one of the earliest works in this literature. By coupling post-Keynesian ecological macroeconomic modelling, grounded in the stock-flow consistent (SFC) accounting framework, with Georgescu-Roegen's Flow-Fund theory, the authors develop a benchmark setup that innovatively integrates monetary and physical stocks and flows in a manner consistent with thermodynamic principles. In addition to the standard balance sheet (BS) and transaction flow matrix (TFM), the model introduces two further accounting devices: a *physical flow matrix*, which details the balance between matter and energy inputs in the socio-economic system (extracted materials, the carbon content of non-renewable energy, and the oxygen embodied in CO_2 emissions) and corresponding outputs (industrial CO_2 emissions and waste); and a *physical stock-flow matrix*, which tracks the evolution of key physical stocks relevant to human activity, including material and non-renewable energy reserves, atmospheric CO_2 concentration, the socio-economic capital stock, and hazardous waste.In Dafermos et al. (2018), the framework is used to examine the transmission of physical climate risks through macro-financial channels and to evaluate the effectiveness of a green quantitative easing programme, while green fiscal policy is further explored in Dafermos and Nikolaidi (2019). Dafermos and Nikolaidi (2021) analyse differentiated capital requirement policies, such as the 'green supporting factor' (GSF) and the 'dirty penalising factor' (DPF), and their implications for credit allocation, low-carbon structural change, and climate-related financial risks. Finally, Dafermos and Nikolaidi (2022) provide a comprehensive systems-based comparison of fiscal, financial, and sufficiency-oriented policies (i.e. decline in consumption combined with less working hours) within the DEFINE framework, linking macroeconomic outcomes to social indicators such as unemployment and functional income distribution.

The EIRIN project represents a post-Keynesian attempt to extend the stock-flow consistent methodology towards the endogenous, behavioural decision-making typical of agent-based models, allowing heterogeneous households and firms to interact through behavioural rules and adaptive habits (Monasterolo & Raberto, 2018). Within this setting, green incentive and green bond policies appear effective in fostering the low-carbon transition, easing credit constraints and reducing raw-material use. However, they are not immune to distributional and wealth-concentration drawbacks, highlighting the need for further work on policy conditionality and financing design. This latter point is examined in a subsequent contribution (Monasterolo & Raberto, 2019), where subsidies to fossil-fuel companies are phased out in favour of renewable-energy production, financed through green taxation or green-bond issuance. The results indicate substantial positive effects on the real economy, green-capital capacity, and credit markets. Notably, this shift in energy policy also improves distributive outcomes, as the lower profitability of mining and energy companies reduces dividend income accruing to capitalists. More broadly, Monasterolo et al. (2022) highlight the increasing complexity of the trade-offs involved in implementing carbon taxes or green-bond programmes to scale up green investment in the EU, examining sustainability in terms of emission reductions, distributional effects, and public-debt dynamics. Their findings show that changes in investors' risk pricing of high-carbon financial assets, triggered by green policies, play a key role in relaxing constraints across all three dimensions. The contribution retained for this survey, Gourdel et al. (2024), assesses physical and transition risks for the euro area by simulating ordered and disorderly Network for Greening the Financial System scenarios. Three main insights emerge: a disorderly transition can undermine financial stability and generate stranded-asset losses; the extent to which banks and firms internalise climate policy in their investment decisions is crucial for enabling an orderly transition and mitigating physical risks, underscoring the importance of policy credibility; and central banks and financial supervisors should incorporate the double materiality of climate risks into their monitoring frameworks.

The ecological economics and degrowth approach is represented here by A. Jackson and Jackson (2021) and T. Jackson and Victor (2020). The first contribution charts an a-growth scenario aimed at addressing environmental and social sustainability in the pursuit of a net-zero objective, using the LowGrow SFC macroeconomic simulator calibrated on the Canadian economy (T. Jackson & Victor, 2020). Some of the dynamics and conclusions of this

model are shared with a related Stock–Flow Consistent Input-Output (SFC-IO) framework, TranSim (A. Jackson & Jackson, 2021). In TranSim, the energy transition is driven by a declining Energy Return on Investment (EROI). This decline raises energy costs and the general price level, eroding real income and wealth. As a result, consumption and employment fall, giving rise to a period of stagflation, worsening inequality, and a heightened risk of asset stranding.

To conclude this overview, the TEMPLE model (Jacques et al., 2023) integrates biophysical constraints, represented by the availability of fossil fuels, energy, materials, and waste-processing capacity, within a comprehensive global SFC framework. It incorporates dynamic Energy Return on Investment metrics for both renewable and non-renewable energy sources. The simulations indicate that market-based mechanisms alone fail to generate the level of low-carbon investment required to meet the 1.5 °C target of the Paris Agreement. Instead, they point to a scenario in which a stronger public-sector role becomes necessary, involving substantial green investment to steer the transition while addressing drawbacks such as high inflationary pressures, declining EROI, and the risk of stranded firms in the energy sector. The model also highlights the potential for slower growth to ease inflationary dynamics and support the transition.

4.3 Transmission Channels

Figure 1 summarises the theoretical mechanisms through which transition policies and technological shifts propagate across the economy, and how the interactions between the non-financial, financial and public sectors shape aggregate dynamics.

Changes in the energy mix required for decarbonisation may affect production through several transmission channels, including cost pass-through for intermediate and final energy use, shifts in firms' production costs, and the downsizing or expansion of specific sectors, thereby altering inter-sectoral linkages and the reallocation of productive factors. The financial sector plays a central role in mobilising the funds needed for low-carbon investment through green finance, yet it can also replicate and amplify tensions originating in the real economy through revised expectations, the emergence of stranded fossil-fuel assets, and balance-sheet pressures stemming from economic losses. The greater the misalignment between transitional expectations and the realised pace of decarbonisation, the higher the likelihood that transition risks materialise, prompting countercyclical and restorative policies, subsidies, or other stabilising measures, with clear implications for public budgeting sustainability. The reinforcing feedbacks among these mechanisms shape aggregate demand and macro-financial dynamics, and ultimately determining the outcome in terms of income distribution.

Table 5 applies the analytical framework developed above to the selected models. For each contribution, it summarises: (i) the drivers of the transition (mitigation policies, technological change, or shifts in green preferences affecting investment or consumption choices); (ii) the transmission channels; (iii) the resulting impacts on economic activity, financial stability, and income distribution; and (iv) the presence of reinforcing feedback loops. The table is organised into MABM and SFC sections, indicating the model name and the specific transmission channels examined in each case.

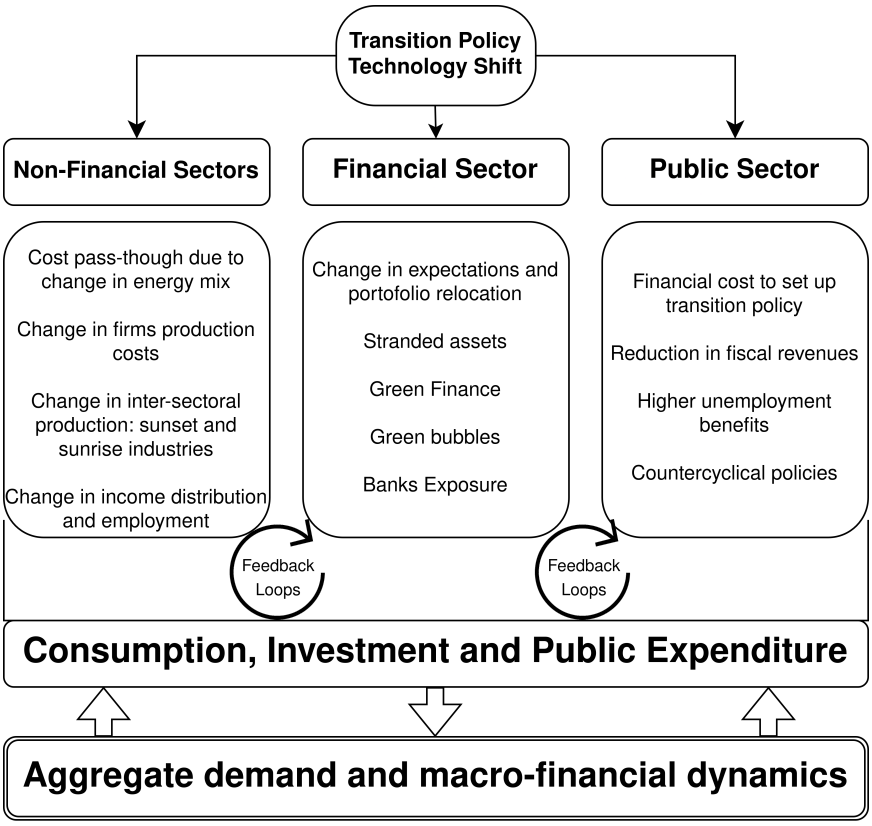


Figure 1: Macro-financial risk map affecting the non-financial, financial, and public sectors. Author's own elaboration based on the reviewed literature.

Table 5: Drivers, transmission channels, impacts and feedback loops across selected models.

Model	Drivers	Channel	Impact	Channel	Impact
MABM					
DSK (Ravaioli et al., 2025)	MP	$\Delta P \uparrow$	HH bottom 60% income ↓, firms' costs ↑	Δ financial position ↓	Defaults ↑ Unemployment ↑ GDP ↓
MATRIX1 (Rizzati et al., 2025)	MP, T, GP	$\Delta P \uparrow$	HH income ↓	Δ purchasing power ↓	Output ↓ Consumption ↓ GDP ↓
MATRIX2	MP	$\Delta\mathbb{E}$	Employment ↑, HH income ↑, constrained output	Δ financial position ↓	Loan defaults ↑ Financial Instability ↑ $\Delta P \downarrow$
MATRIX3	MP, GP	$\Delta P \uparrow$	HH income ↓	Δ purchasing power ↓	Unequal distribution of abatement rents, Inequality ↑
S&B1 (Safarzyńska & Van Den Bergh, 2017b)	MP, T, GP	$\Delta P \uparrow$	HH income ↓	Δ purchasing power ↓	Consumption ↓ GDP ↓ Profits ↓, Unemployment ↑
S&B2	MP, T, GP	ΔP	Changes in income sources across classes	Δ financial position	Redistribution of capital and energy rents, Income/wealth inequality ↑
S&B3	MP, T, GP	$\Delta P \uparrow$	Production costs ↑	Δ financial position ↓	Defaults ↑ Bankruptcies ↑
SFC					
DEFINE1 (Dafermos & Nikolaidi, 2022)	MP	$\Delta P \uparrow$	Firms profitability ↓	Δ financial position ↓	Investment ↓ GDP ↓ Unemployment Rate ↑ Bargaining Power ↓ Wage Share ↓
DEFINE2	MP	$\Delta Regulation \uparrow$	$CAR_{bank} \downarrow$	Δ credit rationing ↑	$i_{brown} \uparrow$ GDP ↓ Unemployment Rate ↑ Wage Share ↓
EIRIN (Monasterolo et al., 2022)	MP	$\Delta P \uparrow$ $\Delta\mathbb{E}$	HH net income ↓	Δ purchasing power ↓ Green-asset prices ↑	Aggregate demand ↓ GDP ↓ Unemployment ↑ Bargaining power ↓
LowGrow (T. Jackson & Victor, 2020)	MP	$\Delta P \uparrow$	HH income ↓	Δ purchasing power ↓	Consumption ↓ Investment ↓ GDP (vs. BS) ↓ (Gini =)
Temple (Jacques et al., 2023)	MP, T	ΔP ↑	Production costs ↑		Broader macroeconomic impacts off-set by 'war-economy' state-led decarbonisation

Continued on next page

Table 5 continued

Model	Drivers	Channel	Impact	Channel	Impact
TranSim (A. Jackson & Jackson, 2021)	MP	ΔP $\uparrow$	HHs Income and Wealth $\downarrow$ Stranded Assets $\uparrow$	Δ purchasing power $\downarrow$	Consumption $\downarrow$ Investment $\downarrow$ GDP Unemployment $\uparrow$ Functional Income Distribution $\downarrow$

Notes: MP = Mitigation Policy; T = Technology policy/shift; GP = Green preferences; ΔP = change in prices; $\Delta\mathbb{E}$= Change in expectations; $\Delta Regulation$ = Change in macroprudential/financial policy ; HHs = households; AbT rent = Abatement rent; BS = Baseline scenario.

4.3.1 Agent-Based Models

The DSK extension by Ravaioli et al. (2025) presents two sets of experiments assessing a range of fiscal-redistributive and environmental policies, both individually and in combination, to investigate their heterogeneous properties and trade-offs in terms of economic dynamics, income distribution, and emission trajectories. A stand-alone carbon tax (**DSK** row in Table 5) raises the price of energy goods, disproportionately burdening households at the bottom of the income distribution, given their higher share of expenditure on energy. The increased tax burden on firms translates into a higher rate of defaults, posing risks for banking-sector stability. Taken together, these mechanisms generate a generally adverse outlook, with weaker economic dynamics, heightened financial instability, and failure to achieve climate targets.

Within the MATRIX project, Rizzati et al., 2025 examines the conditions under which Green Preferences facilitate the energy transition, compared to conventional incentive-based carbon policies, whether coupled with different intensities of subsidies for abatement technology or not. Despite the results showing that net zero emissions occur only for extremely high values of households' and firms' green preferences, the authors identify a Carbon Tax combined with a moderate subsidy policy scheme as the effective tool for addressing the environment-economy-distributive dilemma. For the sake of our analysis, the simulations test a wide range of green preference inclinations and green policies with varying degrees of sensitivity, reporting three broad transmission channels at work in the results. The first assessment (**MATRIX1**) outlines the impact of AGP on firms' higher abatement investment in production costs, which increases output prices and reduces sales. The resulting decrease in real wages for workers, in the case of the strongest green awareness (η= 0.1, with a fall of 12.4%), reduces purchasing power and thus diminishes aggregate demand through feedback loops. A similar dynamics is replicated by the implementation of a CT scheme. The second one (**MATRIX2**) reports the possible rise of economic instability, calculated as the percentage of simulations in which public debt exceeds 500%, originating from a disordered transition after the introduction of a Cap-and-Trade regime. While on one side pushing companies not to invest in abatement efforts to replace fossil fuels by substituting them with labour prevents real wages from falling, the imperfect substitutability threatens financial stability by imposing limits on production, resulting in a slower pace of inflation (Rizzati et al., 2025, p. 16). In the third and last scenario (**MATRIX3**) the policies are coupled with different degrees of abatement subsidy, with a stronger regressive effect the higher the subsidies to abatement investment for two reasons: the unequal distribution of abatement rents based on net worth; the higher cost of living. This raises inequality among workers, with the wealthier 50% of the population gaining at the expense of the poorer 50% (Rizzati et al., 2024, p.18).

In Safarzyńska and Van Den Bergh, 2017a, three transmission channels are acknowledged to study how a rapid transition to renewable energy production can hinder financial stability and worsen inequality: the role of higher energy prices in causing bankruptcies due to lower consumption and aggregate demand on profits (**S&B1**), and in skewing the distribution of wealth among owners of different factors of production (**S&B2**); and the degree of concentration of loans to energy companies on the likelihood of cascading bank failures (**S&B3**). A similar framework is also presented in Safarzyńska and Van Den Bergh (2017b).

4.3.2 Stock-Flow Consistent Models

In the systems-based analysis of climate policies presented in Dafermos and Nikolaidi, 2022, a range of policy experiments is conducted to evaluate ecological (temperature, material use, and waste), macro-financial (firms' default rates, banks' leverage ratios, and the public debt-to-output ratio), and social indicators (unemployment and functional income distribution, proxied by the wage share) under different climate and transition policy scenarios.In the **DEFINE1** scenario reported in the second block of Table 5, an increase in the carbon tax undermines firms' profitability and reduces their desired level of investment, under the assumption of no pass-through of higher costs to prices. The resulting contractionary effects lead to higher unemployment, a weakening of workers' bargaining power, and a decline in the wage share. In the second scenario (**DEFINE2**), a green financial policy in the form of a 'dirty

penalising factor' applied to carbon-intensive loans tightens credit conditions by lowering banks' capital adequacy ratios and increasing interest rates on carbon-intensive borrowing. This generates credit reallocation towards low-carbon activities but also induces recessionary pressures. The associated decline in economic activity, together with higher credit rationing and firms' defaults, results in rising unemployment and a deterioration in functional income distribution through a reduction in the wage share.

The EIRIN contribution (Monasterolo et al., 2022) aligns well with the aim of the current analysis by investigating different transmission channels activated by a green subsidy program financed either by an anticipated carbon tax or the issuance of green bonds. This program examines financial actors' reactions, where the direction and magnitude of the change in risk assessments on high and low-carbon firms imply different degrees of effectiveness of the policy, anticipating trade-offs in decarbonization, distributive effects, and public finance sustainability. Three broad channels are thus explored: the change in the relative price of high-carbon goods triggered by the introduction of the carbon tax on production costs; the assessment of climate transition risks on investors' portfolio choices; and the shift in commercial banks' attitudes toward lending based on firms' debt-to-equity ratios. For our analysis, we focus on the Sc2 and Sc3 scenarios, which encompass a disorderly transition setup with the introduction of an unanticipated carbon tax (CT), coupled or not with a financial reaction. Accordingly, these scenarios show the worst performance regarding the relative net income shares of the worker and capitalist households compared to the Green Sovereign Bonds (Sc4) scenarios, with only slightly less detrimental effects once the financial actors' reaction is introduced. This is due mainly to two reasons, as reported by the authors: first, the downward-sloping dynamics of net workers' income, influenced by the CT on energy prices; second, the poor GDP performance that results in less employment and a more depressed bargaining component in wage setting, which negatively affects GDP growth and investments through demand-side feedback loops. Once the financial reaction is introduced into the picture, the magnitude of the detrimental effects is partially offset by the higher prices in green assets, resulting in a wealth effect for capitalists boosting their consumption (**EIRIN**). Gourdel et al. (2024) extends previous conclusions within an integrated framework that addresses both transition and physical risks, implementing the 2020 NGFS Climate Scenarios. The design model investigates the main direct impacts of climate transition and climate physical shocks, specifically through a negative price adjustment that leads to reduced profitability for high-carbon firms and damages to capital and infrastructure. This adds a layer of complexity considering the cascade effects on the economy, as well as on private and public finance, and their indirect interrelated impacts. According to the simulations, the distributive outcome relies on a variety of counteracting conditions, such as capital replacement due to climate damages, changes in firms' profitability, the role of public debt on capitalists' income, and GDP and employment dynamics. These factors can, to some extent, result in a temporary improvement for workers. All in all, the authors state that transition policies that rely more on public finance than on repairing physical damages can lead to higher payoffs for capitalists, highlighting the role of financial markets in unequally distributing the costs to different classes.

In a specified setup calibrated on Canada, the LowGrow model (T. Jackson & Victor, 2020) measure the performances of three different scenarios by developing a multidimensional composite index targeting macroeconomic, distributive, financial, and environmental metrics: a Baseline aligned with the past 25 years of macro variables, a Carbon Reduction Scenario targeting an 80% reduction in GHG emissions over 1990 levels by 2050, and finally a Sustainable Prosperity Scenario aiming for a faster low-carbon transition coupled with socio-economic policies that redistribute income towards lower classes. Although the paper suggests a sustainable horizon in which environmental and societal burdens can be simultaneously alleviated even without solid growth rates, the second scenario, characterized by a carbon tax on energy sector emissions of $300/ton, highlights the role of increased electricity prices on household balance sheets, which has a depressive effect on aggregate demand. Meanwhile, firms revise their investment plans downward, undermining the demand-led Keynesian engine with respect to the baseline. However, the effect on the income Gini per capita index shows any kind of improvement, resulting in a flat line (**LowGrow**).

The Temple model (Jacques et al., 2023) is war-economy like state-led exercise where a rapid energy transition characterised by a declining EROI is imposed by the end of 2060. Then planned transition includes certain policies that, for the sake of our analysis, mitigate some of the counteracting effects of the energy transition on macroeconomic variables. These policies prevent the full impact of the increasing exogenous level of renewable energy and the shift to a more expensive energy source from affecting socio-economic needs. For example, a ceiling on energy price inflation is set at 10%, while public subsidies to energy firms prevent profits from turning negative and provide a public guarantee on their debt. This leads to a war-like scenario where the full transition is achieved through a planned policy that reinvests forced savings into low-carbon renewables, offsetting many of the widely studied detrimental effects of green energy transitions (**Temple**). Overall, growth is viewed as a detrimental effect rather than an asset for the transition, aligning with the post-growth ecological economics strand of research (Kallis et al., 2025).

To explore a related case where previous transition risks are free to fully materialise through the simulations, we now consider the SFC-IO TranSim model. This model accounts for inter-sectoral interrelations and allows for a thorough realization of lower energy return on investment (EROI) implications due to a green energy transition. As a result, higher energy prices negatively affect growth and functional income distribution. Accordingly, the setup provides the two baseline transition scenarios -the high capital (HC) and the low capital (LC) cases- stating the different requirements for green capital per unit of energy output, reflecting the authors' views on the uncertainty surrounding this process. The main transmission channel explored is the usual cost of production-price nexus (**TranSim**). As the energy transition progresses, the increased need for energy and capital investments initially supports growth and employment, bolstering real wage claims. However, this soon compels firms to raise their markups and increase prices, triggering a cost-price spiral. Inflation erodes households' real income and wealth, leading to reduced consumption and undermining the Keynesian aggregate demand engine, eventually resulting in a recession. On the distributive side, unemployment decreases real wage claims, while higher capital intensity supports the profit share and reduces the wage share, with more severe implications in the HC scenario. On the financial side, although fossil-fuel-stranded assets materialize over time, their impacts are contained for two main reasons: first, the energy sector performs well overall, and second, losses incurred by energy firms are mitigated as they account for the rate of return on both low- and high-carbon capital assets, which contributes to higher prices. Overall, the economy will achieve transition by 2060, reaching a new steady state but experiencing persistent inflation, unemployment, and a worsening of the functional income distribution.

4.4 Discussion and Policy implications

The results outlined in the previous section, and summarised in Table 5, point to a picture in which two principal transmission channels dominate as sources of macro-financial transition risk across simulations, i.e. the change in energy input and price (ΔP) and the expectations about the speed of the decarbonisation ($\Delta \mathbb{E}$).

In almost all MAB and SFC models, the first real-economy channel operates through an increase in energy prices. This acts as the main mechanism by which firms' production costs rise and, where modelled, households face a higher final-energy price burden. The resulting regressive inflationary pressure disproportionately erodes the purchasing power of lower-income households, reflecting both their limited ability to insure against price increases and their higher share of energy expenditure compared to top-income groups. The extent to which rising energy costs affect energy-intensive production and sectoral profitability can trigger adverse impacts on firms' liquidity stress and, eventually, default rates, with clear negative effects on labour demand. Together with reduced consumption, these dynamics push the economy towards lower growth, higher unemployment and persistent inflation, with the banking and financial sector acting as a propagator and amplifier of these shocks.

A second financial-macro channel, although less explored across models and featured only in the MATRIX and EIRIN contributions, stresses the role of changes in expectations about decarbonisation following policy announce-

ments or macroeconomic signals, as described in the real-economy channel. In EIRIN, shifts in expectations after a carbon tax implementation can affect the pricing of green financial assets, leaving wealthy households better off and thereby contributing to wealth inequality. In MATRIX, this channel can act as a detrimental force in the case of a disorderly transition, posing severe threats to financial stability by limiting production due to the difficulty of substituting between energy and non-energy production factors, and placing firms' financial positions under pressure, increasing the risk of defaults.

As the macroeconomic repercussions of a delayed or disorderly decarbonisation unfold, severe economic costs emerge, calling for countercyclical restorative and supportive policy measures. At the same time, the complexity of balancing economic, social and environmental objectives, together with the trade-offs inherent in reaching carbon neutrality, introduces challenges for policy design in delivering a 'fair' societal outcome. The achievement of a 'just transition' as a work-centred concept (Wang & Lo, 2021) aims to ensure a more equitable distribution of the economic gains of the low-carbon transition (Vona, 2023), maintain a high and stable wage share and robust employment (García-García et al., 2020; Wang & Lo, 2021), protect vulnerable income groups, and guarantee that the costs of the transition are allocated on the basis of social and environmental responsibility criteria (Galanis et al., 2025).

Table 6 reports, for each contribution assessed in the previous section, the target of the simulation exercises and the recommended policy option. As clearly gets visible in the second column, distributive issues represent a valuable dimension on which to focus. Alongside the policy suggestions aimed at achieving a fair societal transition along sustainable pathways, two points emerge. The first is that no model proposes a stand-alone policy capable of resolving economy-society-environment dilemmas, given the multidimensional layers entailed in the low-carbon transition. Policy coordination arises as a common ground for action, spanning fiscal, redistributive and innovation policies.

Second, across the different approaches, some degree of bias in policy prescriptions has to be acknowledged, depending on the theoretical foundations of the models. In particular, these interventions range from supply-side measures such as carbon taxes and subsidies for energy innovation and efficiency, which are more common among MABMs where growth is driven mainly by technological progress in capital-goods productivity, to redistributive tools, and further towards more demand-led approaches such as state-led transitions in SFC models, where growth is largely exogenous. Policy design appears to mirror these theoretical foundations across evolutionary and complexity approaches, post-Keynesian and ecological traditions. Nonetheless, the transition, and the risks it generates, call for renewed and coordinated policy mixes to address environment-economy-society trade-offs.

Table 6: Models: Policy suggestion in governing the energy green transition risks

Contribution	Focus/Targets	Policy Suggestions
MABM		
DSK (Ravaioli et al., 2025)	Fiscal and environmental policies to governor the economy-distributive-emission nexus	Combination of progressive fiscal policies, green subsidies to reduce carbon intensity of production and a mild carbon tax
Matrix (Rizzati et al., 2025)	Emissions reduction, economic and distributive performance	Carbon Tax with a moderate level of green abatement subsidies
S&B (Safarzyńska & Van Den Bergh, 2017a)	Energy use reduction and economic performance	Energy tax with a redistributive policy
SFC		
DEFINE (Dafermos & Nikolaidi, 2022)	Ecological sustainability and macrofinancial and social stability	Combination of several fiscal, monetary/financial and sufficiency climate policies to smooth socio-ecological trade-offs
EIRIN (Monasterolo et al., 2022)	Decarbonization, distribution and public finance sustainability	Green subsidies financed with green sovereign bonds. Higher role of climate finance in policy design
LowGrow (T. Jackson & Victor, 2020)	Environmental, social and financial outcome	Price on carbon emissions, public transfer payments to reduce the inequality of incomes
Temple (Jacques et al., 2023)	Rapid energy transition within the Paris Agreement 1.5° threshold	State-led transition and Post-Growth Scenarios
TranSim (A. Jackson & Jackson, 2021)	Energy technology transition with a EROI reduction	Inclusion of EROI in policy analysis. Fiscal and monetary policy financing the transition and ease detrimental effects

5 Conclusion

This paper has reviewed 21 non-equilibrium climate–energy models drawn from the Evolutionary, Complexity, Ecological and Post-Keynesian traditions, including both Macro Agent-Based (MAB) and Stock–Flow Consistent (SFC) approaches, with a particular focus on macro-financial risks and income distribution.

We developed and applied a multi-step meta-model. In the first phase (Identification), we retrieved the relevant contributions and assigned each to one of the two classes, providing a brief overview of their structural features (type, definition, calibration, time scale and sectors or agents included). In the second phase (Analysis and Eligibility), we examined the models across several key dimensions to provide a broad comparative overview and to extract common structural information[8]. Furthermore, we narrowed our focus to the models that met four specific criteria: the presence of an energy sector explicitly modelling the low-carbon transition; an explicit treatment of income-distribution dynamics; the inclusion of a financial sector; and the specification of transitional transmission channels summarising macro-financial transition risks. Ultimately, we selected eight model families for the final formal review: three MAB models and five SFC models. On this basis, our analysis leads to three main conclusions and suggests possible further developments:

- We systematised the main transmission channels through which decarbonisation can generate negative macro-financial and distributional risks. The first is the real-economy channel driven by changes in energy costs, leading to innovation in firms' production processes, shifts in sectoral profitability, and a higher energy burden on households. This channel tends to produce regressive inflationary pressures, disproportionately eroding the purchasing power of lower-income groups and, where energy-intensive sectors are strongly affected, heightening firms' liquidity stress, defaults, and unemployment. The second, a financial-macro channel, is driven by changes in agents' expectations regarding the speed of decarbonisation, which alter the valuation of green financial assets, reshape portfolio allocation, and, under a disorderly transition, amplify instability.

- Second, stand-alone and market-based policies (carbon taxes and emissions-trading schemes) and innovation incentives appear insufficient to drive the low-carbon transition. While market mechanisms such as carbon pricing and subsidies for green technology are relevant, our findings suggest that relying solely on these instruments is unlikely to achieve the structural shift away from fossil-fuel energy production. The complexity of the transition, characterised by sectoral interdependencies, particularly in models incorporating input–output relationships, calls for stronger interventions to ensure compliance with the Paris Agreement (Jacques et al., 2023; WMO, 2024). These interventions include public investment, industrial policies, and regulatory frameworks.

- Third, the potential negative outcomes for income distribution can be severe, especially if the transition is delayed and uncoordinated. Such a transition may generate unequal economic shocks, disproportionately affecting lower-income groups and sunset industries, thereby increasing inequality, unemployment, and financial instability. Policy coordination and income redistribution are essential for managing transition risks. Effective climate action requires strong coordination between fiscal, monetary and industrial policies. A 'just' socio-ecological transition must be designed to mitigate redistributive effects from wages to profits, ensure a fair distribution of the economic gains of the low-carbon transition, maintain a high and stable wage share and employment levels, protect the most vulnerable income groups, and uphold social responsibility in allocating environmental costs (Fierro et al., 2024; Galanis et al., 2025). As global climate action remains inconsistent with the ambitious GHG containment required (Climate Action Tracker, 2024; Greenpeace European Unit, 2021), the likelihood of a disorderly transition increases. The analysis presented in this study can serve as

[8] See Table 1 for a summary of the topics, Sections in Appendix .1–.7 for a description and Tables A1–A7 for results.

a starting point for addressing this challenge, acknowledging the potentially destabilising effects of financial transitional risks.

Concerning the trend in non-equilibrium modelling developments, energy and climate integration has become a well-established line of research, reflecting a shared interest in linking the real and financial dimensions of the low-carbon transition and its climatic implications. Yet we acknowledge an important gap in the literature concerning future modelling directions, particularly the integration of nature and biodiversity loss, as reported in Table A3, representing an under-explored topic in the pool of MABM and SFC contributions considered in this review.

The results presented here should be interpreted in light of the aims of the current analysis, which leaves room for multiple extensions and improvements. The comparative analysis employed can be used to address other issues and can, of course, be expanded to incorporate additional models informed by other theoretical approaches, as well as to examine 'windows of opportunity' rather than focusing solely on the potential drawbacks of the 'green' transition, in terms of job creation, sustainable growth and social inclusion. This would allow for a broader and more realistic perspective, helping to steer integrated policy interventions towards a more equitable and sustainable future.

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7 Disclosures

During the preparation of this work the author used Chat-GPT 5 and Grammarly in order to check grammar and improve the fluency of the text. After using this tool/service, the author reviewed and edited the content as needed and take full responsibility for the content of the work.

8 Appendix

.1 Production function

As depicted in Table A1, the models considered in this review are polarized by two different approaches to modelling the technology. This reflects the theoretical framework adopted, as pointed out in Hafner et al. (2020). On one side, there is the Constant Elasticity of Substitution (CES) production function, whose inclusion is justified in the pooled models either for its capability of capturing various types of rebound effects (Safarzyńska & Van Den Bergh, 2017b), either its alignment with empirical literature and its capacity in collapsing to a Leontief or a Cobb-Douglas, depending on the value of the elasticity of substitution imposed (Ciola et al., 2023). On the other side, the most common technology implemented is the Leontief, both in a static and dynamic form, to capture innovation with changing production coefficients. This class of production function is generally adopted to overcome the empirical flaws and the shortcomings of the neoclassical hypothesis behind the alternatives (Caiani et al., 2016), as well as formalise the supply-side constraints arising from environmental problems (Dafermos et al., 2017). Whenever the cell says 'Other', it indicates that the production technology employed in the model doesn't fit the prevailing general taxonomy, which typically includes CES, Cobb-Douglas and Leontief.

.2 Demand-led or Supply-led

The second fundamental topic is whether the models are demand or supply-led. For demand-led we refer to the capacity of aggregate demand to trigger output and growth, whose deficiency can lead to the possibility of involuntary unemployment. On the contrary, in the supply-led models, the growth is determined by supply factors, based on price capacity in allocating resources at best, ruling out the possibility of unconsidered unemployment among production factors. More deeply, we focus on three main aspects in addressing the topic:

i) Existence of demand factors such as consumption, investment, or public expenditure in triggering output

ii) How the single demand components are determined

iii) The role of credit in financing the investment and the consumption

On the third point, we aim to stress the fundamental role played by credit on aggregate demand, growth and its implication in terms of financial fragility, throughout endogenous boom-and-bust cycles (Botta et al., 2025). In Tables A2 we report the investment drivers in the final good/manufacturing sector. For simplicity, we include social transfers in public expenditures.

.3 Environmental representation and biophysical limits

This third section examines how the environment is represented in the models considered and whether any biophysical limits are explicitly incorporated. The first aspect concerns how these models integrate physical flows of matter and energy between the economy and the ecosystem, and the extent to which they reflect the environmental dimensions of economic activity, including material extraction, pollution, waste generation and biodiversity loss.

The second aspect focuses, in line with Georgescu-Roegen's contribution (Georgescu-Roegen, 1986) and the ecological economics perspective, on the explicit presence of biophysical limits in the models, arising from thermodynamic constraints. The economic process transforms low-entropy matter, which is finite and cannot be fully recycled, and energy into high-entropy waste and dissipated heat. Within the Earth system, which is closed system, inescapable thermodynamic limits related to energy conservation and entropy production constrain the extent to which resource use can be decoupled from economic growth (Berg et al., 2015). These constraints may imply the need for 'sufficiency' or 'post-growth' scenarios aimed at achieving sustainability within planetary boundaries (Kallis et al., 2025).

.4 Treatment of finance

Finance is a key factor in aligning private investment with climate targets and mobilizing resources toward low-carbon activities. Also, it plays a critical role in spreading the costs and the instability due to inaction in addressing effective climate change and low-carbon transition policies, essential for preventing a crushing rise in global temperatures Carney (2015). The current research focuses extensively on evaluating the impacts of the transitional risks triggered by the energy transition (Caldecott, 2017; Semieniuk et al., 2021; Van der Ploeg, 2016; Van der Ploeg & Rezai, 2020) and the 'cascade' impacts of its interrelation with the broader real economy (Cahen-Fourot et al., 2021). We consider the following five items:

i) The existence and features of the banking sector

ii) The type of financial markets modelled

iii) The presence and behaviour of Central Bank

iv) The interest rate rule

v) Loan interest rate

Additional details about possible layers of complexity are included in the last column. Results are reported respectively in Tables A4.

.5 Income distribution

Growing concerns in the literature focus on the fact that lower social classes are more likely to bear higher costs transitioning to a low-carbon economy. This has led to questions about policies that are considered 'just,' aiming to reduce the burden on the most vulnerable groups while also accounting for the unequal responsibility in contributing to emissions and climate damage (Galanis et al., 2025; Oswald et al., 2021). Income distribution is thus a fundamental aspect of this review, in investigating the impacts of transitional risks associated with the low-carbon energy transition. The bidirectional joint analysis of inequality and finance is a well-established strand of research (Botta et al., 2024; Cardaci, 2018; Cardaci & Saraceno, 2016; Dosi et al., 2013; Russo et al., 2016). Some contributions under scrutiny have extended the analysis on the interplay between distribution and finance in the contest of energy green transition (Bazzana et al., 2023; Botte et al., 2021; Safarzyńska & Van Den Bergh, 2017a, 2017b). In evaluating the suitability of simulation environments for analysing distribution we assess whether they consider functional

-distinguishing between wages and profits- or personal income distribution, which accounts for multiple income sources. The functional income distribution category is further divided into three subcategories, each representing different levels of complexity incorporated into the models (see Table A5 for further details).

i) Workers or Capitalists distinction

ii) Mixed, if additional intermediate classes are added

iii) Multiple, if the functional income distribution is coupled with other income sources depending on the class under scrutiny

The last column reports the analysis performed in addressing this topic.

.6 Energy Sector

Energy is fundamental to the entire economic process (Georgescu-Roegen, 1984). Therefore, the presence of an energy sector in the models is an essential condition for the current analysis for three main reasons. First, as outlined in the Introduction, the energy sector is fundamental in addressing the green transition given its significant role in causing GHG emissions (Lee et al., 2023), i.e., to assess the economic impacts of the shift from 'brown' or fossil-fuel plants to more sustainable energy production on renewable resources (A. Jackson & Jackson, 2021). Second, it provides a natural basis for investigating the most suitable policies in mitigating the impacts on the ecosystem (Jacques et al., 2023), fostering a timely and orderly phase-out of fossil fuels. Moreover, it represents a necessary extension in investigating a wide range of collateral topics, such as carbon footprint (Marques et al., 2012), the interplay with climate damages, and, notably, the macroeconomic effects of the recent surge in energy price due to the war and the geopolitical frictions in Europe and West Asia (Canelli et al., 2024; Ciola et al., 2023; Turco et al., 2023; Wildauer et al., 2023). Thus, in In Tables A6, we query the models to determine whether they include the energy sector, the availability of fossil fuels, renewables, and any kind of EROI measurement (Diesendorf & Wiedmann, 2020; Fizaine & Court, 2015; A. Jackson & Jackson, 2021) namely, the return on energy investment, which assesses the efficiency of different production methods, given by

$$EROI = \frac{\text{Energy Delivered}}{\text{Energy required to deliver it}}$$

.7 Climate box and climate-economy feedbacks

Table A7 shows some common features of the climate-energy modelling approach, specifically the inclusion of a relationship between the economy and the ecosystem. According to the principle of 'double materiality', we can distinguish two causal chains: one recognizing the environmental impact of economic activity on the climate, and the other acknowledging the extent to which climate change can affect the economy (Commission, 2019). We identify the following three features covering:

- The emission tracker, which records all the emissions generated by the economic processes
- The carbon cycle, a stylised form to represent how CO2 redistributes once emitted throughout the seas, Earth's surfaces, and atmospheres' different layers, resulting in a change of radiative forces and then the global temperature.
- The damage function is the way climate- weather-related events are introduced in the Integrated Assessment Models which can be aggregated in terms of GDP loss or micro-funded, coupled with bottom-up approaches.

A Tables

Table A1: Production functions employed in the models

Model	Capital Sector	Consumption Sector	Energy sector
MABM			
C&C		Dynamic Leontief-type	
DSK/DSK-SFC[a]	Dynamic Leontief-type	Other	Other
EURACE		Nested Cobb-Douglas (C&L)-Leontief production function (E)	Leontief type
MATRIX	CES[b]	CES[b]	CES[b]
S&B		CES[c]	Cobb-Douglas
SFC			
Berg et al. (2015)		Leontief-type	Leontief-type
Bovari et al		Leontief-type	
Carnevali et al. (2024)	Leontief-type	Leontief-type	
DEFINE		Leontief-type	Leontief-type
Dunz et al. (2021)	Leontief-type	Leontief-type	
EIRIN	Leontief-type	Leontief-type	Other
GEMMES	Leontief-type	Leontief-type	
HARMONEY	Leontief-type[d]	Leontief-type[d]	
LowGrow		Other	
Naqvi and Stockhammer (2018)	Leontief-type[f]	Leontief-type[e]	
TEMPLE	Leontief-type[f]	Leontief-type[f]	Leontief-type[f]
TranSim	Other	Other	Other
Triode	Leontief-type	Leontief-type	Leontief-type

[a] This note refers to Lackner et al. (2025), Ravaioli et al. (2025), Reissl et al. (2025), and Wieners et al. (2025), since all three contributions are extensions of the DSK model (Lamperti et al., 2018).

[b] Elasticity of Substitution between production factors: 0.25.

[c] Elasticity of Substitution between capital, labour and energy: 0.5.

[d] In the HARMONEY model, the capital and goods sectors coincide.

[e] The production process requires three complementary inputs: labour, capital and resources.

[f] In the TEMPLE model, the capital and consumption goods coincide. The energy and the final goods sub-sectors behave according to a Leontief production function with three non-substitutable factors of production: energy, labour, and capital, which depreciates over time.

Table A2: Demand-led or supply-led and demand drivers decomposition

Model	Demand-led			Supply-led	Credit	
	Consumption	**Investment**	**Public Expenditures**		**Investment**	**Consumption**
MABM						
C&C	Class-specific disposable income	Profit rate as ratio between profit and physical capital	Pensions and unemployment benefits		✓	
DSK/DSK-SFC[9]	Households consumption depends on wage and benefit income out of taxes, dividends and deposit's interest and stock of deposits, with different propensities	Driven by the difference between the expected demand and the current capital stock, with replacement of obsolete vintages	Unemployment benefits, interest and principal payment on debt		✓	
EURACE	Households set the consumption budget out of their income following a wealth-to-income target ratio	Net present value calculations discounting expected future revenues at their weighted average cost of capital	Wages, Transfers, Coupon payment, Feed-in-tariff Subsidy		✓	
MATRIX	Linear combination of permanent income and a fraction of accumulated financial wealth	Cost minimization problem given desired quantity of output	Social transfers to low-income individuals, Green subsidies		✓	
S&B	Utility-constrained optimization	Investments take place only if the amount of capital owned is less than the capital required to produce the desired level of production			✓	
SFC						

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[9] This row refers to Lamperti et al. (2025), Ravaioli et al. (2025), and Reissl et al. (2025), since they all are extension version of DSK model (Lamperti et al., 2018)

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Model	Demand-led			Supply-led	Credit	
	Consumption	**Investment**	**Public Expenditures**		**Investment**	**Consumption**
Berg et al. (2015)	Household consumption is a convex function of the wage bill net of taxes and a smaller fraction of wealth (money stock)	Based on a quasi-accelerator principle on inventory target, aiming at absorbing unexpected fluctuation in demand	Exogenous, set in nominal terms		✓	
Bovari et al. (2020)	Consumption is pinned down by the macro balance Production minus Investment	Real investment is driven by the profit share capturing the risk appetence of the corporate sector		✓	✓	
Carnevali et al. (2024)	Households' consumption is a function of disposable income, net wealth, price expectations and global warming	Private investment plans are affected by firms' expectations concerning the output level, climate change-related damages and government policies	Exogenous, it grows at constant rates		✓	
DEFINE	Households consumption, adjusted for climate damages and subject to supply constraints, depends on lagged income and lagged financial wealth	Investments depend positively on the rate of profit and the rate of capacity utilization, while negatively for high level of employment or scarcity of energy and material resources	Government current expenditures (consumption, green subsidies and interests on public debt) and investments (green and conventional) are set exogenously as a fraction of GDP		✓	
Dunz et al. (2021)	Households consumption is a function of disposable income (wages, dividends, interest payments on bank deposits, net of taxes) and wealth	Investments are determined by a target capital stock and firms' preference for slack production capacity to adjust to short-run changes in demand	Government levies taxes on firms, households and carbon emissions, and undertakes infrastructure investment in both green and brown capital.		✓	

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Model	Demand-led			Supply-led	Credit	
	Consumption	**Investment**	**Public Expenditures**		**Investment**	**Consumption**
EIRIN	Households set their consumption path around their net income, considering a target level of liquid wealth-to-income ratio	Investment decisions are endogenous based on the expected production plans that determine a capital stock target level	Fixed percentage of revenues from taxes (welfare expenditures, subsidies, public service wages, and consumption)		✓	
GEMMES	Households' consumption follows a two-stage decision process. In the first stage, they determine a target aggregate nominal consumption via their marginal propensity to consume out of total income. In the second stage, they allocate this consumption across agriculture, processed food, and non-food goods according to a linear specification.	Investment at each point in time depends on the gap between the target and the actual capital stock. Target capital investment for domestic firms depends positively on the return on capital net of producer price inflation and on real private-sector investment in adaptation.	Government levies taxes, and public spending consists of public wages and employers' social contributions, intermediate consumption, interest payments on public debt, transfers to households, and subsidies to firms. In addition, the government invests in adaptation and capital, and, as part of fiscal policy, borrows a fixed fraction of the trade deficit as foreign loans.		✓	✓[1]
Harmoney	Households' consumption is fully accommodating, as a residual left from subtracting investment and change in the value of inventories from net output	Total investment in both sectors is some proportion of depreciation added to a multiple of net profit			✓	

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Model	Demand-led			Supply-led	Credit	
	Consumption	**Investment**	**Public Expenditures**		**Investment**	**Consumption**
LowGrow	Consumption is a linear sum of the expected disposable income and the real net household worth in the previous period	Based on a capital-stock adjustment process (non-residential inv.). Firms target a capital-to-output ratio to meet an expected level of the output	The real government consumption spending follows the GDP instantaneous rate plus a countercyclical component. Public investments follow a similar logic		✓	✓[2]
Naqvi and Stockhammer (2018)	Consumption decisions are based on the marginal propensity to consume out of income and the marginal propensity to consume out of wealth (past deposits)	Real investment depends on the gap between the target capital stock and the past capital stock and the capital stock replacement from depreciation. By adding the firms' expense for R&D we obtain the nominal investment	The government expenditure is given by a fixed-minimum component and a variable component ensuring a zero-balance net position. The public expenditure for innovation is a fraction of the variable component		✓	
TEMPLE	Workers spend their entire wages on energy and final goods consumption, while capitalists spend only a fraction of their revenues (from energy, goods, and bank industry profits)	Investment decisions in the final good sector depend on an autonomous component, the expected profits and the depreciation term. On the contrary, in the energy sector investment depends on the difference between a target and an actual level of capital stock, plus a depreciation component	The Government levies tax on energy products turning it into subsidies to foster the green energy transition	✓[3]	✓	

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Model	Demand-led			Supply-led	Credit	
	Consumption	**Investment**	**Public Expenditures**		**Investment**	**Consumption**
TranSim	The real household consumption is a function of an autonomous term, growing according to labour productivity's rate, expected real disposable wage and profit income, the inflation loss/gain term and lagged real wealth	Firms' investment choices depend on the difference between its target fixed capital and fixed capital in the previous period, plus a depreciation term			✓	
Triode	In each period, households set their consumption budget by considering their average past income and their wealth, in terms of units of a desired consumption basket	The investment process follows the accelerator mechanism of the Sraffian supermultiplier model, whereby industries invest to adjust their productive capacity to match expected demand at the normal degree of capacity utilisation, which is assumed to be exogenously set	The government levies taxes on industries' net profits and undertakes final consumption		✓	

[1] Credit provided to households to invest in housing and durable consumption (Yilmaz et al., 2025)
[2] In this model, banks issue unsecured loans and mortgages to households for long-term residential investment (T. Jackson & Victor, 2019)
[3] Jacques et al. (2023) also include an alternative, supply-led, closure of the model

Table A3: Environmental representation and biophysical limits

Model	Environment				Biophysical limits
	Resources/energy	Pollution/GHG	Waste	Biodiversity	
MABM					
C&C	✗	✓	✗	✗	✗
DSK/DSK-SFC	✓	✓	✗	✗	✗
EURACE	✓	✗	✗	✗	✗
MATRIX	✓	✓	✗	✗	✗
S&B	✓	✗	✗	✗	✗
SFC					
Berg et al. (2015)	✓	✓	✗	✗	✓
Bovari et al. (2020)	✗	✓	✗	✗	✗
Carnevali et al. (2024)	✓	✓	✗	✗	✓
DEFINE	✓	✓	✓	✗	✓
Dunz et al. (2021)	✗	✗	✗	✗	✗
EIRIN	✓	✓	✗	✗	✗
Gemmes	✗	✗	✗	✗	✗
HARMONEY	✓	✗	✗	✗	✓
LowGrow	✓	✓	✗	✗	✗
Naqvi and Stockhammer (2018)	✗	✓	✗	✗	✗
TEMPLE	✓	✗	✗	✗	✗
TranSim	✓	✗	✗	✗	✗
Triode	✓	✓	✓	✗	✗

Note: 'Biophysical limits' refers to the explicit modelling of the Earth as a closed system, in line with Georgescu-Roegen (1984) and grounded in the two laws of thermodynamics, a central feature of the Ecological Economics paradigm, and not merely to the inclusion of environmental variables.

Table A4: Monetary and financial side

Model	Banking sector	Financial markets	Central Bank	Policy rate	Loan interest rate	Other information
MABM						
C&C	Commercial banks	Credit	✓[1]	Set by central bank and held constant over the whole simulation	Calculated by charging CB Policy Rate	Government bonds proxied by interest payment to households relative to their wealth
DSK/DSK-SFC	Heterogeneous commercial banks	Credit, Bonds	✓[2]	Taylor Rule	Calculated by adding a homogeneous mark-up over the CB lending rate, with higher charges applied to customers with a higher debt-service-to-revenue ratio	Interbank payments by means of CB reserves
EURACE@GE	Disaggregated commercial banks	Credit, Bonds, Equity	✓[3]	Taylor rule	Mark-up on the CB policy rate	Centralized Walrasian market for stocks and bonds
MATRIX	Heterogeneous banks	Credit, Bonds	✓	Inertial Taylor rule which depends on the observed deviations in inflation and unemployment rates from policy target values	Depending on (i) the policy rate, (ii) a bank-specific component related to its financial soundness (iii) a firm-specific risk component (iv) a systemic risk component	T-bills purchased by banking sector

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Model	Banking sector	Financial markets	Central Bank	Policy rate	Loan interest rate	Other information
S&B	Disaggregated commercial banks	Credit, Interbank funds	✓[4]		Interest rate in the interbank market differentiated by sectoral riskiness	Banks are modelled as a node in a financial network
SFC						
Berg et al. (2015)	Consolidated Gov't/Banks	Credit	✓	Exogenous	Exogenous	Unlike most SFC models, the role of the banking sector (which is consolidated as a simplification into the government sector along with the central bank) is very limited here.
Bovari et al. (2020)	✓	Credit, Corporate and Public Bonds	✓	Taylor-like Rule	Adjusted with a lag to the policy rate	Banks satisfy credit demand up to a credit rationing function
Carnevali et al. (2024)	Consolidated Commercial/Central banks	Credit, T-bills	✓	Exogenous	Mark-up on Policy Rate	The return rates on government bills are assumed to be steered by the central bank, who sets the policy rate and purchases government bonds in the secondary market to ensure financial conditions are consistent with its monetary policy stance.
DEFINE	✓	Credit, Government securities, Conventional/Green Corporate bonds	✓	Exogenous	The lending interest rate on green and conventional loans is set as an endogenous spread over the CB policy rate	Banks decide not only about the proportion of demanded loans that they reject but also about the interest rate imposed on these loans. In this decision, they take into account their financial position.

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Model	Banking sector	Financial markets	Central Bank	Policy rate	Loan interest rate	Other information
Dunz et al. (2021)	✓	Credit	✓	Exogenously-defined	The base rate depends on policy rate and the CAR level	The effective loan interest rate is sector-specific and depends on the base rate,the sector-specific NPL-to-loans ratio, on the expected profits, on the corrections for forecasts for the current time period relative to actual profitability, and on the potential impact of macro-prudential policies affecting the risk-weighting of loans for green and brown firms.
EIRIN	✓	Credit, Corporate and Public Bonds	✓	Taylor-like rule	Mark-up on policy rate	The CB sets the policy interest rate based on the inflation gap and output gap measured as employment gap, as the distance to a target level of employment.
Gemmes	✓	Deposits, loans, bonds	✓	Pure inflation-targeting Taylor rule	The domestic-currency loan premium over average funding costs depends on private indebtedness, particularly the ratio of interest payments to gross operating surplus.	This is the most highly refined model in terms of financial-system structure, featuring domestic and foreign financial assets and flows.
HARMONEY	✓	Credit			Exogenous	

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Model	Banking sector	Financial markets	Central Bank	Policy rate	Loan interest rate	Other information
LowGrow	✓	Credit, Equities, Gov. Bonds and Life Insurance & Pensions	✓	Varies according to changes in unemployment rate	Determined on fixed spread on Policy rate (4 %)	Banks are subject to Basel III-like regulations. CB provides liquidity through reserves and collects bonds. Profits are returned to Gov't. All the interest rates have fixed spreads anchored to the Policy rate
Naqvi and Stockhammer (2018)	✓	Credit	✓	Exogenous	Exogenous	Commercial banks are a passive entity in the model playing the role of intermediaries between households and firms
TEMPLE	✓	Credit, Bonds	✓	Taylor rule	Mark-up on policy rate	The CB is consolidated in the public sector. Government bonds are bought or sold by the capitalists and households as a form of savings, without bearing any interest. Energy and final-good equity is the difference between capital stock and debt, which is private and not traded
TranSim	✓	Credit, Deposits, Equity			Determined as a fixed spread over an exogenously determined deposit rate	No central bank is modelled
Triode	✓	Credit	✓			

[1]In this model, the central bank keeps a current account for the government (including overdraft facilities) and provides deposit facilities for banks. It also acts as lender of last resort. In the current version, no monetary policy is implemented. Moreover, banks must refinance themselves by managing their assets (loans) and liabilities (savings). If banks lack liquidity, they request loans from the central bank (Rengs et al., 2020).

[2]The central bank implements monetary policy following a Taylor-type rule and acts as the macroprudential authority. It also facilitates interbank payments by supplying the reserves required to settle transactions (Reissl et al., 2025).

[3]The central bank provides standing facilities for banks at a given base rate, pays interest on overnight deposits, may provide fiat money to the government, conducts monetary policy by setting the policy rate, and monitors the banking sector by setting the maximum leverage ratio (Cincotti et al., 2010; Ponta et al., 2018).

[4]The central bank is not explicitly modelled; however, it acts as lender of last resort to rescue banks at the verge of bankruptcy (Safarzyńska & Van Den Bergh, 2017b).

Table A5: Functional and personal income distribution, and distributional analyses performed

Model	Functional			Personal	Analysis performed
	Workers/Capitalists	Mixed	Multiple		
MABM					
C&C		✓[1]			Real wealth of capitalists under different green-policy and tax scenarios
DSK/DSK-SFC				✓	Depending on the vintage considered[2]. The check-mark refers to Ravaioli et al., 2025
EURACE				✓[3]	
MATRIX	✓[4]				Wealth distribution under different energy shocks and climate-damage scenarios
S&B	✓[5]				Wealth, income and consumption inequality under different assumptions in network and snob-effect scenarios
SFC					
Berg et al. (2015)					Household sector is consolidated
Bovari et al. (2020)					Household sector is consolidated; the labour share is used as a proxy for distribution
Carnevali et al. (2024)	✓[6]				Income and wealth inequality[7]
Define	✓[8]				Evolution of the wage share
Dunz et al. (2021)					Household sector is aggregated and does not feature income distribution. Analysis focuses on changes in households' budget constraints
EIRIN	✓[9]				Labour share in total income
GEMMES					Household sector is consolidated
HARMONEY					Evolution of wage-share

Table A5: (continued)

Model	Functional			Personal	Analysis performed
	Workers/Capitalists	Mixed	Multiple		
LowGrow				✓[10]	Gini index across income deciles
Naqvi and Stockhammer (2018)	✓[11]				
TEMPLE	✓[12]				
TranSim	✓				Changes in profit and wage shares are used as a proxy for functional income distribution
Triode	✓				Workers and Capitalists

[1]The household sector is populated by Workers, Wealthy Workers, and Capitalists (Rengs et al., 2020).

[2]The household sector is modelled as an aggregate entity that earns wages (in exchange for supplying labour), unemployment benefits, and dividends from firms, banks, and the energy sector in (Lackner et al., 2025; Reissl et al., 2025; Wieners et al., 2025). In Ravaioli et al. (2025), personal income distribution is measured using top 10, middle 30, and bottom 60 percent income groups.

[3]The household sector is populated by heterogeneous households acting as workers, consumers, and financial investors (Ponta et al., 2018).

[4]A household sector populated by heterogeneous agents divided into Workers, Entrepreneurs, and Bankers (Ciola et al., 2023).

[5]The household sector is populated by consumers divided into three categories based on the source of their income: Workers, Capital Owners, and Electricity Producers (Safarzyńska & Van Den Bergh, 2017a).

[6]The sector is divided into 'LC households', earning labour income and a share of interest payments on bank deposits, and 'UC households', including firms' owners, managers, and rentiers earning entrepreneurial profits and financial income Carnevali et al. (2024).

[7]Income inequality is measured as 'UC household income' (including capital gains) relative to total income after taxes. Similarly, wealth inequality is measured as 'UC household' net wealth relative to total net wealth Carnevali et al. (2024).

[8]The wage share captures functional income distribution, which is positively correlated with income inequality (Dafermos & Nikolaidi, 2022).

[9]The model includes the working class, living on wages, and the capitalist class, which earns income from financial markets through government bond coupons and corporate dividends (Gourdel et al., 2024).

[10]The model displays an initial distribution of incomes in the Canadian economy in terms of income deciles (T. Jackson & Victor, 2019).

[11]The household sector is composed of Capitalists and Workers. Workers earn wage income plus interest on past deposits, while Capitalists earn dividend income from firms, profit income from banks, and rents from selling resources, in addition to interest on past deposits.

[12]Workers earn only wages, while Capitalists have two sources of revenue: dividends from banks and dividends paid by energy and final-goods firms (Jacques et al., 2023).

Table A6: Presence of an energy sector in these models

Model	No Energy Sector	Energy Sector	Fossil Fuel Sector	EROI	Additional Information
MABM					
C&C	✓			✗	Scenario: governmental subsidies for more energy-efficient technologies.
DSK-SFC		✓	✓	✗	The energy sector consists of a single agent selling energy to capital and final-goods firms. Energy is produced using both green and brown technologies of various vintages. The fossil-fuel sector provides inputs to the energy sector.
EURACE		✓		✗	The sector includes a fossil-fuel-based electricity company, a renewable electricity producer, and a fossil-fuel-exporting foreign economy.
MATRIX		✓	✓	✗	Energy firms purchase fuel from a stylised fossil-fuel sector with an infinitely elastic supply.
S&B		✓		✗	The sector includes three heterogeneous plants characterised by age, productivity, energy source, capacity, lifespan, and capacity factor.
SFC					
Berg et al. (2015)		✓		✓	The energy sector requires consumer/industry goods and energy goods as inputs.
Bovari et al. (2020)	✓			✗	
Carnevali et al. (2024)		✓		✗	The model includes renewable and non-renewable energy, with only the latter producing GHG emissions.
DEFINE	✓			✗	Energy required for production depends on output; declining energy intensity reduces energy per unit of output.
Dunz et al. (2021)	✓			✗	

Continued from previous page

Model	No Energy Sector	Energy Sector	Fossil Fuel Sector	EROI	Additional Information
EIRIN		✓	✓	✗	The energy sector includes a fossil fuel mining company, a high-carbon electricity producer, and a renewable energy producer. Green energy has grid priority.
GEMMES	✓			✗	
HARMONEY			✓	✓	
LowGrow		✓		✓	The electricity sector produces energy using both non-renewable and renewable sources, with investment decisions varying by scenario.
Naqvi and Stockhammer (2018)	✓			✗	
TEMPLE		✓	✓	✓	The energy sector supplies demand while maintaining a capital utilization target. The energy transition is exogenously imposed, achieving 100% renewable-based production (solar and wind) by 2050, with energy price caps and sector subsidies. EROI analysis is included for both fossil and renewable energy production.
TranSim		✓		✓	Energy firms can produce energy using either green or fossil-fuel capital goods. The green transition is guided by adjusting the desired proportion of green capital in the energy supply. EROI analysis is included for both sources.
Triode		✓	✓	✗	The model builds on an inter-industry real-world input-output data, embeds technological progress to capture the electrification process, and is calibrated to IEA energy-transition scenarios.

Table A7: Opening the climate boxes

Model	Carbon Cycle	GHG emissions	Climate damage function	No climate box
MABM				
C&C	✗	✓	✗	
DSK/DSK-SFC	✓	✓	✓	
EURACE	✗	✓	✗	
MATRIX	✓	✓	✓	
S&B	✓	✓	✓	
SFC				
Berg et al. (2015)	✓	✓	✓	
Bovari et al. (2020)	✓	✓	✓	
Carnevali et al. (2024)	✓	✓	✓	
DEFINE	✓	✓	✓	
Dunz et al. (2021)				✓
EIRIN	✗	✓	✓	
GEMMES				✓
HARMONEY				✓
LowGrow	✗	✓	✗	
Naqvi and Stockhammer (2018)	✗	✓	✗	
TEMPLE				✓
TranSim	✗	✓	✗	
Triode	✗	✓	✗	

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Green Transition, Housing Retrofits and Inequalities in a Macro-Financial AB-SFC Model

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Abstract

This paper extends the hybrid Agent-Based Stock-Flow Consistent model presented in Botta et al. (2025) to evaluate the macro-financial implications of a residential green retrofit programme. We incorporate low-carbon investment and 'green' loans to both firms and the heterogeneous household sector within a modern, financialised economy, where securitisation grants investors access to complex instruments such as asset-backed securities (ABSs). These mechanisms foster investor demand for yields, reinforce short-termism and contribute to income and wealth inequality. A housing module calibrated on EU Eurostat data on tenancy and ownership rates is also introduced. Preliminary results indicate that, in the absence of bold policy design, the aggregate macroeconomic effects of a green retrofit programme remain modest, particularly in terms of GDP and unemployment dynamics. Credit rationing emerges as a key friction, i.e. a significant share of loan applications from highly indebted lower-income households is not granted, slowing the pace of diffusion of energy-efficiency upgrades across the housing stock. These preliminary findings point to the need for complementary fiscal, redistributive, and financial policies to ease residential decarbonisation along both environmental and socially sustainable pathways.

Keywords: Economic Modelling; AB-SFC; Income Inequality and Distribution, Green Securitisation, Green Finance.
JEL Codes: C63, E12, E17, D31.

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1 Introduction

A rapid and effective transition towards a low-carbon economy, as well as a fair societal pathway, is losing attention in the European policy agenda in the face of recent warfare contexts and geopolitical frictions. However, average global temperatures are rising inexorably (WMO, 2024), while climate targets and actions risk being too little and too late, as the lack of global governmental action highlights a "weakening" of countries' GHG emissions-reduction pledges by 2030 (Climate Action Tracker, 2024a).

The European Union's strategy to comply with the temperature threshold set by the Paris 2015 Agreement and to fulfil the United Nations' 2030 Agenda for Sustainable Development has been framed as part of the broader plan to recover from the Covid-19 pandemic crisis, under the name of the 'European Green Deal' legislative package (EC, 2019a, 2019b), promoted by the European Commission to govern the climate crisis and the green transition. The ambitious target is to make Europe the first climate-neutral continent, achieving a 55% reduction in GHG emissions relative to 1990 levels by 2030 and net-zero emissions (NZE) by 2050. Such a green structural change has been estimated to require EUR 350 billion in additional investment per year over the 2021–30 decade to meet the 2030 Climate Target Plan in energy systems alone, as well as a further EUR 130 billion to address other environmental goals (European Commission, 2020, 2021).

As several independent observers have pointed out, the implementation of the 'Fit for 55' legislative package (Council of the European Union, 2021) could nevertheless prove insufficient to remain on track with the announced 2030 emissions targets and, at the same time, may be inconsistent with containing the rise in temperature below 2°C (Climate Action Tracker, 2024b; Greenpeace European Unit, 2021).

Within a broader climate strategy, EU institutions have devoted significant effort to defining a legislative framework aimed at aligning private investment with climate targets and mobilising resources towards low-carbon activities. The European sustainable finance initiative is designed to incorporate Environmental, Social, and Governance (ESG) considerations when assessing the environmental and societal impacts of investments within the financial sector. These initiatives are to be adopted on a voluntary basis and certified by external reviewers under the supervision of European authorities[1]. However, this entire strategy relies heavily on a key point: defining when an activity or financial instrument can be considered 'green' or 'low carbon', which remains a fuzzy issue with significant potential for greenwashing practices within the financial sector.

Over the past decade, there has been increasing issuance of 'green' financial instruments in the European securities market, driven either by legislative interventions, such as the European Green Bond Standard (EU, 2023), or by international guidelines, such as the Green Bond Principles issued by the International Capital Market Association (ICMA, 2022). These guidelines aim to define 'sustainability' in finance by ensuring market transparency regarding the use of proceeds and reporting, with a view to facilitating the allocation of funds towards activities supporting the green transition[2]. According to these points, and in the view of the main financial representation groups, the European framework leaves green securitisation underdeveloped. In their view, scaling up securitisable green lending would ease banks' regulatory capital constraints by unlocking green finance for small and medium-sized businesses and projects that foster the transition (CBI, 2022). Furthermore, it has been estimated that three securitisable asset classes alone (residential mortgage loans on energy efficient properties, loans for green home renovations, and electric-vehicle financing) could provide more than EUR 300 billion in securitisable green lending annually by 2030 (AFME, 2022).

[1] For a broad summary of the European green financial framework, see Appendix C.
[2] See Table A.3 for a closer look at the EU Green Bond requirements.

Preliminary results in the literature, mainly focused on the United States, highlight however a potentially uneven contribution of green securitisation to addressing climate and transition risks. Ouazad and Kahn (2022) show that natural disasters can drive the securitisation of assets in areas prone to extreme events, encouraging banks to grant securitisable mortgages and transfer climate risks off their balance sheets. Mueller et al. (2022) identify the role of institutions in shaping banks' climate commitments, finding that the securitisation of loans to brown firms reduces interest rates for polluting borrowers without increasing the supply of green credit. In the EU context, Cusano et al. (2024) assess the role of green securitisation in Italy and provide empirical evidence that banks tend to retain loans for green activities on their balance sheets while derecognising loans to brown activities. This dynamic leads to a mispricing of transition and physical risks by the banking sector, producing outcomes that are misaligned with the EU's climate and transition objectives.

The debate on the effectiveness of green securitisation in facilitating low-carbon structural change, the EU regulatory framework, and initial findings in the literature motivate the present work, which builds on the AB-SFC model developed in Botta et al. (2025). By incorporating green capital, green investment, and green ABS, this study represents, to the best of our knowledge, the first attempt in the macro-modelling literature to examine inequality, finance, and economic performance within the context of a green transition mediated by securitisation processes.

The present paper is structured as follows. Section 2 reviews the state of the art in macroeconomic modelling. Section 3 presents the current development of the model and the recent improvements introduced. Section 4 discusses the baseline properties and results, while Section 5 explores a preliminary green retrofit programme scenario for private dwellings. Section 6 concludes and outlines the main limitations, areas for further investigation, and avenues for future extensions.

2 Literature Review

In the last decade there has been a significant increase in interest by policymakers in the possibility of 'tilting' the financial sector toward more sustainable and green pathways. A clear example of this is the establishment of the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) at the Paris 'One Planet Summit' in December 2017, where it took on the mission of raising awareness about climate risk management and promoting 'green' loans for low-carbon investments. The aim of decoupling GDP from CO2 emission growth rates, at least relatively, made room for new macroprudential and monetary policy to improve financing conditions for climate investments, addressing the 'green' trade-off between financial stability and the low-carbon transition. On this line of research, a growing number of contributions in the macro-finance literature have focused on new banking and monetary practices for easing and financing the transition. For a review of the principal proposal see the NGFS technical document (NGFS, 2021).

As an example of this necessary change in the attitude on the institutional side, Campiglio, 2016 argue how the widespread call for the implementation of a carbon tax as the sole tool to address the effects of climate change may not be effective in achieving carbon neutrality, as it overlooks the mechanisms of credit creation and allocation, and thus the true effectiveness of price signalling. More importance should be placed on green macroprudential policies, i.e. Green Differentiated Capital Requirements in the banking sector, which can be seen as quite unconventional in developed countries, while also representing an already exploited tool in global south institutions. Aligning with a similar approach, Krogstrup and Oman, 2019 questions the theoretical benchmark 'first-best' response to climate change in the literature, which comprises a path of taxes on emissions combined with subsidies for R&D. In doing so, it presents a comprehensive review and a critical assessment of fiscal, financial and monetary tools for climate change mitigation, stressing the role

of coordination and addressing 'controversial' policy hypotheses that arise from the central bank mandate debate, such as green quantitative easing (GQE), credit allocation policies, and the adaptation of the monetary policy framework. A further taxonomy and analysis underpinning the ecological mandates of central banking in the literature are contained in Oman et al., 2024.

Popoyan and Galanis, 2022, by acknowledging the permanent nature of climate-related financial risks compared to transitory economic shocks, highlights the role of climate change in paving the way for non-traditional measures to address these shocks on the monetary and macroprudential regulatory side. This analysis examines the current state of the art among central banks and financial institutions, as well as how new geography is emerging worldwide, with developing countries -those most susceptible to being impacted by climate change- implementing a wider spectrum of alternative green policies. Some proposals for a green Basel Requirement framework are further addressed in D'Orazio and Popoyan, 2019.

A particular stream of research stresses how, in the European context, central bank policies are affected by a no-longer-sustainable carbon bias, such as the Quantitative Easing program following the global financial crisis in 2008 and the Sovereign Debt crisis (Dafermos et al., 2020; Matikainen et al., 2017). In addition to the proposal of a Green QE, other contributions explore the role of greening the Eurosystem Collateral Framework and implementing green capital requirements (Dafermos et al., 2021, 2022b) and the Bank of England's corporate bond purchases (Dafermos et al., 2022a). On this regard, despite initial attempts by the Bank of England (BoE) and the European Central Bank (ECB) to explore ways to 'green' their corporate bond purchase programs, aiming to align their monetary policies with climate objectives (Dafermos et al., 2022a; European Central Bank, 2022; H. M. Treasury, 2021), the continuation of more effective policy shifts raised important questions about market neutrality and price signalling, while reducing the scope of such interventions (Dafermos, 2024; Dafermos et al., 2023).

Finally, Dafermos, 2024 point out that a significant challenge in implementing monetary policy "tilted" toward climate objectives would require a shift from a *risk exposure approach* -which focuses on the impact of climate change on finance but ignores the feedback loop- toward a more pronounced *allocative green credit policy*. Regarding this issue, Kedward et al., 2024 argue that it would be within policymakers' discretion to choose which sectors to incentivize or not in order to achieve the green transition. They also emphasize the need for more forceful policy measures to direct credit, such as setting maximum or minimum lending targets.

On the non-equilibrium modelling stream of research, several macro-setups have addressed green policy, and we will present a summary of the main conclusions found in this strand of literature. Draft upon the evolutionary Schumpeter meeting Keynes (K+S) family (Dosi et al., 2013, 2015), the Dystopian Schumpeter meeting Keynes (DSK) is an agent-based Integrated Assessment Model including a carbon cycle and a damage function, allowing for economy-ecosystem-climate feedback. Lamperti et al., 2019 stress the challenging role of macro-prudential regulation in mitigating the financial climate risks, while Battiston et al., 2021 investigate which policies are able simultaneously to reduce the climate risks and the financial instability in the economic system. They propose a mix of macro-prudential policy, public guarantees to credit on green projects and carbon-risk adjustment in credit ratings. Based on a recent SFC update (Reissl et al., 2024) coupled with the materiality of transition risks explored in the WITCH model, Fierro et al., 2024 state on how an expansionary monetary policy, seems effective during the later stages of the transition, calling for a higher role for monetary-fiscal policy coordination.

The DEFINE model (Dafermos et al., 2018) by coupling the post-Keynesian Ecological macroeconomic investigates the impact of physical risks of climate change through different transmission channels on financial stability, and how

effective a green Quantitative Easing program would be in limiting the detrimental effects. Evidence from the simulations shows a modest average reduction in CO2 global emissions, calling for the implementation of green fiscal policies, which are at the core of the exploration contained in Dafermos and Nikolaidi, 2019. Moreover, Dafermos and Nikolaidi, 2021 elaborate further on possible green differentiated capital requirements policies on credit provision and the financial sector, such as the 'green supporting factor' (GSF) and the 'dirty penalizing factor' (DPF), on low-carbon structural change and physical climate-related financial risks. Lastly, for a comprehensive overview of the model and the tests run, Dafermos and Nikolaidi, 2022 details a comparative systems-based analysis of macroeconomic, financial and sufficiency policies to address climate risks prompted in the DEFINE framework.

On analogous line, Dunz et al., 2018 delves into the role of Carbon Tax and Green Supporting Factor (GSF) microprudential banking scheme in fostering green investment towards the low-carbon transition. Moreover, the authors emphasize the central role of banking expectations in lending decisions anticipating climate policies, thus affecting the success or not of green interventions. All in all, the main conclusion draws upon a strong commitment to credibility in implementing green policies, favouring a policy mix to mitigate the negative outcomes on the economy and financial stability instead of relying on single measures. A similar conclusion is drafted in the EIRIN simulation environment Gourdel et al., 2024, stressing the way banks and firms internalize the climate policy in investment decisions is crucial in fostering an ordered low-carbon transition and mitigating physical risks, and thus policy accountability; a call for the inclusion of the double materiality of climate risks by central banks and financial supervisors in their monitoring activities of the financial system.

Despite the comprehensive insights provided by the literature, current contributions have yet to develop a well-defined financial sector that addresses how, in a finance economy, the private credit market is characterized by securitisation and the creation of complex financial products. These factors fuel investors' appetites for returns and promote short-termism, while simultaneously driving income and wealth inequality (Botta et al., 2021). Consequently, an inherent conflict arises in the broader context of the long-term investments required for carbon neutrality. Climate change mitigation can exacerbate inequality both within and between countries (Krogstrup & Oman, 2019), complicating the situation further.

In the following section, we present the model's building blocks and the main behavioural equations governing the macro-financial dynamics.

3 The model

The present contribution builds upon the hybrid Agent-Based Stock-Flow Consistent model presented in Botta et al., 2024, 2025. The model is a demand- and policy-driven framework featuring six institutional sectors: one heterogeneous sector populated by 1,000 households (HH)[3] and five consolidated sectors, namely commercial banks (CB), special purpose vehicles (SPVs), investment funds (IFs), non-financial firms (NFF), and the government together with the central bank (GOV'T).

In this current vintage, the model has been extended along three main dimensions.

- We include a housing module incorporating private dwellings allowing for more realistic assumptions regarding the composition and formation of household wealth, calibrated on EU EUROSTAT data on housing tenure and ownership rates.

[3]The model is fully scalable, i.e. increasing or decreasing the number of heterogeneous household agents does not alter macro-financial dynamics.

- We include green capital and low-carbon private firm investment in the model. Moreover, households can demand green loans for green refurbishment and retrofit activities on private dwellings.
- We model the presence of green asset-backed securities, whose underlying assets are commercial bank loans financing green investment by both firms and households.

Figure 1 provides a general overview of the interrelations between balance sheets in the artificial economy, Figure 2 illustrates the flows among the featured sectors, while the following paragraph briefly presents and discusses the main equations driving agents' and sectors' behaviour.

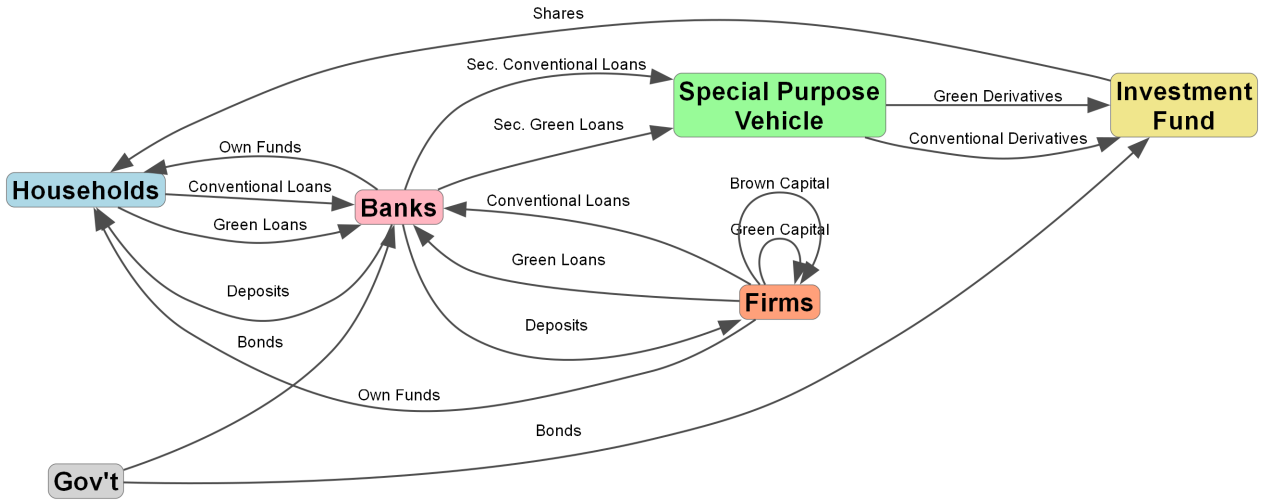


Figure 1: Balance Sheets interrelation of the model

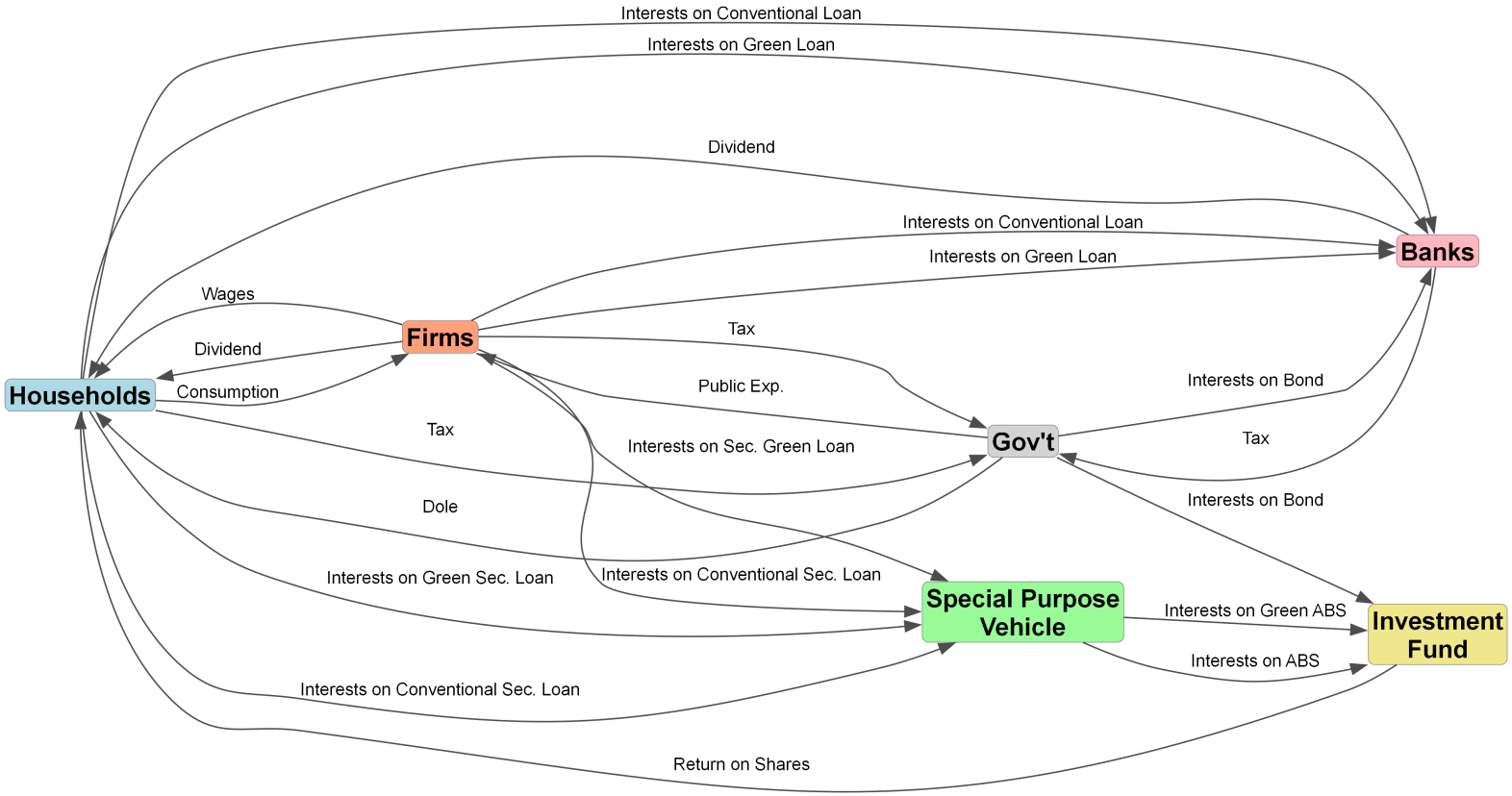


Figure 2: Model flow diagram. Arrows indicate the direction of real and financial flows across sectors.

3.1 Equations

In this section, we present the main behavioural equations driving the dynamics of the model. In particular, when applicable, the subscript t refers to the time point in the simulation, i indexes the individual heterogeneous household, while the asterisk denotes target or desired variables, defined prior to the realisation of their actual values.

3.1.1 Firms

Non-financial firms (NFF) are represented as a consolidated sector producing a single homogeneous good that can be used for both consumption and investment, according to a Leontief production function employing capital goods and labour. In line with standard Post-Keynesian production theory (Godley & Lavoie, 2006), firms determine their level of production by updating the desired level of activity (denoted by the superscript '*' in equation 1) based on the previous period's desired supply $Y^*_{S,t-1}$ and the gap between aggregate demand $Y^*_{D,t-1}$ and desired production $Y^*_{S,t-1}$ in the preceding period, augmented by an exogenous growth component (υ_2).

$$Y^*_S = [Y^*_{S,t-1} + \upsilon_1 \cdot (Y^*_{D,t-1} - Y^*_{S,t-1}] \cdot (1 + \upsilon_2) \tag{1}$$

The Leontief production function specifies the maximum level of output achievable, given the available input factors and their respective productivity rates, respectively X^K for capital goods and X^L_t for labour.

$$Y^{\text{MAX}}_K = K_{t-1} \cdot X^K \tag{2}$$

$$Y^{\text{MAX}}_L = \overline{N} \cdot X^L_t \tag{3}$$

$$Y^{\text{MAX}} = min[Y^{\text{MAX}}_K, Y^{\text{MAX}}_L] \tag{4}$$

The effective level of production equals the desired level only insofar as the latter does not exceed maximum productive capacity, in which case the attainable level of production is constrained.

$$Y_S = \begin{cases} Y^*_S & \text{if} \quad Y^*_S \leq Y^{\text{MAX}} \\ Y^{\text{MAX}} & \text{if} \quad Y^*_S > Y^{\text{MAX}} \end{cases} \tag{5}$$

The labour productivity term in Equation 3 depends positively on the previous-period value X^L_{t-1}, scaled by an exogenous factor χ^L_1, and on a scaling factor linked to the growth rate of aggregate demand. The latter term is intended to capture demand pressure on labour productivity, in accordance with the Kaldor–Verdoorn law.

$$X^L = X^L_{t-1} \cdot \left[\chi^L_1 + \chi^L_2 \cdot \left(\frac{Y^*_{D,t}}{Y^*_{D,t-1}} - 1 \right) \right] \tag{6}$$

Accordingly, the amount of labour required at a given point in the simulation is determined by output divided by labour productivity. The level of labour productivity therefore determines the employment.

$$N_t = \frac{Y_S}{X^L_t} \tag{7}$$

In the labour market, the wage bill is assumed to depend positively on its value in the previous period, on the factor ω_t, and on the current employment rate. This reflects the inertia of wage dynamics with respect to macroeconomic conditions, as well as their sensitivity to labour demand.

$$W_t = W_{t-1} \cdot \left[1 + \omega_t + \left(\frac{N_t}{N_{t-1}} - 1\right)\right] \tag{8}$$

The term ω_t in the previous equation denotes the growth rate of nominal wages, which is assumed to depend on the previous-period inflation rate π_{t-1}, negatively on the unemployment rate, and positively on the growth rate of labour productivity.

$$\omega_t = (\pi_{t-1}) \cdot \left[\frac{\omega_1}{\omega_2 + un_t} + \omega_3 \cdot \frac{X_t^L - X_{t-1}^L}{X_{t-1}^L}\right] \tag{9}$$

The price of the single homogeneous good, p_t, is determined according to a mark-up rule applied to the average total cost of production, including wages and loan servicing, relative to the level of output supplied.

$$p_t = \frac{W_t + i_{t-1}^f \cdot Lf_{t-1}}{Y_S} \cdot (1 + \mu_t) \tag{10}$$

Additionally, the mark-up is modelled to evolve endogenously in response to imbalances in the relationship between demand Y_D and supply Y_S. In the case of excess demand over supply, firms' adaptive pricing behaviour allows them to take advantage of the context by raising prices.

$$\mu_t = max\left(\mu_{\text{MAX}}, \mu_1 + \mu_{t-1} \cdot \frac{Y_{D,t-1}^*}{Y_{S,t-1}}\right) \tag{11}$$

Turning to firms' investment behaviour, and according to the standard Post-Keynesian and Kaleckian literature (Godley & Lavoie, 2006), the desired rate of growth of the real capital stock depends positively on an autonomous component γ_1 (Keynesian "animal spirits" in investment decisions) on the profit share from the previous period, and on the deviation of actual capacity utilisation in the previous period u_{t-1} from its normal level u_N, which is calibrated heuristically to a reasonable value that allows for some degree of spare capacity to face unanticipated peak in the demand.

$$g_t^* = \gamma_1 + \gamma_2 \cdot \frac{\Pi_{t-1}}{Y_{t-1}} + \gamma_3 \cdot (u_{t-1} - u_N) \tag{12}$$

Then, the gross desired/targeted investment level is given by

$$I_t^* = K_{t-1} \cdot g_t^* \tag{13}$$

As reported previously, in the current version of the model new green features have been incorporated to simulate the dynamics of a low-carbon transition. The share of green investment in total investment is set at a plausible value consistent with empirical evidence from EU investment patterns. Based on historical EU data[4] for the period 2000-2020, green investment accounted for approximately 23 per cent of total investment over the past decade. This baseline share is endogenously adjusted according to the interest-rate differential between brown and green loans, capturing the role of

[4] ECB, 2023

financial incentives in driving the green transition.

$$I^*_{green,t} = I^*_t \cdot \left(\alpha_1 + \alpha_2 \cdot \left(i^f_{brown,t-1} - i^f_{green,t-1}\right)\right) \tag{14}$$

where α_1 represents the historical share of green investments in the EU, and α_2 captures the sensitivity to interest rate differentials, as also adopted in Dafermos et al., 2017, 2018. The latter value is parametrized to align with the EU's 2030 target, where green investments must reach 7.8% of GDP, constituting about 37% of all investments to be consistent with EU climate targets. Conventional investments are then calculated residually as

$$I^*_{brown,t} = I^*_t - I^*_{green,t} \tag{15}$$

Accordingly, two law of motion for each type of capital (green and brown) are included, reading, in compact form, as

$$\begin{bmatrix} K_{green,t} \\ K_{brown,t} \end{bmatrix} = \begin{bmatrix} (1-\delta) & 0 \\ 0 & (1-\delta) \end{bmatrix} \begin{bmatrix} K_{green,t-1} \\ K_{brown,t-1} \end{bmatrix} + \begin{bmatrix} I_{green,t} \\ I_{brown,t} \end{bmatrix} \tag{16}$$

3.1.2 Households

The household sector comprises 1,000 heterogeneous agents differing in income, consumption, and saving behaviours, in the composition of financial wealth (deposits and investment fund shares), in the value of private dwellings, and in indebtedness positions. The model is initialised with an exogenous log-normal income distribution, allowing for an upper fat tail in the income share distribution and, similarly, in dwelling ownership. Financial wealth then arises as an emergent property, driven by saving and investment decisions throughout the simulation, together with wealth inequality.

Households' disposable income ($yd_{i,t}$) consists of three sources, namely the nominal wage paid by firms when employed ($w_{i,t}$), interest income derived from holdings of financial assets (rsh_{t-1}), and bank and firm dividends ($Div_{i,t-1}$), net of direct income and property taxes on dwellings ($tax_{i,t}$), and debt-servicing costs, given by the effective stock of debt multiplied by the interest rate applied ($i^h_{i,t-1} \cdot Lh_{i,t-1}$)

$$yd_{i,t} = w_{i,t} - tax_{i,t} + rsh_{t-1} \cdot Sh_{i,t-1} + Div_{i,t-1} - \widetilde{i^h_{i,t-1} \cdot Lh_{i,t-1}} \tag{17}$$

As previously mentioned, the wage bill is distributed according to an exogenous log-normal distribution, while employment status is determined by a random draw. The desired level of consumption, $c^*_{i,t}$, depends on a variety of factors and on different propensities to consume out of net wages ($yw_{i,t}$), financial income represented by return on share and dividends ($r^{sh} \cdot Sh_{i,t} + Div_{i,t}$), net wealth ($NW_{i,t}$), and a social component (a "keep up with the Joneses" term) based on the average consumption level in the previous period ($\overline{c}_{t-1}$).

$$c^*_{i,t} = c_w \cdot (yw_{i,t}) + c_r \cdot [r^{sh} \cdot Sh_{i,t} + Div_{i,t} + c_{wealth} \cdot (NW_{i,t}) + c_n \cdot \overline{c}_{t-1}] \tag{18}$$

After setting their desired levels of consumption and, consequently, saving, households determine their desired holdings of financial assets, in the form of deposits and shares. Desired deposits ($Dh^*_{i,t}$) are assumed to represent a fixed proportion

of each household's wealth stock in the previous period, to face unforeseen events.

$$Dh^*_{i,t} = \eta_H \cdot Wh_{i,t-1} \tag{19}$$

Meanwhile, the desired holdings of investment fund shares are modelled as a function of their previous level ($Sh^*_{i,t-1}$), adjusted dynamically according to the observed difference between the return on those shares ($\frac{r^{sh}_{t-1} Sh_{i,t-1}}{Sh_{i,t-1}}$) and the cost of borrowing from commercial banks to finance the investment ($i^h_{i,t-1}$).

$$Sh^*_{i,t} = Sh^*_{i,t-1} \cdot \left[1 + \sigma \left(\frac{r^{sh}_{t-1} Sh_{i,t-1}}{Sh_{i,t-1}} - i^h_{i,t-1} \right)\right] \tag{20}$$

Consequently, the volume of household borrowing is determined by the desired flows of deposits and shares, net of internal funding represented by saving:

$$\Delta L_{h,i,t} = \Delta D_{h,i,t} + \Delta S^*_{h,i,t} - S^*_{h,i,t}. \tag{21}$$

However, actual holdings of deposits, investment fund shares, and loans may differ from their desired or target levels when households are credit-rationed, because they are judged by commercial banks to be unable to obtain new loans given their level of indebtedness. In such cases, households revise their consumption and financial assets plans according to a pecking-order mechanism. First, they hold a smaller quantity of shares than desired, followed by a reduction in deposits. If rationing intensifies further, they begin to decumulate both shares and deposits and ultimately reduce consumption down to a subsistence level (see Eq. A.34 in the Appendix).

3.1.3 Government and Central Bank

Monetary, fiscal, and redistributive policies are the prerogative of a consolidated public sector, comprising a central bank and a government. Specifically, the central bank is responsible for conducting monetary policy aimed at price stability. The policy interest rate is set according to an "inertial" Taylor rule, whereby the policy rate evolves as a function of parameter ρ, capturing the degree of gradualism in responding to inflation, and of the deviation of the CPI inflation rate (π_t) from its target (π^T) from one period to the next. Accordingly, the higher current inflation and its positive deviation from the target, the bolder the increase in the policy rate relative to its previous level.

$$i^T_t = \rho \cdot i^T_{t-1} + (1-\rho) \cdot \{\pi_t + \rho_\pi \cdot [\pi_t - \pi^T]\} \tag{22}$$

The government provides unemployment benefits to jobless households and purchases goods to supply public services. Public expenditure is determined by the previous period's public spending, captured by a time-persistence parameter ξ_1, and by aggregate consumption (ξ_2), in order to reflect the observed proportionality between government demand and overall aggregate demand over time.

$$G_t = \xi_1 \cdot G_{t-1} + (1-\xi_1) \cdot \xi_2 \cdot C_t \tag{23}$$

The government also levies taxes on household income, with progressive taxation based on income thresholds, as well as property taxes on private dwellings and taxes on the profits of banks and non-financial firms.

$$T_t = \tau_\pi \cdot \Pi_t + \sum_{i=1}^{N} \tau_i^w w_{i,t} + \sum_{i=1}^{N} \tau_i^{WH} WH_{i,t-1} \tag{24}$$

In the event of a budgetary deficit, the government issues public bonds to finance the gap between revenues (T_t) and expenditures (G_t, unemployment benefits, and interest payments $i^b t-1 \cdot GDt-1$).

$$\Delta GD_t = G_t + dole \cdot [\overline{N} - N_t] + i_{t-1}^b \cdot GD_{t-1} - T_t \tag{25}$$

Since the central bank is highly stylised, without a proper balance sheet, it does not act as a lender of last resort. For this reason, the interest rate on public bonds is determined recursively as a function of its previous value and the proportion of public debt held on banks' balance sheets (B_B). As banks act as residual purchasers of government securities, an increase in this share is interpreted as a proxy for weaker market demand for public bonds, which in turn drives up interest rates.

$$i_t^b = i_{t-1}^b \cdot \left[1 + \alpha \left(\frac{B_{B,t}}{GD_t} - \frac{B_{B,t-1}}{GD_{t-1}}\right)\right] \tag{26}$$

3.1.4 Commercial Bank

The commercial banking sector plays a central role in the model, as in highly financialised advanced economies, and is consistent with the principles of endogenous money theory (McLeay et al., 2014). The bank acts as follows:

- Through credit creation, it supports the production of goods, household consumption, and firms' investment plans, both green and conventional.
- It sustains households' demand by providing loans for investment in financial assets and for the green refurbishment of private dwellings.
- By extending credit, it generates the underlying assets for the securitisation process, encompassing both conventional and green asset-backed securities (ABSs).

The commercial bank's ability to extend credit in response to households' loan demand is conditional on a creditworthiness assessment. When households are unable to service their debt obligations, they default, and the resulting non-performing loans (NPLs) affect their credit history, preventing them from applying for new credit. In addition to this preliminary criterion, further assessments are required. First, the bank computes the "expected" household-specific interest rate ($i_{i,t}^{e,h}$) by applying a mark-up to the observed policy rate in the previous period ($i^T t-1$), plus a component capturing the financial fragility of the applicant (ι_h), defined as the ratio of the prospective new loan stock, conditional on loan approval, to net income.

$$i_{i,t}^{e,h} = i_{t-1}^T + \iota_h \cdot i_{t-1}^T \cdot \frac{Lh_{i,t-1} + \Delta Lh_{i,t}^*}{yn_{i,t}} \tag{27}$$

Additionally, $mh_{i,t}^*$ represents the 'notional' individual debt-service ration the household has to cover if the new loan ($\Delta Lh_{i,t}^*$) is granted

$$mh_{i,t}^* = i_{i,t}^{e,h} \cdot \frac{Lh_{i,t-1} + \Delta Lh_{i,t}^*}{yn_{i,t}} \tag{28}$$

Accordingly, the final evaluation of households' creditworthiness is performed by comparing the term $mh^*_{i,t}$ with the endogenous parameter Ψ_t, which represents the commercial bank's acceptable threshold for the borrower's debt burden. The loan is ultimately granted if

$$\text{if } mh^*_{i,t} < \Psi_t \text{ then } \begin{cases} i^h_{i,t} = i^e_{i,t} \\ \Delta Lh_{i,t} = \Delta Lh^*_{i,t} \end{cases} \tag{29}$$

In this version of the model, no credit rationing is applied to firms, either for 'green' or for 'conventional' loans, with interest being calculated in a similar way to that on household loans.

$$i^f_{i,t} = i^T_{t-1} + \iota_f \cdot i^T_{t-1} \cdot \frac{Lf_{i,t-1} + \Delta Lf^*_{i,t}}{Pf_t} \tag{30}$$

The endogenous parameter Ψ_t of the commercial bank reflects its macroprudential stance and is bounded according to the following rule:

$$\Psi_t = \max\left[\Psi_{\min}, \min\left(\Psi_{\max}, \Psi^*\right)\right] \tag{31}$$

Higher values of Ψ_t correspond to more relaxed lending standards, whereas Ψ_t decreases as the ratio of non-performing loans (NPLs) in the economy relative to due instalments increases, and as the distance between the actual own-capital asset ratio $k_{B,t}$ and the regulatory capital adequacy requirement $\overline{k}$ widens.

$$\Psi^* = \overline{\Psi}_{\min} - \psi_1 \cdot \frac{NPL}{\epsilon \cdot Lh_{t-1}} + \psi_2 \cdot \left(k_{B,t} - \overline{k}\right) \tag{32}$$

In this extended version, $k_{B,t}$, the actual commercial bank's capital assets-ratio, is given by the observed commercial bank own funds $\tilde{\Omega}^B_{t-1}$ over the total balance sheet assets, corresponding to the share of 'green' and 'conventional' loans granted to households and firms, net of the derecognised portion moved to SPVs for the securitisation process (z_t), plus public bond holdings ($B_{B,t}$).

$$k_{B,t} = \frac{\tilde{\Omega}^B_{t-1}}{(1 - z_t) \cdot \left(L^{green}_{h,t} + + L^{brown}_{h,t} + L^{green}_{f,t} + L^{brown}_{f,t} + B_{B,t}\right)} \tag{33}$$

The bank's own funds depend on their value in the previous period, reduced by the share of households' non-performing loans (NPLs) that remain on its balance sheet.

$$\tilde{\Omega}^B_t = \Omega^B_t - (1 - z_{t-1}) \cdot NPL_t \tag{34}$$

In this framework, commercial banks securitise loans in the amount required to meet the demand for asset-backed securities (ABSs) from investment funds (IFs) via special purpose vehicles (SPVs). Accordingly, z_t is an endogenous variable representing the fraction of loans, to households as well as to conventional and green non-financial firms, that are securitised to satisfy this demand.

$$z_t = \min\left(1, \frac{ABS^D_{IF}}{L^{green}_{h,t} L^{brown}_{h,t} + L^{green}_{f,t} + L^{brown}_{f,t}}\right) \tag{35}$$

In conclusion, the distribution of a commercial bank's taxed dividends is subject to Basel-type macroprudential requirements.

$$P_t^B = \Pi_t^b(1 - \tau_\pi) \tag{36}$$

First the bank compute the level of own capital compliant with required capital adequacy ratio

$$\Delta\overline{\Omega} = [(1 - z)L_t + B_{B,t}] \cdot \overline{k} \tag{37}$$

Second, they set the desired level of capital injection Ω_t^*, and thus retained profit. This is a fixed share ζ_B of the distance between required and observed own capital whenever needed or zero.

$$\Delta\Omega_t^* = \begin{cases} \text{if } k_{B,t} < \overline{k} \implies \Delta\Omega_t^* = \zeta_B \cdot (\overline{\Omega}_t^B - \Omega_{t-1}^B) \\ \text{if } k_{B,t} \geq \overline{k} \implies \Delta\Omega_t^* = 0 \end{cases} \tag{38}$$

Whenever net profits are higher than required capital injection, dividend payable results as residual after retained profits are detracted.

$$\text{if } \Delta\overline{\Omega} \leq P_t^B \implies \begin{cases} \Omega_t = \Omega_{t-1} + \Delta\Omega_t^* \\ Div_B = P_t^B - \Delta\Omega_t^* \end{cases} \tag{39}$$

Otherwise, all net profits are fully retained as bank's actual capital injection is lower than required desired one

$$\text{if } \Delta\overline{\Omega} > P_t^B \implies \begin{cases} \Omega_t = \Omega_{t-1} + P_t^B \\ Div_B = 0 \end{cases} \tag{40}$$

3.1.5 Investment Funds

Investment funds (IFs) act as a financial intermediary for households, collecting their savings and investing them in asset-backed securities (ABSs) and public bonds, financed through the issuance of shares (Sh_t). At the beginning of each period, redeemed loans are converted into IF deposits, while non-performing loans (NPLs) arising from defaulted securitised loans translate into capital losses. These losses reduce the value of outstanding ABSs and, consequently, the value of shares held by households. Subsequently, the portfolio allocation strategy takes place. IFs retain a portion of the collected funds in the form of deposits, while allocating the remainder across ABSs and public bonds according to expected returns.

$$D_{IF,t} = \eta_{IF} \cdot Sh_t \tag{41}$$

then the remaining funds are allocated between ABSs and Bonds, the latter decreasing when the difference between the return on securitised instruments (r_t^{abs}) and the interest rate on public bond (i_t^B) observed in the current period are higher than the previous one.

$$q_{if,t}^b = q_{if,t-1}^b \cdot \{1 - \beta[(r_t^{abs} - i_t^B) - (r_{t-1}^{abs} - i_{t-1}^B)]\} \tag{42}$$

The demand for bonds ($B_{IF,t}^D$) is obtained by multiplying $q_{if,t}^b$ by the amount of funds collected by IFs, net of those held in the form of deposits.

$$B_{IF,t}^D = q_{if,t}^b \cdot (1 - \eta_{IF}) \cdot Sh_t \tag{43}$$

Finally, the demand for ABSs is computed as a residual.

$$ABS^{*D}_{IF,t} = Sh_t \cdot (1 - \eta_{IF}) - B_{IF,t} \tag{44}$$

In conclusion, in the case of excess demand for ABSs, demand will adapt to supply.

$$ABS^{*}_{IF,t} = min(z_t L_t, ABS^{*D}_{IF,t}) \tag{45}$$

3.1.6 Housing equations

A core contribution of the present work is the introduction of a new private asset in the household balance sheet, namely private dwellings. This asset represents an additional source of heterogeneity and wealth inequality driver, influencing consumption and saving decisions, as well as indebtedness positions. Housing does not operate within a proper market (that is, households do not trade or adjust their housing stocks), and, for simplicity, its value is assumed to follow the general price level. Instead, houses are distributed exogenously, reflecting the log-normal distribution of income and incorporating an element of stochasticity. The allocation mechanism operates as follows. At the initialisation of the simulation (period one), households are weighted proportionally to their gross wage shares, such that wealthier households have a higher probability of receiving dwellings. Housing units are then sequentially assigned to agents according to these probabilistic weights. Once a household reaches its desired number of dwellings, which is a function of its gross wage share, its allocation weight is set to zero, preventing it from receiving additional units. The process continues until the available housing stock is fully distributed among households. The total number of available dwellings is calibrated to replicate empirical evidence on home ownership and tenure structures across Europe, based on the Eurostat database.[5]

Rent Households that are not assigned a dwelling are nevertheless required to pay rent. In this simplified version of the model, there is no direct redistribution of owned dwellings to households without housing over the course of the simulation. The amount of rent paid depends on each household's employment status, differing between employed households and those receiving unemployment benefits. Rent levels are heuristically calibrated using Eurostat data on the average share of housing costs in disposable household income. [6].

$$\text{rent}_i = \begin{cases} \mu_2 \cdot yw_{i,t}, & \text{if household } i \text{ has income} \\ \mu_3 \cdot \text{dole}_i, & \text{if household } i \text{ has no income} \end{cases} \tag{46}$$

Rents are subsequently distributed among owners, that is, households holding a positive stock of dwellings, in proportion to each agent's share of total real estate wealth, in a manner analogous to the distribution of profits and dividends. This extension affects agents' behaviour by determining who benefits from, and who bears the cost of, rent payments, with implications for disposable income, desired consumption, the calculation of individual interest payments, debt servicing, and saving and investment decisions.

[5] Eurostat data page
[6] Eurostat data page

Capital Gains and Private Net Wealth We assume that house values depend on the general price index of the homogeneous goods produced, consumed, and invested in the economy in the previous period, P_{t-1}, and on a random innovation term that can be either positive or negative, capturing short-run fluctuations without lasting effects. Since there is no dedicated housing market in the model, this measure represents a book value and does not feed back into the aggregate price level.

$$hw_{i,t} = h^*_{i,t}\, P_{t-1}\left(1 + \varepsilon^H_t\right), \tag{47}$$

where $h^*_{i,t}$ denotes the stock of dwellings held by agent i at time t, and ε^H_t is a mean-zero stochastic term reflecting transitory valuation shocks.

The total wealth of each agent is then given by:

$$wealth_{i,t} = D^*_{h,i,t} + S^*_{h,i,t} + hw_{i,t} \tag{48}$$

where $D^*_{h,i,t}$ and $S^*_{h,i,t}$ denote, respectively, deposits and shares. Finally, net wealth is defined as total wealth net of household debt, plus realised capital gains on housing:

$$nw_{i,t} = wealth_{i,t} - Lh_{i,t} + hCG_{i,t} \tag{49}$$

As with other forms of capital, the housing stock is subject to depreciation. However under the transition scenario, households holding a green loan for housing refurbishment are exempt from depreciation on their real estate wealth, as renovation activities are assumed to offset the loss in value. Formally, this mechanism is implemented by applying depreciation only to households without a refurbishment loan. In addition, in line with real-world fiscal frameworks, a property tax is levied on housing wealth, introducing an additional channel through which housing affects disposable income, wealth accumulation, and the transmission of policy effects. In particular, we introduce a differentiated tax burden, with a lower average tax rate applied to the first dwelling and a higher rate applied to housing holdings exceeding the median EUROSTAT level (1.05 houses per capita).

3.2 Parameters

The model's main parameters (see Table A.7 in the Appendix) have been retrieved from (Botta et al., 2025), and are heuristically calibrated using plausible values and are not intended to replicate any specific institutional setting. This modelling choice reflects a deliberate strategy aimed at capturing the general features of a highly financialised economy. However, for the purposes of the present analysis, and in order to parametrise the newly introduced housing module, we rely on EU-level macroeconomic data from EUROSTAT on owner-occupancy rates, tenancy rates, and average rents.

4 Baseline simulation

In this section, we present the simulation results for the baseline configuration. Figures 3–6 report the outcomes of 200 Monte Carlo simulations. The results are computed after an initial burn-in phase, during which the model completes its transient dynamics and converges to a quasi-steady state for the main macroeconomic and financial variables. All stocks in the economy are initialised at zero at the beginning of the simulation, except for a small set of variables required to

activate the economic processes. We report the last 100 time steps of the simulation following the burn-in period. In this configuration, no discretionary policy interventions are implemented. Instead, fiscal and monetary authorities follow simple rule-of-thumb behaviour: the government adjusts its fiscal stance mechanically, while the central bank sets the policy interest rate according to an 'inertial' Taylor rule. The figures display the median across simulations together with the 5–95% confidence interval, represented by the shaded area, for a set of key macro-financial variables grouped into four categories: (a) real economy and activity; (b) credit and non-performing loans; (c) prices and public sector variables; and (d) inequality measures.

Across the panels, aggregate macroeconomic and financial variables display stable dynamics over time, consistent with a quasi-steady state. Within this regime, the simulations demonstrate the model's ability to reproduce cyclical macroeconomic behaviour, as reflected in the fluctuations of real GDP growth around a stable median (upper-left panel of Figure 3). The unemployment rate is anchored at around 8%, while capacity utilisation exhibits persistent slack, with an average degree of capital utilisation of approximately 80%. As shown in Figure 5, the ratio of public debt to GDP stabilises at a high level, around 120%, consistent with a high-income economy characterised by low growth rates and a large stock of public debt.

The extensions introduced by the housing module are primarily reflected in the inequality panel. When considering the indicators reported in Figure 6, which display different measures of income and wealth inequality, a subtle divergence emerges. While income- and consumption-based Gini indexes remain broadly stationary, wealth inequality exhibits a slow but persistent upward drift, although very limited in magnitude. This pattern arises from the introduction of private housing wealth, which constitutes an additional driver of wealth inequality through a revaluation channel. In particular, the value of private dwellings is partially anchored to the general price level, net of small random fluctuations, leading to a gradual appreciation of real estate wealth over time. As a result, asset-holding households disproportionately benefit from price-level dynamics. Importantly, the magnitude of this increase remains limited and does not compromise the overall stability of aggregate dynamics, instead capturing a long-run and plausible secular distributive mechanism operating through.

To further enhance the model's external validity, we additionally assess its ability to replicate selected real-world trends (see Table 1). Overall, the model performs reasonably well in reproducing several euro area aggregates, notably the unemployment rate, the consumption share of GDP, housing-related variables, and inequality indicators. By contrast, the model tends to underperform relative to euro area averages in terms of GDP growth and public finance indicators, such as the debt-to-GDP ratio. Again, these outcomes are more consistent with the macroeconomic profiles of large southern peripheral economies within the euro area, which are characterised by low growth rates and high public debt stocks.

(a)

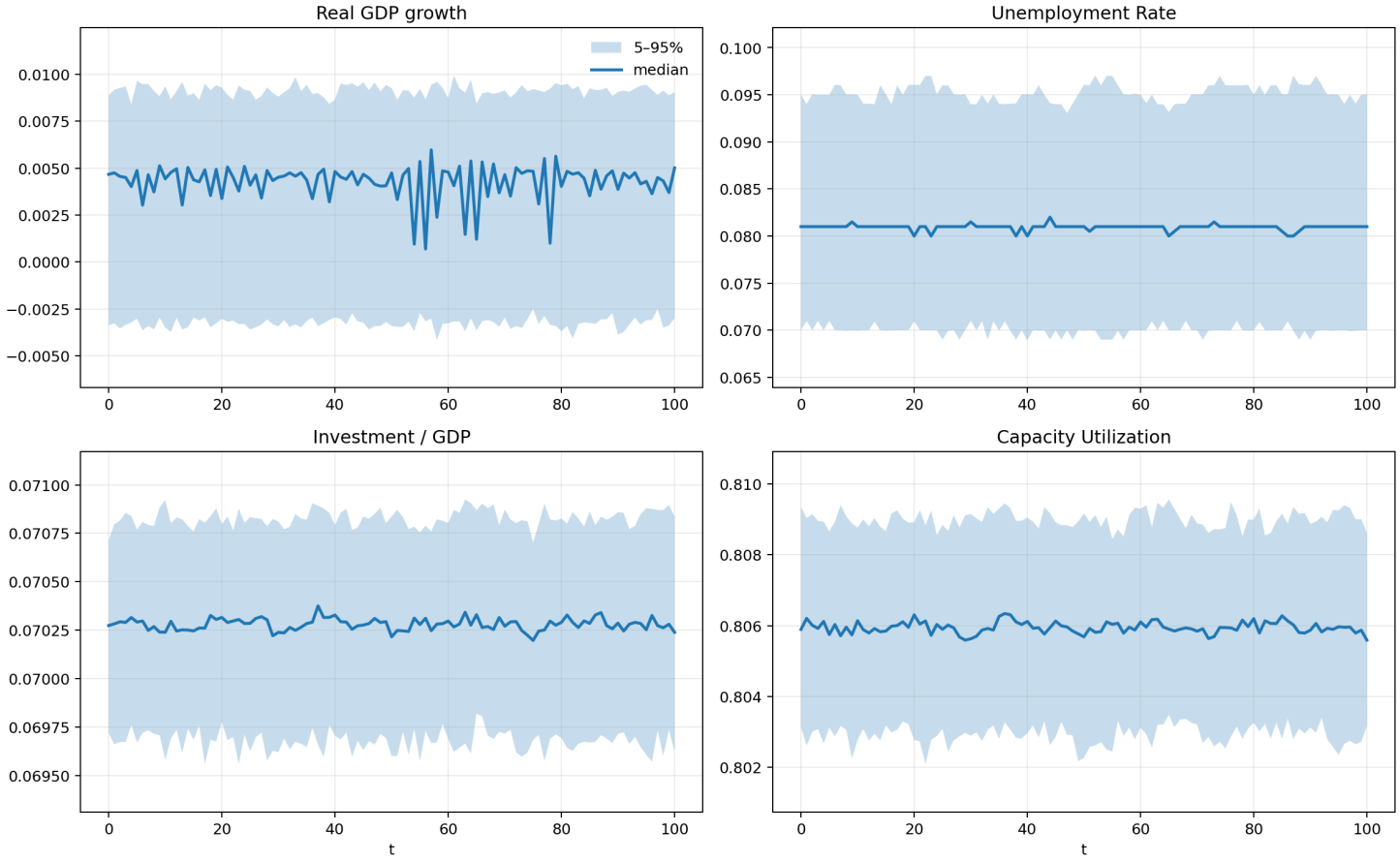


Figure 3: Real Economy and Activity. Median and 5–95% confidence bands from 200 Monte Carlo simulations of the baseline scenario, reporting real GDP growth, unemployment, investment intensity, and capacity utilisation after the burn-in period.

(b)

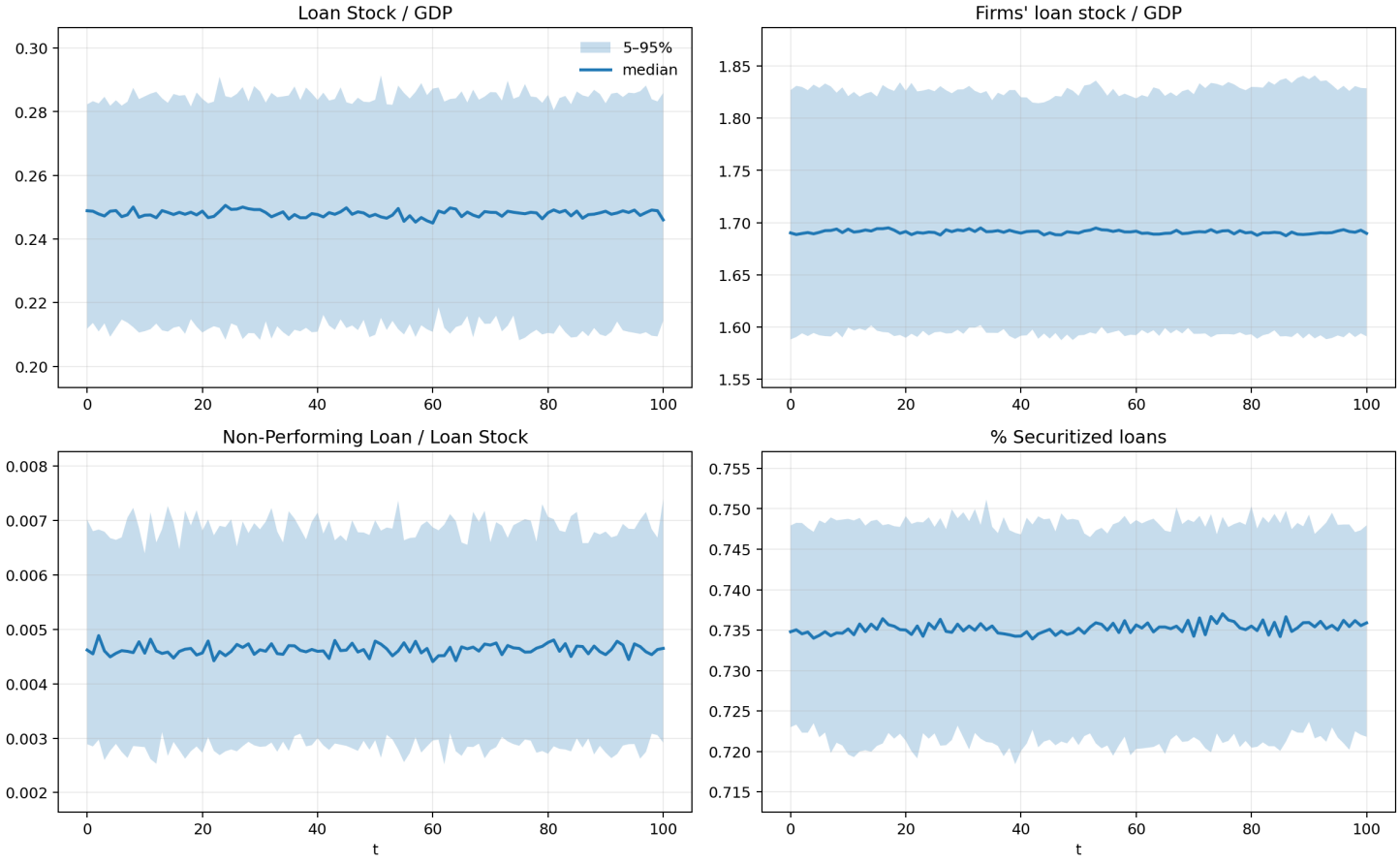


Figure 4: Credit and Non-Performing Loans. Median and 5–95% confidence bands from 200 Monte Carlo simulations of the baseline scenario, reporting the evolution of household and firm loan stocks relative to GDP, total non-performing loans in the economy, and the share of securitised loans after the burn-in period.

(c)

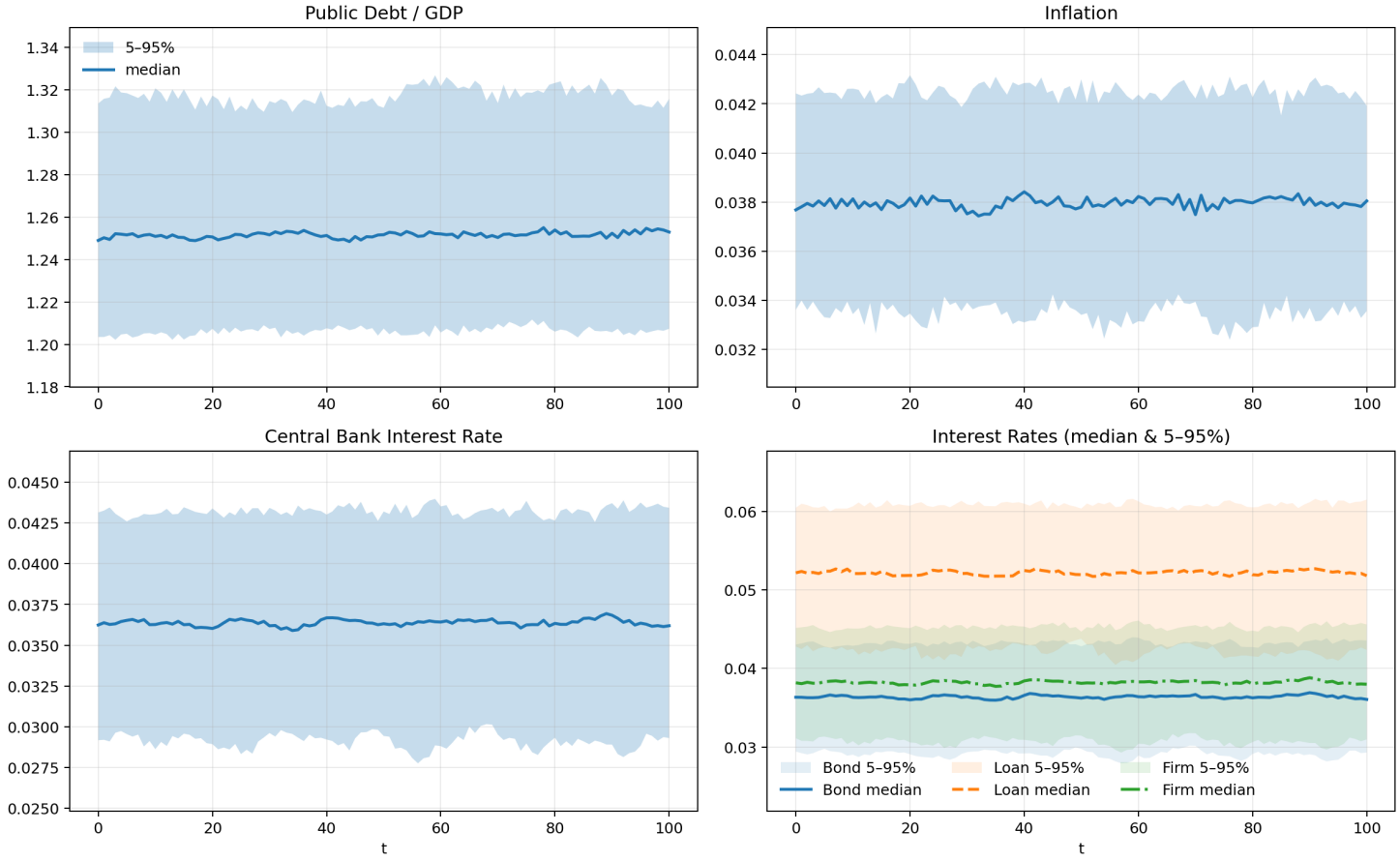


Figure 5: Prices and Policy. Median and 5–95% confidence bands from 200 Monte Carlo simulations of the baseline scenario, reporting public debt relative to GDP, inflation, the policy interest rate, and interest rates on household loans, firm loans, and public bonds after the burn-in period.

(d)

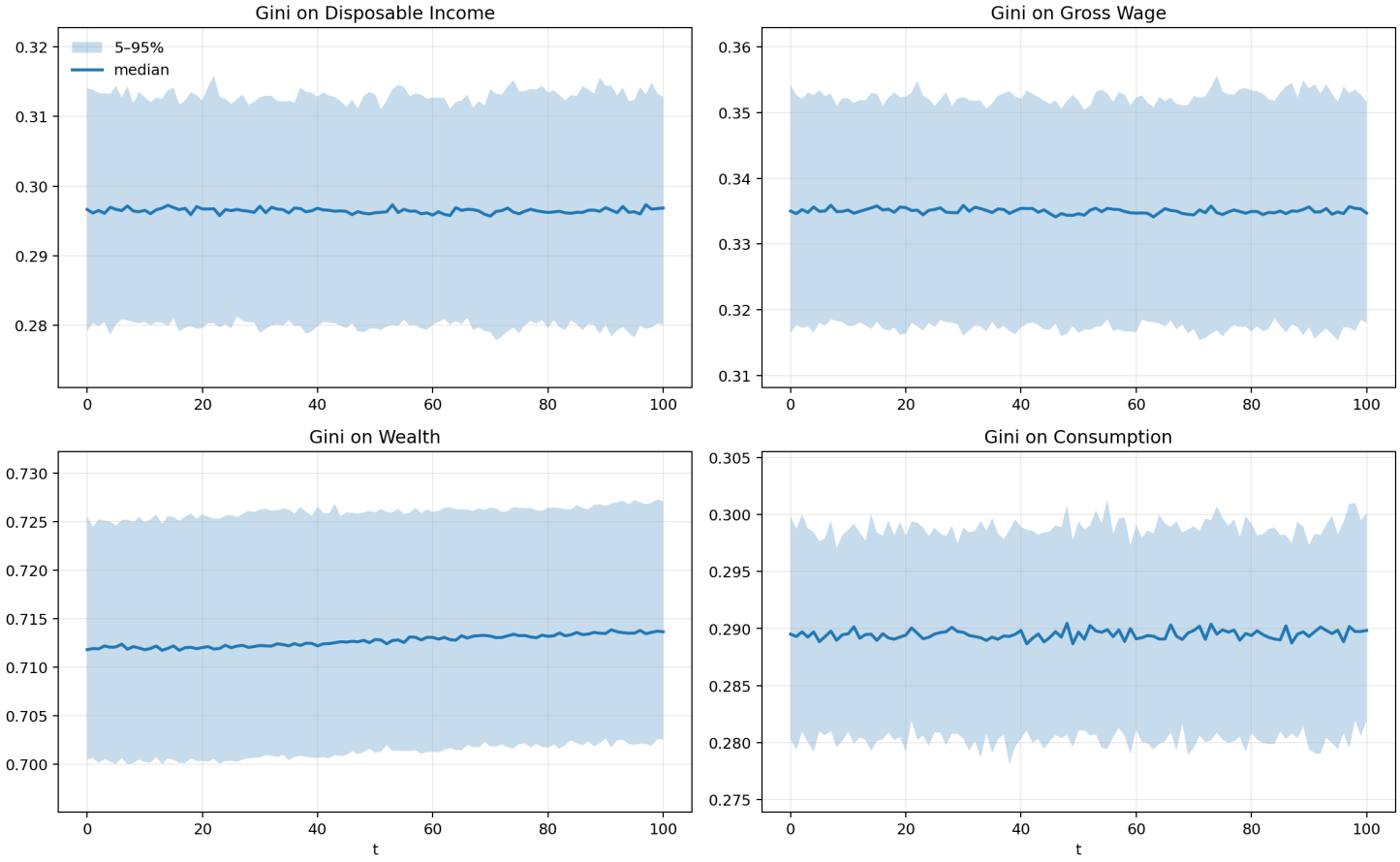


Figure 6: Inequality. Median and 5–95% confidence bands from 200 Monte Carlo simulations of the baseline scenario, reporting the Gini coefficients for disposable income, gross wages, wealth, and consumption after the burn-in period.

Table 1: Macroeconomic Variables: Average Comparison. Model-simulated values are averages across 200 Monte Carlo runs computed after the burn-in period. Reference values are obtained as averages across EU countries from the Eurostat database.

Variable	Model	Euro Area	Source
Real GDP			
(% change compared with the previous year)	0.32	1.9	Eurostat
Unemployment			
Average rate (%)	8.2	8.1	Eurostat
Consumption			
Consumption share (% of GDP)	64.5	51.5	Eurostat
Public Finance			
Deficit/GDP (%)	-0.6	-1.8	Eurostat
Debt/GDP (%)	123.0	90.0	Eurostat
Housing			
Owner-occupancy rate (%)	70.2	68.8	Eurostat
Tenancy rate (%)	29.8	31.2	Eurostat
Income Inequality			
Gini Index on Disposable Income (%)	32.26	30.29	Eurostat

5 Green Transition Scenario

An important pillar of the EU strategy for achieving net-zero emissions by 2050 is the Energy Performance of Buildings Directive[7]. Around 85 per cent of the European building stock was constructed before 2000, and roughly 75 per cent of it displays poor energy-efficiency performance. Buildings constitute the single largest energy-consuming sector in Europe, accounting for around 40 per cent of total energy use across the continent, with almost 50 per cent of gas consumption attributable to residential and commercial structures. It is therefore evident that meeting emission-reduction targets requires major improvements in energy performance through building-envelope retrofits, system upgrades, and the deployment of renewable energy technologies. In this policy-driven scenario, we introduce an exogenous programme of mandatory green renovation targeting the private stock of dwellings. From the period in which the policy is activated, $t = T_0$, the planned renovation rate is set at 3 per cent of the existing housing stock per period. The matching protocol functions as follows: in each time-step of the simulation, dwellings are selected at random from the total stock $H_t = \sum_i h_{i,t}$, with selection probabilities proportional to individual housing holdings. Let $\Xi_{i,t} \in \{0, 1\}$ denote an indicator equal to one if household i has at least one dwelling selected in period t. Those households formulate a desired green-loan demand proportional to

[7] Energy Performance of Buildings Directive, European Union

the value of their housing assets, given by

$$L_{i,t}^{g,*} = \lambda\, p_{h,t-1}\, h_{i,t}, \qquad \lambda = 0.25. \tag{50}$$

Eligibility for green credit remains conditional on the household not being subject to credit rationing and on satisfying the model's solvency requirement set by the credit system from Equation 27-29. Additionally, if the green-loan request is granted, the household receives a temporary 'green shield' that suspends housing-asset depreciation from the period, after which it may reapply under the same conditions. In the following section we present some relevant results.

5.1 Results

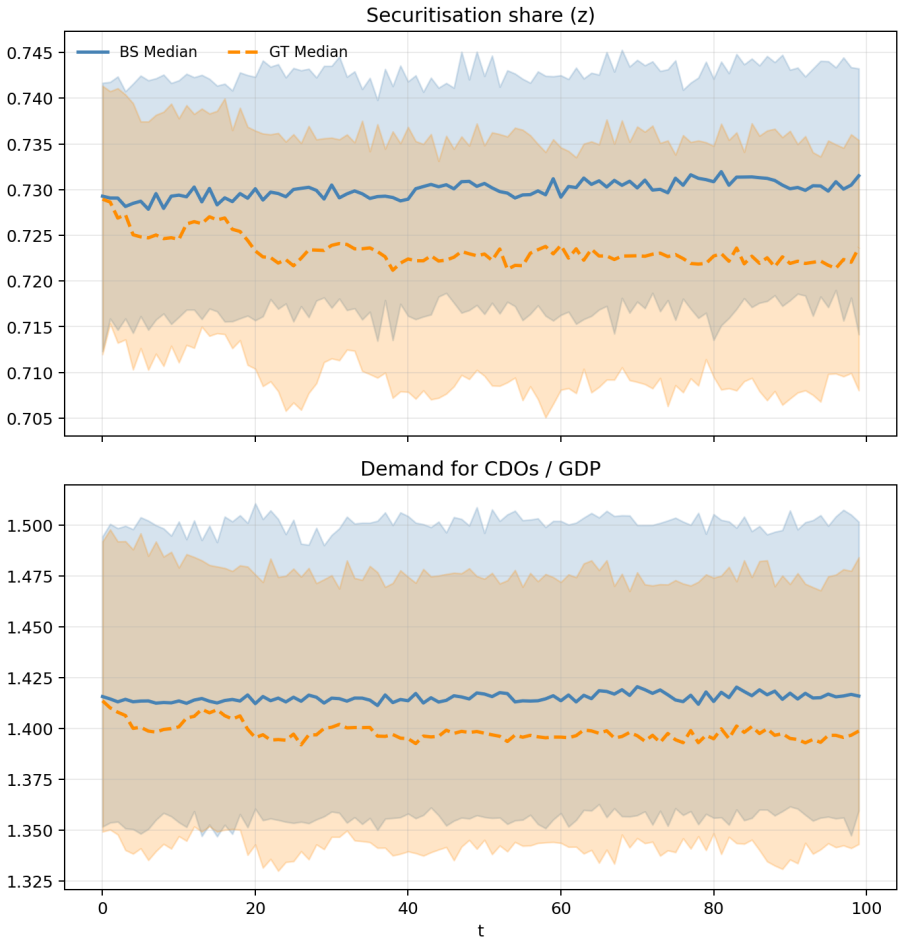


Figure 7: Securitisation and CDO demand: Baseline (BS) versus Green Transition (GT). The figure reports the securitisation share of bank loans (top panel) and the demand for collateralised debt obligations scaled by GDP (bottom panel). Solid lines denote the Baseline median, dashed lines the Green Transition median; shaded areas represent the 5–95% 200 Monte Carlo run bands.

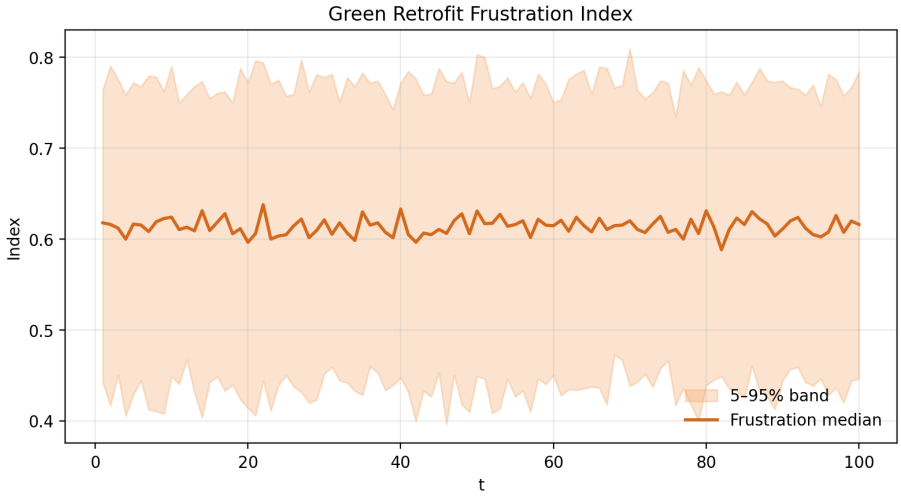


Figure 8: Green Retrofit Frustration Index. Median and 5–95% Monte Carlo band for the share of denied green renovation loan requests over total green loan applications in the Green Transition scenario, after the burn-in period.

Panels 9-12 in the Appendix report the Baseline (BS) and Green Transition (GT) scenarios for the key variables of interest. Overall, standard macroeconomic variables do not exhibit marked differences in their median dynamics across the two scenarios. This aligns with the design of the GT specification, which implements a limited green housing retrofit programme based on households' financial conditions, rather than a regime shift akin to a conventional fiscal or monetary intervention. Aggregate activity and labour-market conditions (GDP and unemployment, see Appendix 9) remain statistically close to baseline median values, indicating no significant effects to report.

Turning to the macro-financial dimension, the upper panel of Figure 7 illustrates the dynamics of the securitisation share (z) over the post-burn-in period in the BS and GT scenarios. The BS case displays a relatively stable median trajectory. Under the GT configuration, the median path remains slightly below the baseline, suggesting a qualitative yet modest reduction in the demand for CDOs from investment funds. This pattern is confirmed by the lower panel of the same figure, which reports the value of CDO demand relative to GDP across the simulation period. Taken together, these dynamics imply a lower volume of securitised loans, which constitute the underlying 'material' for the securitisation process.

A possible explanation for these qualitative results, when reporting the baseline with the green-retrofit scenario, lies in the model's behaviour regarding households across different distribution tiers, their access to loans, and, depending on their income and financial position, the likelihood of facing credit constraints when seeking additional green energy-efficiency loans for housing refurbishment. This point is clarified in Figure 8. The figure reports a Green Retrofit Frustration Index (0-1 scale) measuring the share of households selected by the programme to apply for green retrofit loans but, given their income and balance-sheet position, are unable to obtain the desired amount from the banking sector. These households remain financially constrained and unable to refurbish their real-estate assets.

Overall, almost 60 percent (median value) of loan demand is not granted by the credit system. Depending on the tier to which households belong, they are more or less likely to access green financing. Households in higher tiers, characterised by lower indebtedness and stronger repayment capacity, as well as a greater ability to accumulate financial wealth in the

form of IFs shares, are more likely to be successfully selected by the green-retrofit programme algorithm. The matching protocol described earlier leads these households to reduce their financial-wealth buffers in order to allocate resources to green retrofits, resulting in a lower share of IFs holdings, reduced CDO-over-GDP demand, and consequently a smaller proportion of securitised loans z_t.

These results should be interpreted primarily in a qualitative and exploratory sense. The analysis is subject to a number of limitations, including a stylised and partial implementation of the green transition scenario, simplified financing conditions and behavioural mechanisms that are not yet fully empirically calibrated. Nonetheless, the framework provides informative insights into the potential bottlenecks that may arise when retrofit investment relies predominantly on households' internal financing capacity, in the absence of strong fiscal support and redistributive mechanisms. Within this setting, binding credit constraints give rise to a non-negligible share of unmet green loan demand, thereby slowing the pace of residential energy-efficiency upgrades required to meet climate targets.

6 Conclusions

The present contribution has provided a preliminary construction and exploration of the macro-financial outcomes of a green retrofit programme in an agent-based stock–flow consistent (AB-SFC) model with heterogeneous households, private dwellings, and a highly financialised environment characterised by securitisation. Methodologically, the model extends the non-equilibrium environment in Botta et al. (2025) through the following additions:

- incorporating a housing module, allowing for more realistic assumptions regarding the composition and formation of household wealth, calibrated on EU Eurostat data on housing tenure and ownership rates;
- introducing green capital formation and low-carbon investment by private firms, alongside household demand for green loans to finance energy-efficiency retrofits and refurbishment of private dwellings;
- modelling green asset-backed securities, whose underlying assets are commercial-bank loans financing green investment by both firms and households.

On this basis, we test the model in a baseline scenario and in a green housing-retrofit programme, drawing two preliminary conclusions and identifying starting points for more ambitious policy scenarios and future extensions:

- First, the aggregate macroeconomic effects of a retrofit programme financed predominantly through household balance sheets are limited. Output and employment exhibit only marginal improvements, suggesting that, in the absence of public co-financing or risk-sharing mechanisms, the macroeconomic transmission of retrofit investment remains weak.
- Second, the current parametrisation generates a substantial share of unmet loan demand. Eligibility conditions tied to income and balance-sheet indicators result in credit rationing that disproportionately affects households in the lower tiers of the distribution, thereby slowing the diffusion of energy-efficiency improvements across the housing stock.

These preliminary findings should be interpreted in light of the limitations of the present work, which reflect the stylised nature of the exercise, the simplified financing conditions, and the absence of empirically grounded calibration of behavioural parameters. Further work is required in two main directions. First, a more accurate calibration of household

decisions regarding green retrofits would enhance the model's external validity. Second, alternative policy instruments capable of supporting a 'just' ecological transition, particularly with respect to income distribution and wealth inequality, should be explored. Public guarantees, redistributive measures, and combined fiscal-and-credit interventions, such as green macroprudential policies and targeted credit allocation, could help ease financial constraints for middle- and lower-tier households while fostering the transition towards a low-carbon economy and clarifying the trade-offs between financial stability, economic performance, and green transition objectives. Such instruments may be essential to ensure that decarbonisation proceeds at a pace consistent with environmental targets while maintaining the conditions for a fair societal transition.

A Disclosures

During the preparation of this work the author used Chat-GPT 5 and Grammarly in order to check grammar and improve the fluency of the text. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

B Acknowledgment

I am very grateful to Stefano Di Bucchianico, Alberto Botta, Eugenio Caverzasi, and Alberto Russo for their availability and support. I also wish to thank the participants at the IAERE Annual Conference in Rome (2024), the participants at the Macro Agent-Based Workshop at the Scuola Superiore Sant'Anna in Pisa (2024), and the participants at the PhD Workshop 'Economic Policies in the Context of Socio-Ecological Transition II' at Queen Mary University of London (2024) for their helpful comments and discussion. All remaining errors are my own.

C EU Green Financial Framework

Three main pillars are intended to foster green awareness and transparency among financial markets and investors:

- The European Taxonomy, whose aim is to classify economic activities in terms of environmental sustainability[8] (European Union, 2020);
- The European Green Bond Standard, which establishes disclosure requirements for green bonds financing low-carbon assets based on the EU Taxonomy of sustainable activities (EU, 2023);
- ESG Rating Activities, which outline a methodology for rating the environmental, social, and governance performance of companies or financial instruments (European Union, 2020).

Table A.1: Tools and Standards for Sustainable Finance in the EU

Tool/Standard	Description
EU Taxonomy for Sustainable Activities	A classification system for sustainable activities to guide investments and ensure transparency.
European Green Bond Standard	The Standard relies on the detailed criteria of the EU taxonomy to define green economic activities, ensures levels of transparency in line with market best practice and establishes supervision of companies carrying out pre- and post-issuance reviews at European level.
ESG Rating Activities	Ratings on environmental, social and governance (ESG) factors provide information about the sustainability performance of a company or a financial instrument, by assessing its exposure to sustainability risks and/or its impact on people and the environment.

The dynamism of the green and sustainable bond market in the European financial sector is often contrasted with reports from industry organisations, which highlight the poor performance of ESG securitisation instruments issued in the EU compared with the rest of the world. Indeed, as shown in the latest report by the Association for Financial Markets in Europe (AFME) on the state of the market, from 2019 to 2022 green securitisation issuance accounted for just 1.4% of total green financing in Europe, compared with 8.1% in China and 32.3% in the United States (AFME, 2022). According to these reports, scaling up securitisable green lending would ease banks' regulatory capital constraints by unlocking green finance for small and medium-sized businesses and projects that foster the transition (CBI, 2022). Furthermore, it has been estimated that just three asset classes of securitisable assets—residential mortgage loans on energy-efficient properties, loans for green home renovations, and electric-vehicle financing—could provide securitisable green lending exceeding EUR 300 billion annually by 2030 (AFME, 2022). However, in the organisations' view, the EU's current lack of a dedicated legislative framework for green securitisation is limiting the potential of these financial tools to support the low-carbon transition (AFME, 2022), while other green-label certifications explicitly applicable to securitised products are provided by international guidelines, including those from CBI (2024) and ICMA (2022).

[8] A contextual and preliminary framework for green finance promoted by the UK Government is outlined in the policy paper H. Treasury, 2021.

Table A.2: ESG Factors in Securitisation - EBA 06/22 Report

Aspect	Description
Collateral with Positive ESG Impact	The assets backing the transaction may include, in full or in part, collateral that positively impacts ESG factors, such as energy-efficient mortgages, electric auto loans/leases, or consumer loans to underserved borrowers.
Use of Proceeds or Capital Relief	The proceeds or the capital relief gained by the transaction (in cases of synthetic securitisation) are used to (re)finance, in full or in part, assets that have a positive impact on ESG factors.
Commitment to ESG-related KPIs	Key counterparties to the transaction (including the originator and the servicer) commit to achieving certain sustainability-related key performance indicators (KPIs), such as financial incentives for the originator upon meeting specified ESG targets.

In 2022, the European Banking Authority published a report mandated by the European Commission to explore the possibility of providing EU legislation with a dedicated framework for sustainability in the securitisation market, as the EU Taxonomy for Sustainable Activities has not been directly addressed to securitisation transactions (EBA, 2022). The EBA's response can be summarised in the following considerations:

- We can consider a securitized financial instrument 'green' when two intertwined criteria occur simultaneously:
  1. The collateral backing the transaction comprises 'green' assets (e.g., energy efficiency home refurbishment loans, green consumption credits, low-carbon energy projects).
  2. The raised proceeds are used exclusively to finance 'green' assets addressing the transition.
- Due to the low activity in the EU green securitisation market, the lack of sustainable assets to collateralise, and the limited attractiveness of such financial activities, it is premature to develop a dedicated framework.
- The EU Green Bond Standard can be applied to sustainable securitisation, with requirements including the use of proceeds, disclosures, and sanctions at the originator level instead of the SSPE[9], consistent with this transition phase.
- Green synthetic securitisation is not included in the prescription, as it is mainly a private market and affected by the difficulty of measuring and monitoring the use of proceeds.

On the third and last point, we recall that Synthetic ABS is the largest ABS issuance in the financial markets outside EU continent and differs from true-sale operations in that the originator does not transfer the ownership of the pool of loans but instead transfers the financial risks to an investor via the ABS structure. This allows the freeing of capital, which can be used for new green loans (CBI, 2022). Actually, the green securitisable issues in Europe, by type of asset,

[9]Securitisation special purpose entity: an objective-limited corporation responsible for carrying out the securitisation operations, separated from the originator of the assets underlying the ABS.

are mainly characterized by ABCP, CMBS, RMBS, and on-balance-sheet ABS[10](AFME, 2022). For these reasons, the EBA's wait-and-see approach in dedicating an appropriate framework to green securitisation, and more relevantly, leaving green synthetic securitisation outside the provisional guidance provided by the EuGBS, has left industry organizations disappointed. In doing so, they claim that it limits the environmental positive effects of a florid ABS market that are otherwise necessary to finance the low carbon transition. Accordingly, the EBA Report's suggestions have been finally adopted in the European Regulation n° 2023/2631 (EU, 2023). Table A.2 shows the ESG factors in securitisation, while Table A.3 displays a summary concerning the green label in the context of securitisation within the European legislative framework.

Table A.3: Eligibility and Transparency Requirements for European Green Bonds (EuGB) - EU Regulation 2023/2631

Category	**Requirements**
Eligibility	-Proceeds must be fully invested before maturity in sustainable economic activities covered by the EU Taxonomy (Regulation (EU) 2020/852) -Alternatively, proceeds can be allocated to a portfolio of fixed or financial assets in accordance with taxonomy requirements (portfolio approach). -Up to 15% of proceeds may be invested in economic activities meeting, but not officially covered by, taxonomy requirements under flexibility rules.
Transparency	Issuers must: - Complete the European green bond factsheet (Annex I) with pre-issuance approval from an external reviewer. - Provide an annual allocation report (Annex II) until proceeds are fully invested. - Obtain post-issuance reviews from an external reviewer. - Publish an environmental impact report (Annex III) at least once during the bond's lifetime. - Publish a prospectus in line with Regulation (EU) 2017/1129, using the term European green bond or EuGB (exceptions for sovereigns). - Make the factsheet, prospectus, reviews, and other relevant information freely available on their website for at least one year after bond maturity.

[10][From the European Banking authority Taxonomy] ABCP: (Re)financing trade receivables generated by companies transitioning to more sustainable business models, such as auto manufacturers, manufacturers of household equipment, or non-toxic cleaning products. CMBS: Mortgages to finance the acquisition or improvement of social or student housing, hospitals, community or educational centres; commercial rooftop solar energy loans. RMBS: Loans to (re)finance energy-efficient houses and/or to improve home energy consumption. On balance sheet ABS: Asset-Backed Securities that are hold in the originator balance sheet. (EBA, 2022)

D Time-step and Process of Events

D.1 List of events

The timeline of events occurring in the simulation is the same one that can be retrieved in Botta et al., 2025.

1. The level of production is set by the firm sector. Firms decide how much to produce by adjusting the previous period's desired production and the gap between demand and desired supply observed in the previous period.

2. The level of firm's production determines the level of employment. Nominal wages are then set according to a Phillips curve-type process. The dynamics of employment and wage inflation determine the total wage bill (W).

3. Employed households receive wages and pay taxes on them, while unemployed households receive a subsidy from the Gov't.

4. Financial payments take place. They includes:

   - Dividends from Commercial Bank and non-commercial firms of previous period are distributed according to the individual share of wealth stock on total in the current time span;
   - Interests on previous period households' and firms' 'conventional' and 'green' loans, both securitized and non-securitized;
   - Interests on the previous period's stock of public bonds in Bank and IF portfolios;
   - Repayment of a fixed portion (ϵ) of loan principals on households' loans;
   - Returns on ABSs ($f_{t-1}\text{ABS}_{t-1}$), equal to interests paid on the fraction z of loans securitized and bundled in such financial products;
   - Returns on IFs' shares ($r^s_{t-1} \cdot S^h_{t-1}$), which equal all interests received by IFs on their assets: ABSs and Public Bond;

5. Households default when they fail to pay back the sum of interest and principal on their debt stock and the exogenous level of subsistence consumption.

6. The portion of debt not repaid is computed as a non-performing loans (NPLs).

   The NPLs affect the balance sheets of other sectors through different transmission channels

   (a) Insolvent households are prevented to obtain credit for the next four periods (stigma process);

   (b) Missing principal repayments affect balance sheets of IFs and commercial banks according to the proportion of securitized (z) and non-securitized loans ($1-z$). In IFs' portfolios, this translates into a loss in the value of ABSs;

   (c) On the liability side, for IFs, the value of their shares (S^h) diminishes by the same amount as capital losses registered on ABSs. For commercial banks, the fraction of non-performing loans is matched by an equal reduction in banks' Own Funds (OF_B). In both cases, capital losses are ultimately borne by households holding financial wealth (either IF shares or bank equities);

(d) Returns on ABSs, and therefore IF shares, also decrease by the amount of missing interest payments on securitized loans;

7. Households set their desired level of consumption and financial asset holdings -deposits and IFs shares- thus defining their demand for credit as the difference between desired financial activities and savings.

8. Commercial banks set borrower-specific interest rates for individual households and non-financial firms, deciding whether to fully accommodate households' credit demand.

9. If households are rationed, they revise their plans through a pecking order process. They first scale down their demand and, if necessary, their holdings of shares, deposits and eventually cut consumption to the minimum subsistence level.

10. Public expenditure, 'conventional' and 'green' investments take place. The government purchases goods from non-financial firms, which in turn purchase capital goods from themselves.

11. The goods market clears. In the case of excess supply, surplus production is disposed, as no inventory is modelled. In the case of excess demand, rationing is proportional to the individual components of aggregate demand.

12. The government collects taxes and, if needed, issues bonds to finance the public deficit.

13. Financial assets: IFs purchase ABSs and public bonds, the latter also being bought by commercial banks.

14. The offer of 'conventional' and 'green' ABSs is demand-driven by households and provided by SPVs on request.

15. Commercial banks set the amount of retained earnings based on their regulatory capital needs.

16. The central bank sets the policy rate according to an inertial Taylor rule aimed at stabilizing inflation.

E Full list of Equations

E.1 Firm

$$X^L = X^L_{t-1} \cdot \left[\chi^L_1 + \chi^L_2 \cdot \left(\frac{Y^*_{D,t}}{Y^*_{D,t-1}} - 1 \right) \right] \tag{A.1}$$

$$Y^*_{D,t} = \frac{(C^*_t + p_t \cdot I^* + G^*)}{p_t} \tag{A.2}$$

$$X^K = \frac{[(X^K_c \cdot K_c) + (X^K_g \cdot K_g)]}{K_c + K_g} \tag{A.3}$$

$$Y^*_S = [Y^*_{S,t-1} + \upsilon_1 \cdot (Y^*_{D,t-1} - Y^*_{S,t-1}] \cdot (1 + \upsilon_2) \tag{A.4}$$

$$Y^{\text{MAX}}_K = K_{t-1} \cdot X^K \tag{A.5}$$

$$Y^{\text{MAX}}_L = \overline{N} \cdot X^L_t \tag{A.6}$$

$$Y^{\text{MAX}} = min[Y^{\text{MAX}}_K, Y^{\text{MAX}}_L] \tag{A.7}$$

$$Y_S = \begin{cases} Y^*_S & \text{if} \quad Y^*_S \leq Y^{\text{MAX}} \\ Y^{\text{MAX}} & \text{if} \quad Y^*_S > Y^{\text{MAX}} \end{cases} \tag{A.8}$$

$$N_t = \frac{Y_S}{X^L_t} \tag{A.9}$$

$$u_t = \frac{Y_S}{X^K K_{t-1}} \tag{A.10}$$

$$Un_t = \overline{N} - N_t \tag{A.11}$$

$$un_t = \frac{Un_t}{\overline{N}} \tag{A.12}$$

$$\omega_t = (\pi_{t-1}) \cdot \left[\frac{\omega_1}{\omega_2 + un_t} + \omega_3 \cdot \frac{X^L_t - X^L_{t-1}}{X^L_{t-1}} \right] \tag{A.13}$$

$$W_t = W_{t-1} \cdot \left[1 + \omega_t + \left(\frac{N_t}{N_{t-1}} - 1 \right) \right] \tag{A.14}$$

$$g_t^* = \gamma_1 + \gamma_2 \frac{\Pi_{t-1}}{Y_{t-1}} + \gamma_3 (u_{t-1} - u_N) \tag{A.15}$$

$$I_t^* = K_{t-1} \cdot g_t^* \tag{A.16}$$

$$I_t^* = K_{t-1} \cdot g_t^* \tag{A.17}$$

$$I_{green,t}^* = I_t^* \cdot \left(\alpha_1 + \alpha_2 \cdot \left(i_{brown,t-1}^f - i_{green,t-1}^f \right) \right) \tag{A.18}$$

$$I_{brown,t}^* = I_t^* - I_{green,t}^* \tag{A.19}$$

$$\begin{bmatrix} K_{green,t} \\ K_{brown,t} \end{bmatrix} = \begin{bmatrix} (1-\delta) & 0 \\ 0 & (1-\delta) \end{bmatrix} \begin{bmatrix} K_{green,t-1} \\ K_{brown,t-1} \end{bmatrix} + \begin{bmatrix} I_{green,t} \\ I_{brown,t} \end{bmatrix} \tag{A.20}$$

$$\mu_t = max \left(\mu_{\text{MAX}}, \mu_1 + \mu_{t-1} \cdot \frac{Y_{D,t-1}^*}{Y_{S,t-1}} \right) \tag{A.21}$$

$$p_t = \frac{W_t + i_{t-1}^f \cdot Lf_{t-1}}{Y_S} \cdot (1 + \mu_t) \tag{A.22}$$

E.2 Household

$$yd_{i,t} = w_{i,t} - tax_{i,t}^w + rsh_{t-1} \cdot Sh_{i,t-1} + Div_{i,t-1} - \widetilde{i_{i,t-1}^h \cdot Lh_{i,t-1}} \tag{A.23}$$

$$r_{i,t}^{sh} = \frac{z \cdot \left(r_{t-1}^f \cdot L_{f,t-1} + \sum r_{t-1} \cdot Lh_{i,t-1} \right) + i_{t-1}^b B_{IF,t-1}}{Sh_{t-1}} \tag{A.24}$$

$$tax_{i,t}^w = \begin{cases} \tau_1^w \cdot w_{i,t} & \text{if} \quad w_{i,t} < \hat{w}_{i,t} \\ \tau_1^w \cdot \hat{w} + \tau_2^w \cdot (w_{i,t} - \hat{w}_t) & \text{if} \quad w_{i,t} \geq \hat{w}_{i,t} \end{cases} \tag{A.25}$$

$$c_{i,t}^* = c_w \cdot (yw_{i,t}) + c_r \cdot [r^{sh} \cdot Sh_{i,t} + Div_{i,t} + c_{wealth} \cdot (NW_{I,T}) + c_n \cdot \overline{c}_{t-1}] \tag{A.26}$$

$$s_{i,t}^* = yd_{i,t} - c_{i,t}^* \tag{A.27}$$

$$Dh_{i,t}^* = \eta_H \cdot Wh_{i,t-1} \tag{A.28}$$

$$\Delta Dh_{i,t}^* = Dh_{i,t}^* - Dh_{i,t-1}^* \tag{A.29}$$

$$Sh^*_{i,t} = Sh^*_{i,t-1} \cdot \left[1 + \sigma\left(\frac{r^{sh}_{t-1} Sh_{i,t-1}}{Sh_{i,t-1}} - i^h_{i,t-1}\right)\right] \tag{A.30}$$

$$\Delta Sh^*_{i,t} = Sh^*_{i,t} - Sh_{i,t-1} \tag{A.31}$$

$$\Delta Lh^*_{i,t} = \Delta Dh^*_{i,t} + \Delta Sh^*_{i,t} - S^*_{i,t} \tag{A.32}$$

$$\text{if } m^*_{i,t} < \Psi_t \implies \begin{cases} \Delta L_{h_{i,t}} = \Delta Lh^*_{i,t} \\ \Delta S_{h_{i,t}} = \Delta Sh^*_{i,t} \\ \Delta D_{h_{i,t}} = \Delta Dh^*_{i,t} \\ c_{i,t} = c^*_{i,t} \\ WH_{i,t} = Dh_{i,t} + Sh_{i,t} \end{cases} \tag{A.33}$$

$$
\text{if } m^*_{i,t} > \Psi_t \implies Lh_{i,t} = 0 \implies \begin{cases}
\text{if } s^*_{i,t} > \Delta Dh^*_{i,t} \implies \begin{cases} \Delta Sh_{i,t} > 0 \\ \Delta Sh_{i,t} = s^*_{i,t} - \Delta Dh^*_{i,t} \\ \Delta Dh_{i,t} = \Delta Dh^*_{i,t} \\ c_{i,t} = c^*_{i,t} \end{cases} \\
\text{if } s^*_{i,t} < \Delta Dh^*_{i,t} \ \wedge \ s^*_{i,t} + Sh_{i,t-1} > \Delta Dh^*_{i,t} \implies \begin{cases} \Delta Sh_{i,t} < 0 \\ \Delta Sh_{i,t} = s^*_{i,t} - \Delta Dh^*_{i,t} \\ \Delta Dh_{i,t} = \Delta Dh^*_{i,t} \\ c_{i,t} = c^*_{i,t} \end{cases} \\
\text{if } s^*_{i,t} + Sh_{i,t-1} < \Delta Dh^*_{i,t} \ \wedge \ s^*_{i,t} + Sh_{i,t-1} > 0 \implies \begin{cases} Sh_{i,t} = 0 \\ \Delta Sh_{i,t} = -Sh_{i,t-1} \\ \Delta Dh_{i,t} > 0 \\ \Delta Dh_{i,t} = s^*_{i,t} + \Delta Sh_{i,t-1} \\ c_{i,t} = c^*_{i,t} \end{cases} \\
\text{if } s^*_{i,t} + Sh_{i,t-1} < 0 \ \wedge \ s^*_{i,t} + Sh_{i,t-1} + Dh_{i,t-1} > 0 \implies \begin{cases} Sh_{i,t} = 0 \\ \Delta Sh_{i,t} = -Sh_{i,t-1} \\ \Delta Dh_{i,t} < 0 \\ \Delta Dh_{i,t} = s^*_{i,t} + Sh_{i,t-1} \\ c_{i,t} = c^*_{i,t} \end{cases} \\
\text{if } s^*_{i,t} + Sh_{i,t-1} + Dh_{i,t-1} < 0 \implies \begin{cases} Sh_{i,t} = 0 \\ \Delta Sh_{i,t} = -Sh_{i,t-1} \\ \Delta Dh_{i,t} = 0 \\ \Delta Dh_{i,t} = -Dh_{i,t-1} \\ c_{i,t} \geq \tilde{c} \\ c_{i,t} = yd_{i,t} + Sh_{i,t-1} + Dh_{i,t-1} \end{cases}
\end{cases} \tag{A.34}
$$

E.3 Government and Central Bank

$$
G_t = \xi_1 \cdot G_{t-1} + (1 - \xi_1) \cdot \xi_2 \cdot C_t \tag{A.35}
$$

$$
T_t = \tau_\pi \cdot \Pi_t + \sum_{i=1}^{N} \tau_i^w w_{i,t} + \sum_{i=1}^{N} \tau_i^{WH} WH_{i,t-1} \tag{A.36}
$$

$$
\Delta GD_t = G_t + dole \cdot [\overline{N} - N_t] + i^b_{t-1} \cdot GD_{t-1} - T_t \tag{A.37}
$$

$$i_t^b = i_{t-1}^b \cdot \left[1 + \alpha \left(\frac{B_{B,t}}{GD_t} - \frac{B_{B,t-1}}{GD_{t-1}}\right)\right] \tag{A.38}$$

$$i_t^T = \rho \cdot i_{t-1}^T + (1-\rho) \cdot \{\pi_t + \rho_\pi \cdot [\pi_t - \pi^T]\} \tag{A.39}$$

$$i_{i,t}^{e,h} = i_{t-1}^T + \iota_h \cdot i_{t-1}^T \cdot \frac{Lh_{i,t-1} + \Delta Lh_{i,t}^*}{yn_{i,t}} \tag{A.40}$$

$$i_{i,t}^f = i_{t-1}^T + \iota_f \cdot i_{t-1}^T \cdot \frac{Lf_{i,t-1} + \Delta Lf_{i,t}^*}{Pf_t} \tag{A.41}$$

$$mh_{i,t}^* = i_{i,t}^{e,h} \cdot \frac{Lh_{i,t-1} + \Delta Lh_{i,t}^*}{yn_{i,t}} \tag{A.42}$$

$$\Psi_t = max[\Psi_{min}, min(\Psi_{max}, \Psi^*)] \tag{A.43}$$

$$\Psi^* = \overline{\Psi}_{min} - \psi_1 \cdot \frac{NPL}{\epsilon \cdot Lh_{t-1}} + \psi_2 \cdot (k_{B,t} - \overline{k}) \tag{A.44}$$

$$k_{B,t} = \frac{\tilde{\Omega}_{t-1}^B}{(1-z_t) \cdot \left(L_{h,t}^{green} + L_{h,t}^{brown} + L_{f,t}^{green} + L_{f,t}^{brown} + B_{B,t}\right)} \tag{A.45}$$

$$\tilde{\Omega}_t^B = \Omega_t^B - (1-z_{t-1}) \cdot NPL_t \tag{A.46}$$

$$\text{if } mh_{i,t}^* < \Psi_t \text{ then } \begin{cases} i_{i,t}^h = i_{i,t}^e \\ \Delta Lh_{i,t} = \Delta Lh_{i,t}^* \end{cases} \tag{A.47}$$

$$P_t^B = \Pi_t^b (1 - \tau_\pi) \tag{A.48}$$

$$\Delta\overline{\Omega} = [(1-z)L_t + B_{B,t}] \cdot \overline{k} \tag{A.49}$$

$$\Delta\Omega_t^* = \begin{cases} \text{if } k_{B,t} < \overline{k} \implies \Delta\Omega_t^* = \zeta_B \cdot (\overline{\Omega}_t^B - \Omega_{t-1}^B) \\ \text{if } k_{B,t} \geq \overline{k} \implies \Delta\Omega_t^* = 0 \end{cases} \tag{A.50}$$

$$\text{if } \Delta\overline{\Omega} \leq P_t^B \implies \begin{cases} \Omega_t = \Omega_{t-1} + \Delta\Omega_t^* \\ Div_B = P_t^B - \Delta\Omega_t^* \end{cases} \tag{A.51}$$

$$\text{if } \Delta\overline{\Omega} > P_t^B \implies \begin{cases} \Omega_t = \Omega_{t-1} + P_t^B \\ Div_B = 0 \end{cases} \tag{A.52}$$

$$B_{B,t} = GD_t - B_{IF,t} \tag{A.53}$$

$$RL^h_{B,t}t = \sum_{i=1}^{N}(1 - z_{t-1}) \cdot [i^h_{i,t-1} \widetilde{\cdot Lh_{i,t-1}}] \tag{A.54}$$

$$RL^f_{B,t} = (1 - z_{t-1}) \cdot [i^f_{t-1} \cdot Lf_{t-1}] \tag{A.55}$$

$$RB_{B,t} = i^b_{t-1} \cdot B_{B,t-1} \tag{A.56}$$

$$\Pi_{B,t} = RL^h_{B,t} + RL^f_{B,t} + RB_{B,t} \tag{A.57}$$

$$ABS_{if,t} = z_t \cdot \sum_{i=1}^{N} Lh_{i,t} + z_t \cdot Lf_t \tag{A.58}$$

$$z_t = \min\left(1, \frac{ABS^D_{IF}}{L^{green}_{h,t} + +L^{brown}_{h,t} + L^{green}_{f,t} + L^{brown}_{f,t}}\right) \tag{A.59}$$

$$r^{abs}_t = \frac{z_t \left[\left(\sum_{i=1}^{N} i^h_{i,t-1} \widetilde{\cdot Lh_{i,t-1}}\right) + i^f_{t-1} Lf_{t-1}\right]}{ABS_{if,t-1}} \tag{A.60}$$

E.4 Investment Funds and Special Purpose Vehicle

$$D_{IF,t} = \eta_{IF} \cdot Sh_t \tag{A.61}$$

$$q^b_{if,t} = q^b_{if,t-1} \cdot \{1 - \beta[(r^{abs}_t - i^B_t) - (r^{abs}_{t-1} - i^B_{t-1})]\} \tag{A.62}$$

$$B^D_{IF,t} = q^b_{if,t} \cdot (1 - \eta_{IF}) \cdot Sh_t \tag{A.63}$$

$$ABS^{*D}_{IF,t} = Sh_t \cdot (1 - \eta_{IF}) - B_{IF,t} \tag{A.64}$$

$$ABS^*_{IF,t} = min(z_t L_t, ABS^{*D}_{IF,t}) \tag{A.65}$$

$$RABS_{IF,t} = r^{abs}_{t-1} \cdot ABS_{t-1} \tag{A.66}$$

$$RB_{IF,t} = i^B_{t-1} \cdot B_{IF,t-1} \tag{A.67}$$

$$RSH_t = RABS_{IF,t} + RB_{IF,t} \tag{A.68}$$

$$r_{i,t}^{sh} = RSH \cdot \frac{sh_{i,t-1}}{SH_{t-1}} \tag{A.69}$$

$$\text{rent}_i = \begin{cases} \mu_2 \cdot yw_{i,t}, & \text{if household } i \text{ has income} \\ \mu_3 \cdot \text{dole}_i, & \text{if household } i \text{ has no income} \end{cases} \tag{A.70}$$

$$hw_{i,t} = H \cdot P_{t-1} \left(1 + \varepsilon_t^H\right), \tag{A.71}$$

$$r_{i,t}^{house} = \text{RENT} \cdot \frac{hw_{i,t-1}}{HW_{t-1}} \tag{A.72}$$

,

$$wealth_{i,t} = Dh_{i,t}^* + Sh_{i,t}^* + hw_{i,t} \tag{A.73}$$

$$nw_{i,t} = wealth_{i,t} - Lh_{i,t} + hCG_{i,t} \tag{A.74}$$

F Stock-Flow Consistency and Revaluation Tables

	Households	Banks	SPVs	IFs	Firms	Gov't	Total
Deposits	$+D_H$	$-D$			$+D_F$		0
Conventional Capital					$+K_c$		$+K_c$
Green Capital					$+K_g$		$+K_g$
Shares	$+Sh$			$-Sh$			0
Bonds		$+B_B$		$+B_{IF}$		$-B$	0
Conventional Loans	$-L_c h$	$+(1-z)L_c$	$+zL_c$		$-L_c f$		0
Green Loans	$-L_g h$	$+(1-x)L_g$	$+xL_g$		$-L_g f$		0
Conventional Derivatives			$-ABS_c$	$+ABS_c$			0
Green Derivatives			$-ABS_g$	$+ABS_g$			0
Own Funds	$+OF$	$-OF_B$			$-OF_F$		0

Table A.4: Aggregate Balance Sheet Matrix (BS)

	Households	Banks	SPVs	IFs	Firms	Gov't	Σ
Own Funds Firms	$+\Delta OF_f$				$-\Delta OF_f$		0
Own Funds Banks	$+\Delta OF_b$	$-\Delta OF_b$					0
Fixed Capital					$+\Delta p \cdot k_{t-1}$		$+\Delta p \cdot k_{t-1}$
Dwelling	$+\Delta p \cdot h_{t-1}$						$+\Delta p \cdot h_{t-1}$

Table A.5: Aggregate Revaluation Matrix (RM)

	Households	**Firms**		**Banks**		**SPV**		**IFS**		**Gov't**	Σ
		CA	KA	CA	KA	CA	KA	CA	KA		
Consumption	$-C$	$+C$									0
Investment		$+I$	$-I$								0
Green Investment		$+I_g$	$-I_g$								0
Public Expenditure		$+G$								$-G$	0
Taxes	$-T_h$	$-T_f$		$-T_b$						$+T$	0
Wages	$+W$	$-W$									0
Dole	$+dole$									$-dole$	0
Interest on Loans	$-i_{hL_h,t-1}$	$-i_{fL_f,t-1}$		$+i(1-z)L,t-1$		$+izL,t-1$					0
Interest on Green Loans		$-i_{gfL_gf,t-1}$		$+i(1-z)L_{gf,t-1}$		$+izL_{gf,t-1}$					0
Return on Derivatives						$-fABS,t-1$		$+fABS,t-1$			0
Return on Green Derivatives						$-fABS_g,t-1$		$+fABS_g,t-1$			0
Return on Share	$+r_{sS_h}$							$+r_{sS_h}$			0
Interest on Bonds				$+r_{bB_b,t-1}$				$+r_{bB_if,t-1}$		$-i_{bB}$	0
Dividends	$+Div$	$-Div_f$		$-Div_b$							0
Profits		$-\pi_f$	$+\pi_f$	$-\pi_b$	$+\pi_b$						0
Deposits	$-\Delta D_h$		$-\Delta D_f$		$+\Delta D$				$-\Delta D_{if}$		0
Loans	$+\Delta L_{h,c}$		$+\Delta L_f$		$-\Delta(1-z)L$		$-\Delta zL$				0
Green Loans	$+\Delta L_{h,g}$		$+\Delta L_gf$		$-\Delta(1-z)L_g$		$-\Delta zL_g$				0
Derivatives							$+\Delta ABS$		$-\Delta ABS$		0
Shares	$-\Delta S_h$								$+\Delta S_{if}$		0
Bonds					$-\Delta B_b$				$-\Delta B_{if}$	$+\Delta B$	0
Loans Defaults	$+NPL$				$-NPL$						0
Total	0	0	0	0	0	0	0	0	0	0	0

Table A.6: Transaction Flow Matrix (TFM)

G Parameters

Table A.7: Baseline Parameter of the model, source: Botta et al., 2025

Symbol	***Description***	***Baseline***
$\alpha 1$	Autonomous component in green gross investment share on total	0.005-0.045
$\alpha 2$	Sensitivity of Green capital share in green gross investment share on total	23.9
$\alpha 3$	Sensitivity to interest rate differential on green gross investment share on total	3.5
α	Sensitivity in public bonds' interest rate setting	0.01
β	Weight of CDO-bond spread in IF portfolio allocation	100
β_g	Exogenous quota of green investments	0.1
γ_1	Autonomous component desired capital growth	0.1
γ_2	Sensitivity to profit rate, capital growth	0.1
γ_3	Sensitivity to capacity utilization share, capital growth	0.3
δ	Capital depreciation rate	0.1
ϵ	Quota of the principal, debt service	0.1
ζ_B	Rate of adjustment, banks' own capital	0.1
η_F	Firms desired deposits to capital ratio	0.25
η_H	Precautionary deposit propensity of households	0.25
η_{IF}	Investment funds desired deposits, quota of wealth	0.25
θ	Log-standard deviation (wage distribution)	0.5
ι_f	Sensitivity to the debt service ratio, Firms interest rate setting	0.03
ι_h	Sensitivity to the debt service ratio, HH interest rate setting	0.3
μ_1	Autonomous mark-up on costs (price determination)	0.015
μ_{MAX}	Ceiling mark-up on costs (price determination)	0.025
μ_2	Rent share on disposable income (employed)	0.2
μ_3	Rent share on dole (unemployed)	0.2
ξ_1	Sensitivity to previous gov't consumption (public purchases)	0.9

Symbol	***Description***	***Baseline***
ξ_2	Sensitivity to previous aggregate consumption (public purchases)	0.1
π^t	Inflation threshold	0.4
ρ	Degree of 'gradualism', interest rate target setting	0.8
ρ_π	Sensitivity to inflation gap, interest rate target setting	0.8
σ	Sensitivity to return on share w.r.t. base rate spread, household portfolio choice	5
τ_1^w	Tax rate on lower income	0.2
τ_2^w	Tax rate on higher income	0.45
υ_1	Sensitivity to production gap, firms desired supply	0.5
υ_2	Expected production autonomous growth	0.05
ϕ	Threshold recursive process, interest rate setting	0.01
χ_1^L	Productivity autonomous growth	0.003
χ_2^L	Demand-led productivity growth	0.05
ω_1	Wage inflation sensitivity to unemployment (numerator)	0.005
ω_2	Wage inflation sensitivity to unemployment (denominator)	0.05
ω_3	Wage inflation sensitivity to labour productivity	0.5
Ψ_{max}	Lower limit, threshold for debt service ratio	0.05
Ψ_{min}	Upper limit, threshold for debt service ratio	0.333
ψ_1	Sensitivity to NPI (threshold for debt service ratio)	1
ψ_2	Sensitivity to distance from regulatory limits (threshold for debt service ratio)	0.3
c_n	Socially determined propensity to consume	0.3
c_r	Propensity to consume out of financial income	0.2
c_w	Propensity to consume out of net wage income	0.65
c_{wealth}	Propensity to consume out of wealth	0.022
$\overline{k}$	Regulatory limit for leverage	0.08
u_t	Capacity Utilization	0.8

H Baseline vs Green Scenario



Figure 9: Real Economy and Activity. Median and 5–95% confidence bands from 200 Monte Carlo simulations of the Baseline (BS) and the Green Transition (GT) scenarios, reporting real GDP growth, unemployment, investment intensity, and capacity utilisation after the burn-in period.

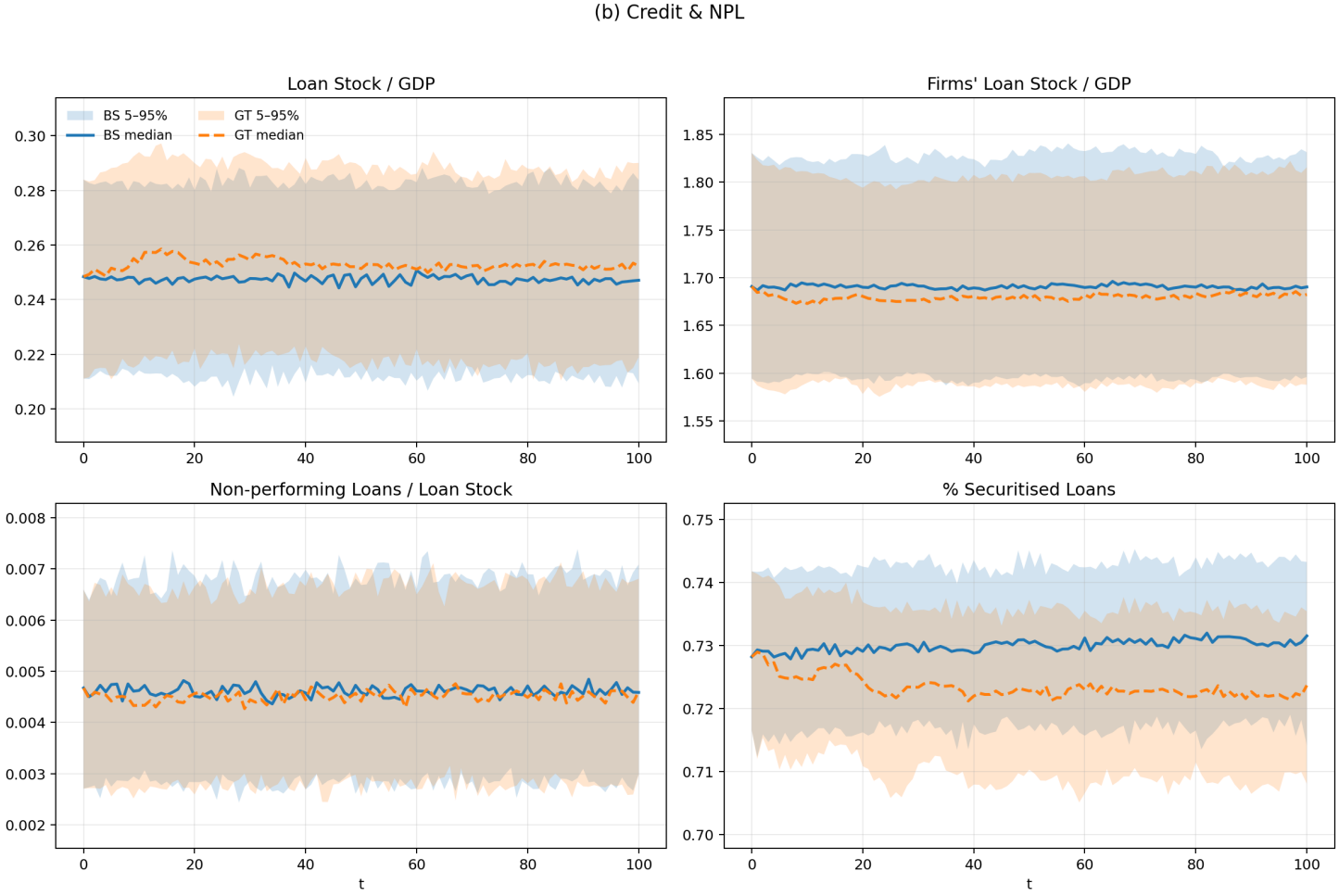


Figure 10: Credit and Non-Performing Loans. Median and 5–95% confidence bands from 200 Monte Carlo simulations of the Baseline (BS) and the Green Transition (GT) scenarios, reporting the evolution of household and firm loan stocks relative to GDP, total non-performing loans in the economy, and the share of securitised loans after the burn-in period.

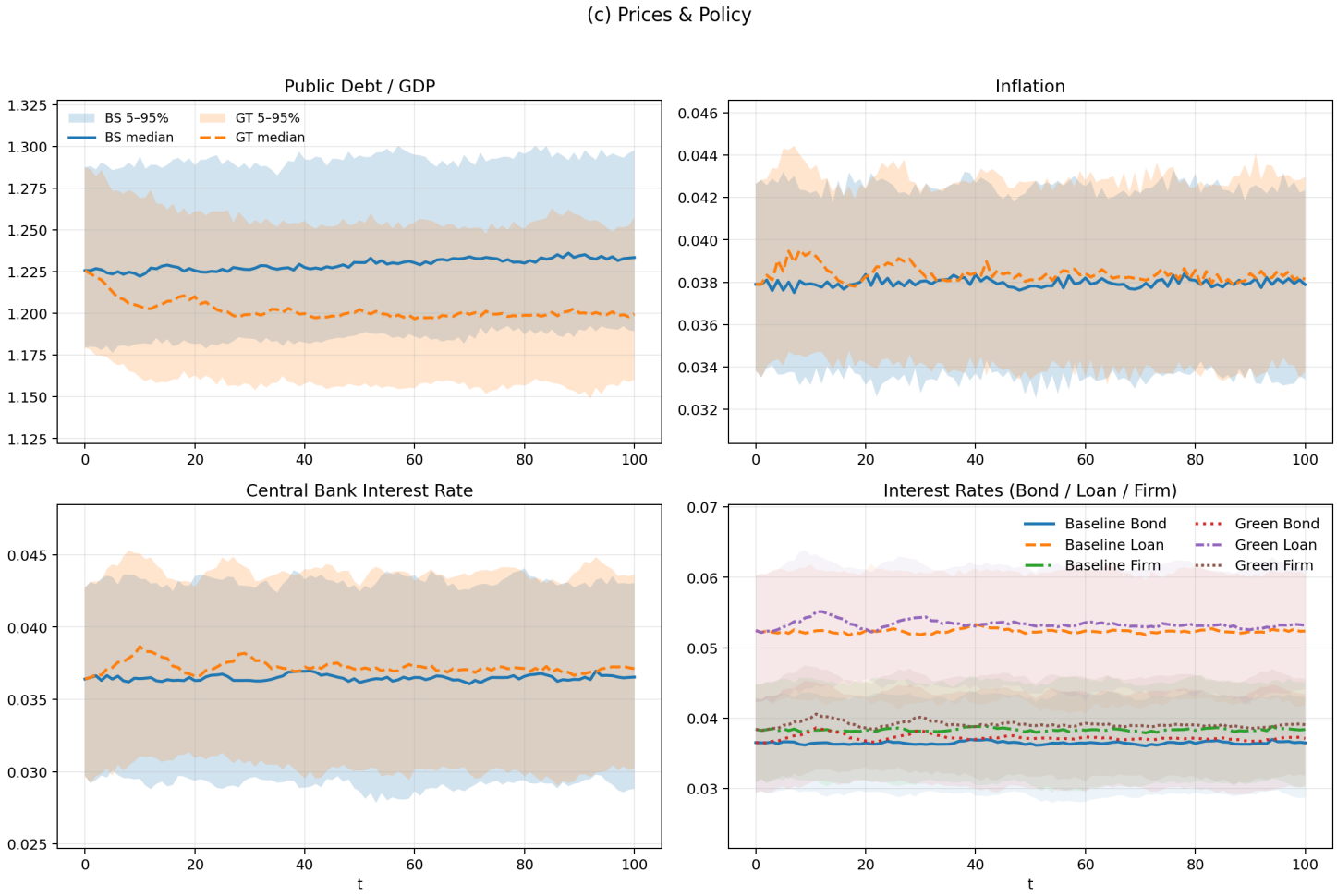


Figure 11: Prices and Policy. Median and 5–95% confidence bands from 200 Monte Carlo simulations of the Baseline (BS) and the Green Transition (GT) scenarios, reporting public debt relative to GDP, inflation, the policy interest rate, and interest rates on household loans, firm loans, and public bonds after the burn-in period.

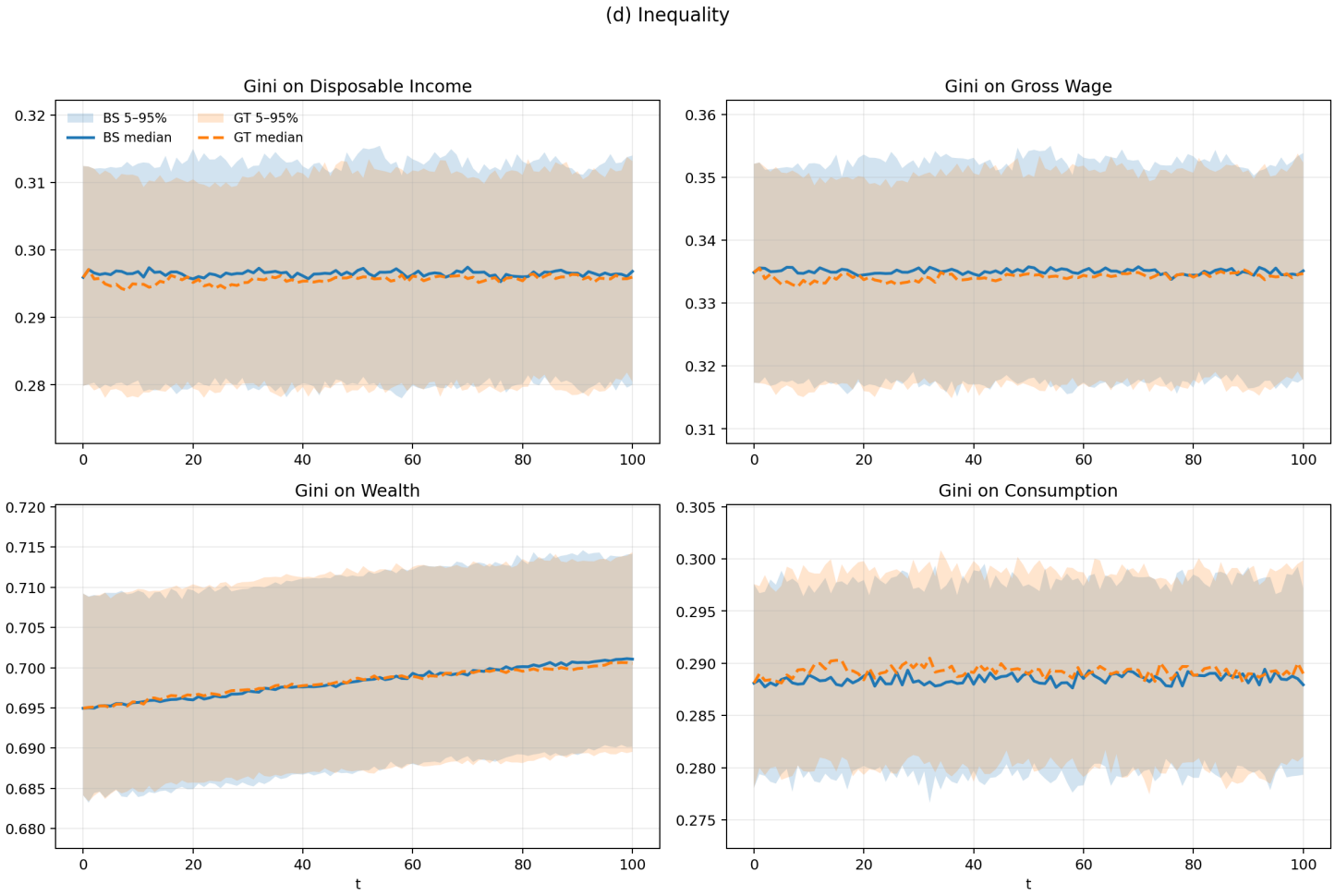


Figure 12: Inequality. Median and 5–95% confidence bands from 200 Monte Carlo simulations of the Baseline (BS) and the Green Transition (GT) scenarios, reporting the Gini coefficients for disposable income, gross wages, wealth, and consumption after the burn-in period.

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Do Climate Policies exacerbate Income Inequality?

Evidence from an IV-Local Projections Approach across 29 OECD Countries

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February 21, 2026

Preliminary work, please do not circulate without author permission

Abstract

This paper investigates the distributive effects of climate change mitigation policies across a panel of 29 OECD countries over the period 1990–2020. We estimate the dynamic impact of a shock to the OECD Environmental Policy Stringency (EPS) Index on multiple income inequality indicators from the World Income Inequality Database. To address potential endogeneity in policy adoption, we employ the Instrumental Variables Local Projections (IV-LPs) method. Our study contributes to the emerging literature on the macroeconomic consequences of climate action in two main ways. First, building on recent evidence regarding the role of institutions in enabling effective climate policies, we propose an innovative instrument based on climate-related speeches by global central banks, combined with country-specific institutional characteristics. Second, the results show that the distributional effects of environmental policy are highly heterogeneous across policy types. We find that climate action in the form of market-based policy leads to regressive, although short-lived, outcomes, while technological support policies, namely public research and development (R&D) expenditure and renewable energy supports, are able to generate positive redistributive effects while also ensuring a stable outlook for employment and the wage share, with gradual long-term improvements in women's participation in the labour market, thus fostering a "just" socio-economic transition.

Keywords: Climate Change; Mitigation Policy; Just Transition; Income Inequality; IV Local Projections.
JEL codes: C33, D63, E25, Q58.

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1 Introduction

The entire world is at a crossroads. The severe and growing material impacts of global warming demand urgent, rapid and coordinated global climate action. The last COP29 reiterated the ambitious Paris 2015 Agreement Article 2 Target of pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels (UNFCCC, 2024). However, the effective achievement of this goal is under threat, as the World Meteorological Organization defines January–September 2024 as the hottest period ever recorded, with an average temperature of 1.54 °C (±0.13) above pre-industrial levels (WMO, 2024). Meanwhile, global climate targets and action risk being too little and too late, with a 'weakening' outlook in the GHG emissions reduction pledges by 2030 (Climate Action Tracker, 2025).

Given this context of urgency, there is growing attention in academia, institutions, and policymaking bodies to understanding the impacts of climate policies, ensuring that they are both effective in preventing biodiversity loss and reducing GHG emissions, and equitable in supporting a fair societal transition. Recent literature has increasingly focused on the concept of a "just transition" (McCauley & Heffron, 2018), emphasising the fair distribution of the economic gains associated with the low-carbon transition (Vona, 2023), the preservation of high and stable wage shares and employment levels (García-García et al., 2020; Wang & Lo, 2021), the protection of vulnerable income groups, and the promotion of social responsibility in allocating environmental costs (Galanis et al., 2025).

Alongside theoretical framing, several contributions have argued that existing levels of income inequality, and not only the expected distributional effects of climate policies (Markkanen & Anger-Kraavi, 2019), may represent a major constraint on the public acceptance of climate action (Vona, 2023). As a result, recent literature has increasingly focused on providing empirical evidence on how the adoption of climate policies affects personal income inequality and distribution (Alexandri et al., 2024; Bettarelli et al., 2024; Brzezinski & Kaczan, 2025; Cevik & Jalles, 2023; Känzig, 2023; Metcalf & Stock, 2023). The final aim is to inform policymakers of potential asymmetric drawbacks, where present, and to support the design of coherent and socially sustainable climate policy frameworks.

The present work aims to contribute to the current debate by examining the effects of climate policy adoption on personal income distribution, as well as the transition channels at play, over a panel of 29 OECD countries ranging 1990–2020 and drawing on the latest release of the World Income Inequality Database (WIID) by UNU-WIDER (UNU-WIDER, 2025). More specifically, we seek to advance the literature in two main core directions.

First, from a methodological standpoint, we employ the expanding Instrumental Variable Local Projections (IV-LPs) framework (Jordà & Taylor, 2025; Jordà et al., 2015; Stock & Watson, 2018) and propose a novel instrument to identify shocks in the adoption of green policies. This instrument relies on the pivotal role of institutions and governance in mediating the relationship between climate change and the effective implementation of climate action (Campiglio et al., 2025; Jourde et al., 2025; Nohrstedt & Parker, 2024; Nohrstedt et al., 2021; Raikes et al., 2022b; Rowan, 2023), rather than on extreme events, exploiting global central bank climate speeches.

Secondly, from an empirical standpoint, we find that environmental policy affects income inequality in markedly different ways: while aggregate measures appear broadly progressive, their components diverge sharply, with market-based and non-market regulations showing negative transitory redistributive patterns. Moreover, we find that technological support policies, namely public research and development (R&D) expenditure and targeted support for solar and wind energy, as proxied by the OECD EPS Technological measure, can contribute to climate mitigation while also promoting a 'just' socio-economic transition. Improvements in income inequality indicators (Gini, Palma, S80/S20 indices, and income shares by quantile group) are consistent with evidence from three main macroeconomic transmission channels: (i) functional income distribution, reflected in a stable labour share captured by the adjusted wage share; (ii) labour market slack, measured by the unemployment rate and employment levels, and (iii) employment composition, with broader participation and greater inclusion of female workers during the low-carbon transition.

The structure of the paper is as follows. Section 2 presents a brief review of recent contributions employing similar macro-

econometric approaches or addressing related topics. Section 3 describes the main variables collected in the dataset. Section 4 outlines the proposed instrumental-variable approach and the methodology based on IV–Local Projections. Section 5 presents the main results, the transmission channels, and their discussion. Finally, Section 6 concludes and highlights the limitations, avenues for future research, and operational implications for policymakers.

2 Literature Review

The empirical literature examining the macroeconomic effects of climate policies on income inequality is at an early stage and remains the subject of growing interest. Recent contributions, however, offer nuanced and often mixed results rather than a clear emerging narrative. Among the latest studies, Bettarelli et al. (2024), analysing 39 high- middle- and low-income countries over 1990–2020 using a Instrumental Variable Local Projections (IV-LPs) approach, finds that climate-policy implementation has significant and persistent effects on key inequality indicators, with stronger impacts in countries characterised by a larger share of low-educated workers and higher initial inequality. In partial contrast, Brzezinski and Kaczan (2025) find no statistically significant effect of carbon-tax introduction on income inequality or poverty across 30 European countries between 1980 and 2018, although they document a positive effect on consumption inequality for the bottom 20 per cent of the distribution, amounting to an improvement of roughly four percentage points. Abbas and Kopp (2025), using a panel GMM model, examine the distributional effects of environmental policy adoption across 20 European countries over 32 years. Their results indicate that higher climate-policy stringency is associated with increased pre-tax and post-tax income inequality, disproportionately affecting lower-income groups. Känzig (2023), employing a semi-structural VAR model identified with high-frequency policy news, investigates the role of carbon pricing in Europe and finds that a restrictive shock reduces GHG emissions but at the cost of lower economic activity and higher energy prices, thereby placing a greater burden on poorer households. By contrast, Metcalf and Stock (2023), using a Local Projections framework, reports zero to modest positive effects on GDP and employment following the adoption of carbon taxes in Europe over the past three decades. It is also reported in Cevik and Jalles (2023), who employ a VAR model with a dataset covering 158 countries, that climate-change vulnerability is positively associated with income inequality. Their estimates show a substantially larger and highly significant coefficient for developing economies, reflecting their limited adaptive and mitigation capacity. The transmission channels highlighted in this literature include macroeconomic activity, aggregate and sectoral employment, and energy-price dynamics arising from the low-carbon structural transition, each offering a different perspective on the distributional consequences of climate policy.

Taken together, these mixed results highlight the importance of identification approaches capable of credibly isolating policy shocks from the economic and social conditions shaping inequality. The variation in findings partly reflects differences in inequality data sources, empirical methodologies, and country coverage.

3 Data

This paper uses an unbalanced panel dataset covering 29 OECD countries[1] over the period 1990–2020. The dataset combines information from three publicly available sources: the OECD, the World Income Inequality Database (WIID), and the World Bank.

As a proxy for the stringency of each country's climate policy, we use the Environmental Policy Stringency (EPS) Index developed by the OECD, which ensures comparability across the countries in our sample and has been widely adopted in the literature since its initial release in 2014 (Botta & Koźluk, 2014). In 2022, the index underwent a major revision and now covers 40 countries over the period 1990–2020, encompassing 13 distinct climate-policy instruments (Kruse et al., 2022). The EPS ranges from 0 to 6 and is

[1] Countries were selected on two grounds: (1) ensuring broad comparability in terms of economic structure, based on the World Bank's 2020 income classification https://blogs.worldbank.org/en/opendata/world-bank-country-classifications-by-income-level-for-2024-2025; and (2) the availability of income-inequality and distributional data in the WIID database expressed in 2021 PPP-adjusted USD, allowing correct international comparability.

composed of three equally weighted sub-indices:

- **Market-based policies**, including pollution taxes, tradable permits, and certificate systems;
- **Non-market-based policies**, such as emissions standards in the power-generation sector;
- **Technology-support policies**, covering R&D subsidies, feed-in tariffs, and auction-based support for renewable electricity generation (notably solar and wind).

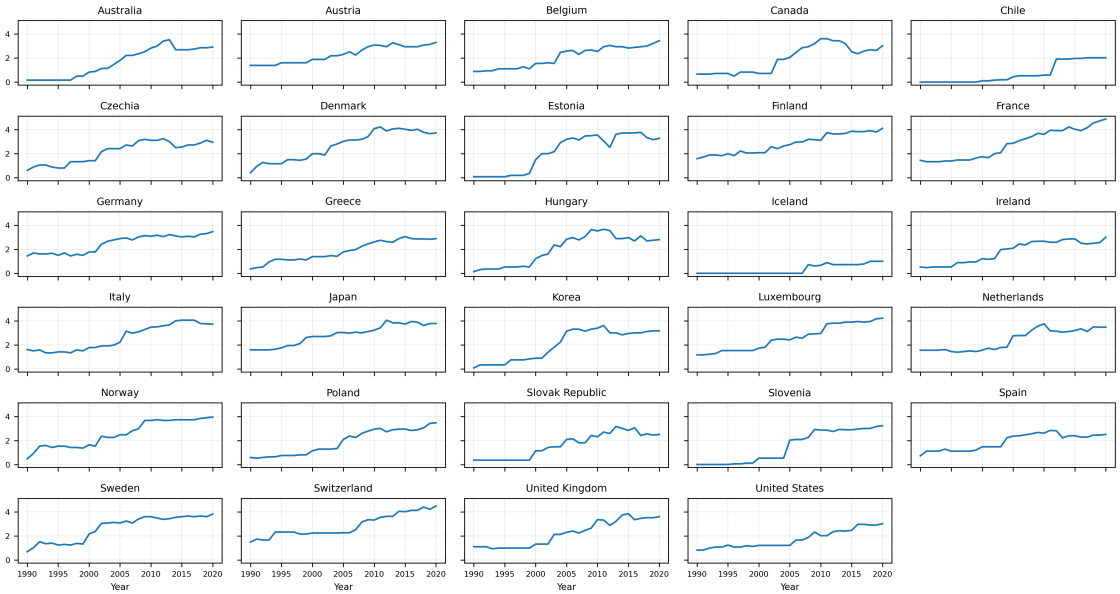
Figure 1a reports the country-specific evolution of the aggregate EPS index over the three decades considered. The figure shows a broadly common upward trajectory in policy stringency, although this rise has slowed in the past decade. Further insights into this recent flattening can be drawn from Figure 1b, which plots countries' average values for each EPS sub-index. The stagnation in the aggregate measure appears largely driven by a decline in technology-based support for low-carbon energy production beginning in 2011, represented by the green solid line. As noted by Kruse et al. (2022), this development may reflect the fiscal consolidation that followed the 2008 Global Financial Crisis, when many governments scaled back support for clean technologies after an initial phase of expansionary intervention.

Data on income inequality and distribution are retrieved from the World Income Inequality Database (UNU-WIDER, 2025), recently updated in a new version released on 29 April 2025, which provides the most comprehensive coverage available, spanning 201 countries. In our analysis, we employ three principal indices and income-distribution shares, all expressed in net per-capita income in 2021 PPP-adjusted USD, for international comparability. The Gini index measures the extent to which the income distribution within a country deviates from perfect equality, ranging from 0 (complete equality) to 100 (maximum inequality). The Palma ratio compares the income share of the top 10 per cent to that of the bottom 40 per cent, while the S80/S20 ratio compares the top 20 per cent to the bottom 20 per cent. To capture changes across the entire income distribution, we also include measures of net-income shares held by the bottom 40 per cent and top 5 per cent, as well as quantiles shares. These indicators allow for a more comprehensive assessment of distributional dynamics and help disentangle how different segments of the income distribution respond to climate-policy shocks.

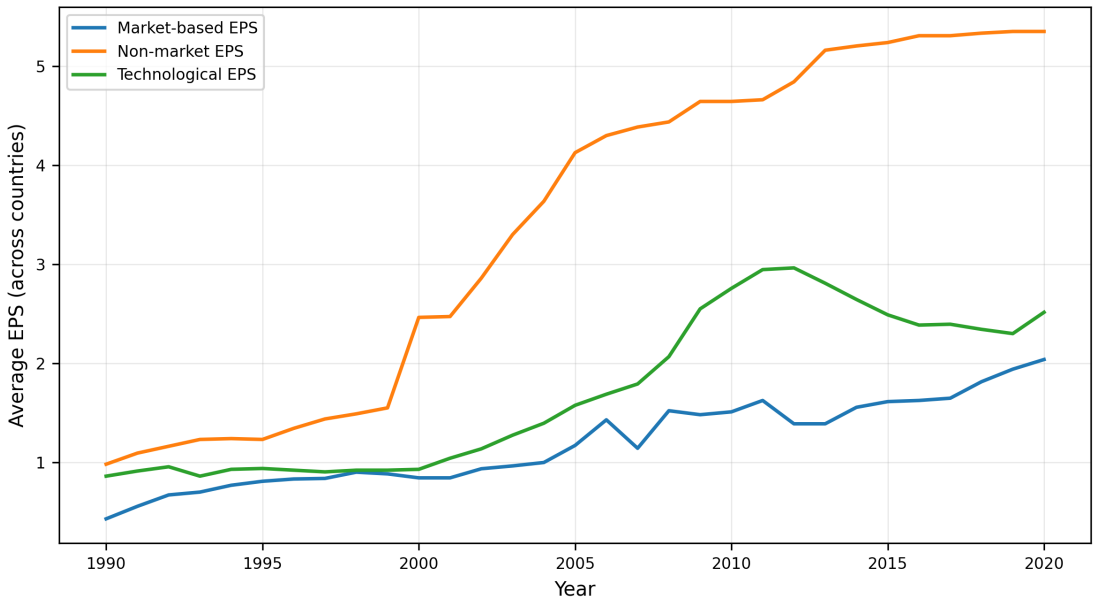
Finally, we draw on World Bank statistics to obtain data for covariates, including the unemployment rate, real GDP growth, and the inflation rate. Table 3.1 presents descriptive statistics for the main variables related to climate policy and income inequality and distribution. A full description of all variables, along with qualitative discussion and detailed data documentation, is provided in the Appendix A.3.

Table 3.1: Main Climate Policy and Income Inequality and Distribution Variables Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max	Source
Climate Policy						
EPS Index	434	2.496928	1.045843	0	4.888889	OECD
Market-based EPS	434	1.384793	0.9001549	0	4.166666	OECD
Non-market EPS	434	4.09735	1.716951	0	6	OECD
Technology-based EPS	434	2.008641	1.373332	0	6	OECD
Income Inequality and Distribution						
Gini Index	434	32.37834	5.155361	20.19	54.96	WIID
Palma Ratio	434	1.298018	0.4633055	0.69	4.19	WIID
S80/S20 Ratio	434	5.590737	2.006112	2.75	17.72	WIID
Bottom 5% income share	434	1.073226	0.3207169	0.22	2.24	WIID
Bottom 40% income share	434	20.34779	2.645168	10.61	27.32	WIID
Top 5% income share	434	15.84894	2.984403	10.39	32.02	WIID



(a) Average total EPS index across countries, 1990–2020.



(b) Average sub-indices of the EPS: market-based, non-market-based, and technology support policies.

Figure 1: Environmental Policy Stringency (EPS) index: Total (Panel a) and sub-components averages (Panel b) across countries in the dataset.

4 Methodology

What are the effects of climate-change policy on income inequality and distribution? Before addressing this question and presenting the results, this section discusses a central contribution of the paper: the development of a new identification strategy for climate-policy shocks. The challenge is straightforward. Robust estimates require dealing with endogeneity concerns, particularly those arising from unobserved variables and reverse causality. Country-specific inequality and macroeconomic conditions may influence the adoption of ambitious climate policies, partly because governments may fear that such measures could worsen distributive outcomes (Markkanen & Anger-Kraavi, 2019).

4.1 An(other) instrument in the band

To address the previous point, we adopt an Instrumental-Variables Local Projections approach (Jordà, 2005; Jordà & Taylor, 2024, 2025). This framework is particularly valuable in contexts where the observed variables may be driven by multiple structural shocks hitting the economy, and IV-LPs remain robust because they rely on an external instrument. According to Stock and Watson (2018), identification of the structural impulse response in IV-Local Projections requires the following conditions:

1. **Relevance**
$$\mathbb{E}\Big[\, u_{1,t}^{\perp}\, z_t^{\perp} \Big] = \alpha \neq 0,$$
i.e. the instrument must be correlated with the targeted structural shock (i.e. ΔEPS).

2. **Contemporaneous exogeneity**
$$\mathbb{E}\Big[\, u_{2:n,t}^{\perp}\, z_t^{\perp} \Big] = 0,$$
meaning that the instrument must be uncorrelated with non-target structural shocks at time t and must not have a direct effect on the outcome variable (i.e. measures of inequality and income distribution).

3. **Lead-lag exogeneity**
$$\mathbb{E}\Big[\, u_{t-j}^{\perp}\, z_t^{\perp} \Big] = 0 \qquad \forall\, j \neq 0,$$
ensuring that the instrument does not forecast past or future structural disturbances.

These conditions guarantee that the external instrument isolates exogenous variation in the policy shock of interest, allowing consistent estimation of impulse responses in the presence of controls.

4.1.1 Limitations of disaster-based instruments

A strand of the empirical literature examining the impact of climate-policy adoption on income inequality relies on instrumental variables constructed from climate disasters (e.g. floods, wildfires, droughts) to capture shifts in the OECD Environmental Policy Stringency (EPS) Index.[2] This disaster-based approach underlying rationale assumes that extreme events lead governments to tighten their environmental policies. However, recent evidence indicates that the effect of natural disasters on governments' climate-policy responses, as captured by the EPS, is highly non-linear and context dependent, with limited support for the notion that extreme events on their own induce stronger environmental policies (Nohrstedt et al., 2021; Rowan, 2023)[3]. Whether such events translate into meaningful policy action, rather than merely prompting short-term restorative or compensatory measures, depends critically on institutional quality and governance (Nohrstedt & Parker, 2024; Raikes et al., 2022a), political dynamics (Cologna

[2] See, for example, Bettarelli et al. (2024) and Furceri et al. (2023), where climate-policy adoption, that is, movements in the EPS Index towards stricter regulation, is instrumented using extreme climate events through the interaction between a country-specific, time-invariant component (e.g. coastline length) and a global, time-varying component (e.g. the annual number of floods).

[3] In addition, a growing strand of the empirical literature highlights that climate disasters operate through direct transmission channels affecting income inequality and the distribution of income (Cappelli et al., 2021; Coronese et al., 2025)

et al., 2025; Peterson, 2021; Wappenhans et al., 2024), and the fiscal space available to governments (Kruse et al., 2022). Only when these factors align can extreme events become a genuine 'window of opportunity' for strengthening environmental policy.

Building on this point, our setting calls for a novel identification strategy to instrument changes in the EPS Index, relying on institutional factors that are not endogenous to government climate policy (as captured by the EPS Index itself) and drawing on climate-related central bank communication.

4.1.2 Rationale for an institutional instrument

Although central banks do not directly set environmental policy, their green narrative is shaped by underlying institutional arrangements and reflects a broader shift towards more promotional climate-related discourse. Evidence from global speech datasets indicates that the intensity of this communication is not driven by countries' exposure to physical or transition risks; instead, institutional characteristics such as supervisory responsibilities and the breadth of a central bank's mandate are stronger predictors of climate-related attention (Campiglio et al., 2025). This communication informs and shapes the salience of the public debate on climate change and the green transition, legitimising physical and transition risks as macro-relevant concerns (Cabrales et al., 2025; Campiglio et al., 2025; Jourde et al., 2025). In doing so, it forms part of the broader informational environment in which climate-policy decisions are taken.

4.1.3 Instrument Construction

Building on these insights, we construct an external instrument based on the interaction of two core components:

$$Z_t = CSI_t \cdot CBI_k \tag{1}$$

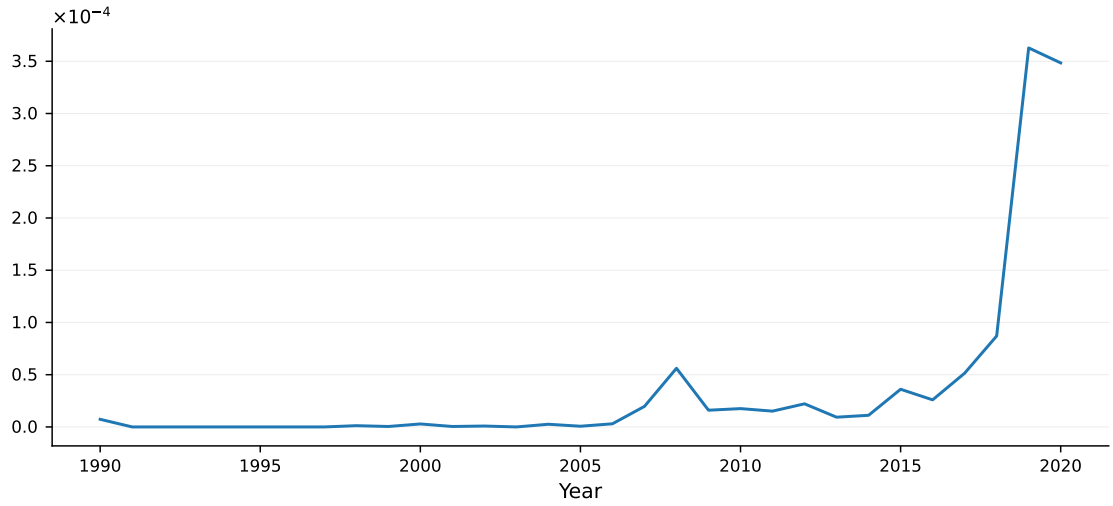
The first component, CSI_t, is a Climate Speech Index derived from the publicly available dataset compiled by Campiglio et al. (2025), which contains central bank speeches for 131 countries over 1989-2023. Using this global corpus, we construct a simple indicator of climate-related communication for the period 1990-2020. For each speech, we count the number of occurrences of climate-related terms such as "climate change" or "global warming" and divide this count by the total number of words in the speech. This yields a length-adjusted measure of climate-policy content. A similar normalisation procedure is employed in Cabrales et al. (2025).

The second component, CBI_k, is the country-specific and time-invariant Central Bank Independence and Transparency (CBI) Index retrieved from Romelli (2022), computed as the average value over 1990-2020. The CBI captures a broad set of institutional features, including transparency provisions, mandate scope, policy objectives, and supervisory authority over financial markets.[4] Comprehensive details on the construction of both indices, their underlying datasets, and the associated screening procedures are provided in Section A.4.1.

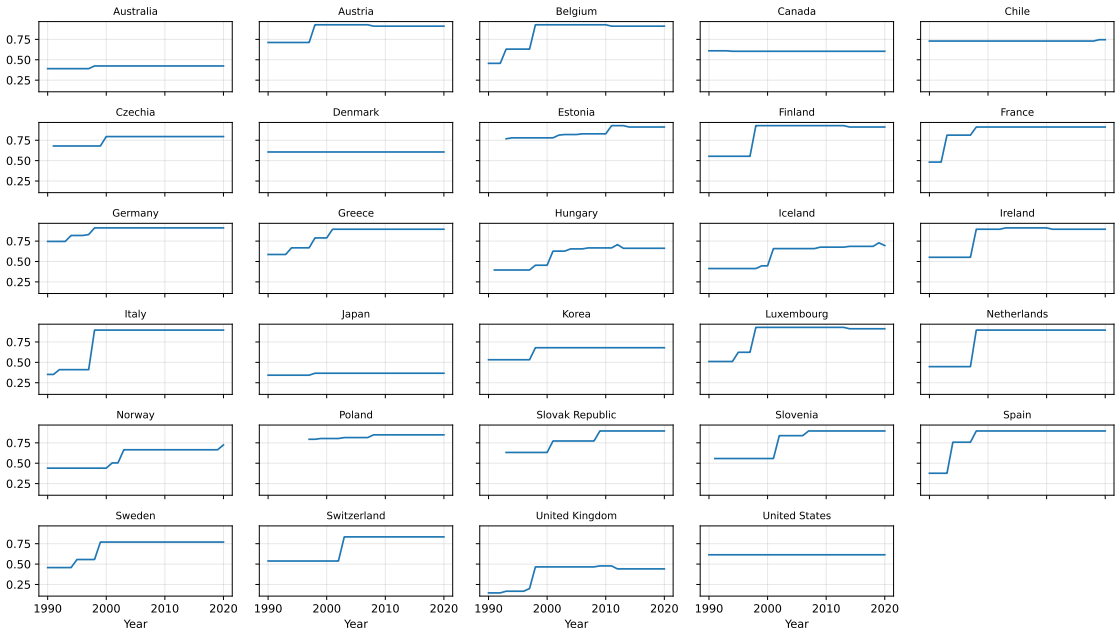
4.1.4 Robustness and diagnostic on the Instrumental Variable

We therefore obtain an interacted-like instrumental variable that combines the global time variation in CSI_t with the country-specific component CBI_k. This design offers a transparent and conceptually distinct alternative to disaster-based instruments for capturing exogenous variation in the timing of climate-policy adoption, as reflected in the variation of the EPS Index. Table A.4 in the Appendix shows the potential for Z_t to be a valid instrument. We estimate a reduced-form, bivariate first-stage panel regression of ΔEPS and its sub-indices on the instrument, including macroeconomic controls (GDP growth and the unemployment rate), and using country-clustered robust standard errors. The results display encouraging features, such as 1% significance for

[4] One may argue that this country-specific measure is limited in the context of the Eurozone. However, the CBI Index retains meaningful cross-country heterogeneity within the Eurosystem, as shown in Figure 2b, with different institutional configurations reflected in distinct index values.



(a) Climate Speech Index (global), 1990-2020.



(b) Central Bank Independence Index by country, 1990-2020.

Figure 2: ***Climate-related central bank communication and institutional independence.*** *Panel (a) shows the global Climate Speech Index (our elaboration based on Campiglio et al. (2025) dataset), while panel (b) reports the central bank independence (CBI) index for all countries in the sample over 1990-2020. Note: The instrument has been scaled by 1000 for readability.*

the coefficients in the 'Market' and 'Non-Market' sub-indices, with associated F-statistics exceeding 24 and 78, respectively. In addition, Table 4.1 reports the Kleibergen-Paap F-statistics from the first-stage IV regressions across horizons for the three main inequality indicators (Gini, Palma, and S80/S20) employed in the main model. The results broadly indicate satisfactory instrument relevance for most EPS components except Non-market policy sub-index across all distributive measures. Notably, the technological sub-index consistently delivers the strongest F-statistics, suggesting that this dimension may constitute the dominant source of exogenous variation underlying movements in the aggregate EPS Index.

Additional diagnostic evidence like orthogonality checks between the instrument and the distributive variables, is presented in Appendix A.4.3. Moreover, weak-instrument diagnostics, including the Hansen J test for overidentifying restrictions, the Anderson-Rubin test for joint significance and instrument validity, and the Wald test for assessing the strength of the instruments under potential weak-identification scenarios, are reported in the regression tables in Section A.7.

4.2 IV-LPs model specification

The fundamental IV–LPs model used to investigate the effect of climate-policy adoption on income inequality is formalised as follows[5]. In the first stage, we regress the yearly change in the EPS Index, ΔEPS_{it} [6], and its subcomponents on the external instrument and its lags, together with a set of predetermined controls and country (i) and year (t) fixed effects:

$$\Delta EPS_{it} = \alpha_i + \lambda_t + \phi\, Z_{i,t-l} + \mathbf{\Gamma} X_{it-l} + \varepsilon_{it}, \tag{2}$$

where α_i are country-fixed effects, λ_t are year-fixed effects, Z_{it} denotes our interacted instrumental variable, and X_{it} is a vector of controls. In our baseline specification, X_{it} includes two lags of the change in the EPS Index, two lags of real GDP growth, and two lags of the unemployment rate. In the second stage, we regress the horizon-specific change in the inequality or income-distribution variable on the fitted values from the first stage, again controlling for X_{it} and fixed effects:

$$y_{it+h} - y_{it-1} = \alpha_i^h + \lambda_t^h + \beta^h\, \widehat{\Delta EPS}_{it} + \mathbf{\Gamma}^h X_{it-l} + u_{it+h}, \tag{3}$$

where $h = 0, \ldots, H$ indexes the forecast horizon, and $\widehat{\Delta EPS}_{it}$ are the fitted values from the first-stage regression. $\Delta y_{it-1}^h = y_{i,t+h} - y_{i,t-1}$ represent the dynamic response of the outcome variables (e.g. Gini, Palma and S80/S20 Indexes) from the base year previous the occurring shock. All second-stage estimates are estimated with Driscoll–Kraay standard errors, ensuring robustness to serial correlation, heteroscedasticity, and cross-sectional dependence typically observed in macro-panel settings. The following section presents the estimated impulse responses, followed by a discussion and dedicated robustness analysis assessing the stability of the results across alternative model specifications.

5 Results

Figure 3 reports the cumulative impulse responses (IRFs) of the estimated IV-LP coefficients, β^h, for each inequality indicator (Gini, Palma, and S80/S20) across the four environmental policy shocks (aggregate, market-based, non-market, and technology-support EPS). The results should be interpreted in terms of sign, timing, and persistence, noting that the three inequality indicators are not numerically comparable: the Gini index is expressed in percentage points (0–100), whereas the Palma and S80/S20 ratios are

[5] See Jordà (2005) and Jordà and Taylor (2024, 2025) for theoretical discussions, and Jordà et al. (2015, 2020) for empirical applications.

[6] A one-standard-deviation increase corresponds to a 0.2-point rise in the Index. We interpret ΔEPS_{it} as capturing an unanticipated increase in climate policy stringency, that is, an unexpected tightening in the regulatory stance reflected by the EPS index. This specification focuses on policy innovations rather than policy levels and is consistent with an impulse–response interpretation of the IV–LP framework. As an additional robustness check, we re-estimate the main specification using the EPS index in levels instead of first differences resulting in quantitatively and qualitatively very similar outcomes to the baseline specification.

Table 4.1: Kleibergen-Paap rk F-statistics for first-stage IV regressions across horizons

Panel A: Gini

	Horizon h					
Shock variable	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$	$h=5$
ΔEPS total	8.376	**33.817**	**16.113**	8.638	**18.886**	**12.378**
ΔEPS market	**14.876**	**11.509**	**21.497**	**11.940**	3.335	2.004
ΔEPS non-market	4.654	5.489	1.547	3.775	3.935	3.593
ΔEPS tech	**15.805**	**56.856**	**37.162**	**24.115**	**39.684**	**51.408**

Panel B: Palma

	Horizon h					
Shock variable	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$	$h=5$
ΔEPS total	9.075	**35.998**	**16.699**	9.164	**17.835**	**12.580**
ΔEPS market	**13.924**	**11.037**	**17.584**	**10.662**	3.619	1.857
ΔEPS non-market	4.253	4.947	1.619	3.352	3.397	3.153
ΔEPS tech	**16.265**	**61.067**	**37.777**	**24.066**	**35.568**	**39.831**

Panel C: S80/S20

	Horizon h					
Shock variable	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$	$h=5$
ΔEPS total	8.034	**32.497**	**15.744**	9.503	**15.896**	**11.374**
ΔEPS market	**16.214**	**10.400**	**19.535**	**12.108**	3.489	1.690
ΔEPS non-market	4.477	4.792	1.221	3.170	3.273	3.031
ΔEPS tech	**11.650**	**51.712**	**39.866**	**27.938**	**40.061**	**50.868**

Notes: Estimates based on the full panel. Specifications include country and year fixed effects. Controls: GDP growth and unemployment. Standard errors are estimated using Driscoll-Kraay errors. Bold values denote Kleibergen-Paap rk F statistics above the conventional threshold of 10. Inequality measures are from WIID (UNU-WIDER, 2025), using net per capita income in 2021 PPP USD. The Gini coefficient summarises overall income inequality on a 0-1 scale. The Palma ratio is the income share of the top 10% relative to the bottom 40%. The S80/S20 ratio compares the income share of the richest 20% to that of the poorest 20%.

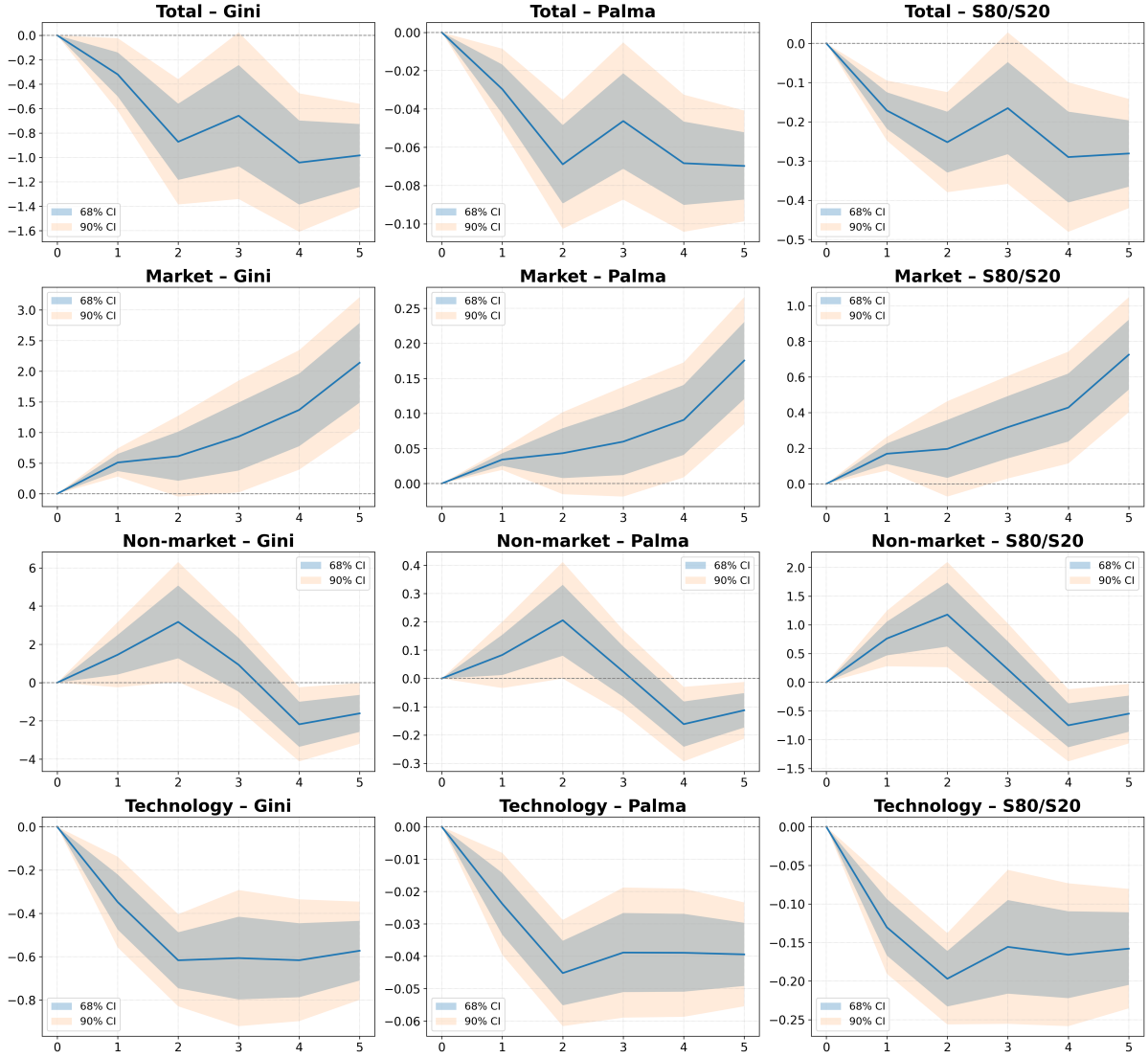


Figure 3: *Cumulative IRFs to a one-standard-deviation shock in the annual difference of the EPS Index and its subcomponents. All inequality and distributional-share indicators refer to standardised WIID net income in 2021 PPP US: (1) Gini, overall inequality index (0 = perfect equality, 100 = perfect inequality); (2) Palma, the ratio of the income share of the richest 10 per cent to the bottom 40 per cent; (3) S80/S20, the ratio of the income share of the richest 20 per cent to the poorest 20 per cent. The Gini index is expressed in percentage points, while the Palma and S80/S20 ratios are level-based measures; impulse responses therefore reflect percentage-point changes for the Gini and level changes for the other two indicators. The model includes country and year fixed effects and Driscoll–Kraay standard errors, and is estimated under standard macroeconomic controls: GDP growth and the unemployment rate.*

level variables. The interpretation of the IRFs should be considered jointly with the first-stage Kleibergen-Paap weak-IV statistics reported in Table 4.1, assessing the strength of the instrument at the corresponding horizon.

Aggregate EPS Index shocks (first row of Figure 3) are associated with statistically significant reductions in income inequality across the country-year sample considered in this study, both in the short term ($h = 1, 2$) and over the medium run ($h = 4, 5$). The point estimates are negative at all horizons, with magnitudes broadly consistent over time. At $h = 3$, the point estimate should be interpreted with caution: although it remains consistent with the overall downward pattern, the corresponding Kleibergen-Paap statistic falls below 10, indicating weaker first-stage relevance, although the overall dynamics appear clear across horizons. At the final horizon, the implied reductions amount to roughly -1.5 percentage points for the Gini index, and to around -0.09 and -0.4 in levels for the Palma and S80/S20 ratios, respectively. To understand the sources of these aggregate effects, the analysis turns to the individual EPS components. Disentangling the sub-indices reveals distinct narratives and heterogeneous outcomes.

For the Market-based component, the KP statistics remain consistently above 10 over the first three horizons, confirming strong first-stage relevance. The corresponding IRFs display negative and persistent redistributive effects, with estimated impacts at horizon 3 of approximately -1.09 percentage point for the Gini, -0.06 for the Palma and -0.32 for the S80/S20 ratio in levels. These patterns are consistent with empirical evidence documenting the redistributive effects of carbon taxes and emissions trading schemes, although the responses do not display persistence at longer horizons. The same sign and direction are also observed in the Non-market scenario (restrictive emissions standards), which qualitatively displays effects of larger magnitude; however, the reliability of these estimates is very low. The KP statistics are unsatisfactory across most horizons, except for a single horizon (either $h = 1$ or $h = 2$ depending on the indicator), suggesting that considerable caution is required when interpreting these IRFs.

Finally, the Technology-support component reveals markedly different dynamics compared with the Market and Non-market categories, with strong first-stage identification that consistently outperforms the others (with almost every estimated horizon above the 5% Stock-Yogo threshold of 18). The associated IRFs display progressive distributional effects, slightly smaller in magnitude than in the other scenarios, but stable and persistent across horizons.

Taken together, the results point to a nuanced distributional impact of different climate-change policies, with the aggregate index masking a high degree of heterogeneity across policy instruments in terms of sign, magnitude, and timing, conditional on our empirical identification strategy and on the high-income countries considered over the period 1990–2020. Technology-support measures emerge as the category delivering robust and well-identified progressive effects, while Market-based and Non-market instruments either display transitory short-run regressive patterns or lack sufficient first-stage IV strength to support long-term firm conclusions.

A consistent picture emerges when examining income shares, which helps to clarify the macro-aggregate inequality results reported above. Figure 4 presents the IRF responses for the bottom 40 percent and the top 5 percent across the four policy scenarios. The bottom-40 share tends to rise after Total and Technology-support shocks and to fall following Market-based and Non-market shocks, while the opposite pattern is observed for the top 5 percent. These movements help account for the behaviour of the Gini, Palma, and S80/S20 indices, which reflect shifts in income shares across the distribution. Appendix A.8 provides a more granular quantile-disaggregated analysis based on the UNU-WIDER (2025) database, which again yields a consistent overall picture.

We conduct a broad set of sensitivity checks to verify that the results remain qualitatively robust across alternative lag specifications, different sets of control variables, and various truncation lags used to compute Driscoll-Kraay standard errors, that is, the assumed order of autocorrelation and cross-sectional dependence in the panel[7]. Section A.5 reports a range of plots illustrating

[7]Given the high persistence of macroeconomic variables and the strong serial correlation indicated by panel unit root and autocorrelation diagnostics, our inference is based on Driscoll–Kraay standard errors, which are robust to both serial and cross-sectional dependence and require the specification of a truncation lag. We adopt a conservative specification and set the truncation lag equal to four in the baseline estimates, a medium period consistent with materialization of effects of climate policies in the literature, reflecting the medium-term horizon over which climate policies typically produce observable effects, and comparable to the time horizon central banks use for financial stability policy strategy, often extending up to ten years, as reported by Carney (2015, 2016).

the qualitative stability of the main results for the Gini coefficient, the Palma ratio, and the S80/S20 index across different country subsamples and alternative time spans. Section A.7 presents the regression tables for each indicator and scenario, together with a static TWFE specification using the baseline model to assess the sign and magnitude of the estimated relationships, as well as additional weak-instrument diagnostics based on Kleibergen–Paap statistics. Whenever the first stage is sufficiently strong, the Hansen J test does not reject the null of instrument validity at any horizon, supporting the exogeneity assumption. The Anderson–Rubin statistics indicate statistically significant joint effects of the instrument on both the endogenous regressor and the outcome variable at all horizons. Overall, these results suggest that identification is broadly acceptable, although caution is warranted at horizons where first-stage strength is comparatively weaker.

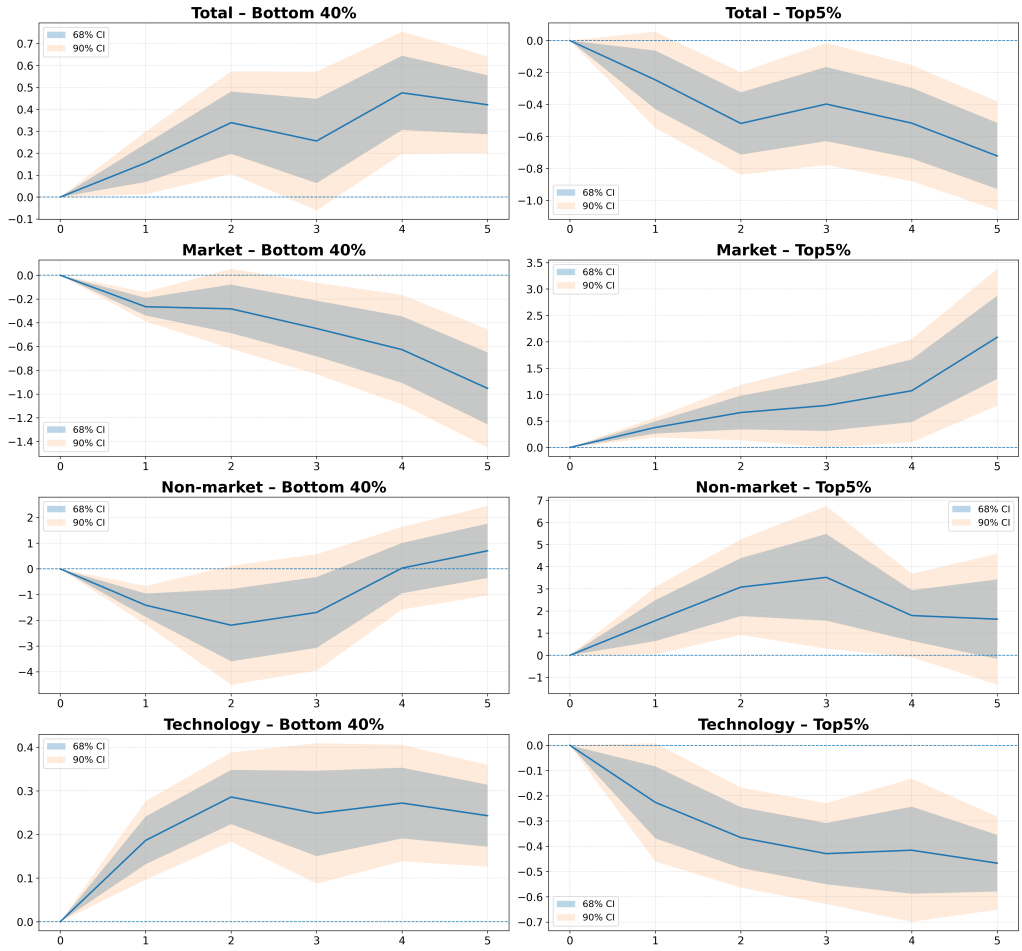


Figure 4: *Cumulative IRFs to a one-standard-deviation shock in the annual change of the EPS Index and its subcomponents. Distributional outcomes are measured in levels using standardised WIID net-income shares in 2021 PPP US: (1) Bottom 40, the income share of the poorest 40 per cent; and (2) Top 5, the income share of the richest 5 per cent. All indicators are expressed in percentage points of total net income; impulse responses therefore represent percentage points in the corresponding income shares. The model includes country and year fixed effects and Driscoll-Kraay standard errors, and is estimated under the following controls: GDP growth and the unemployment rate.*

5.1 Transmission Channels

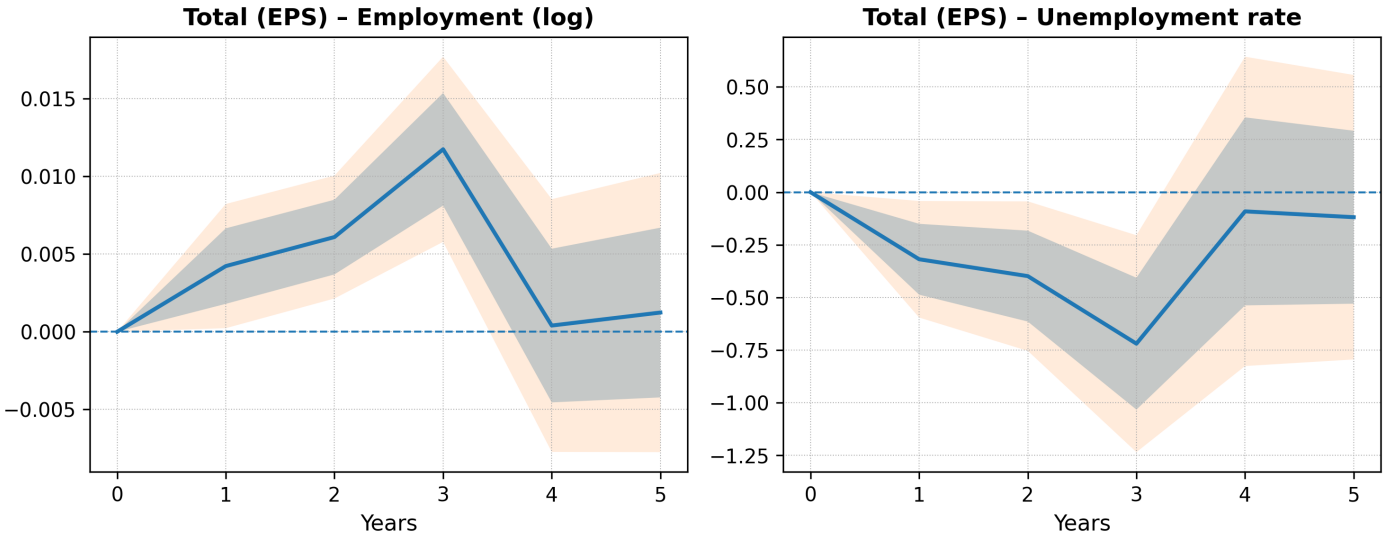


Figure 5: *Impulse responses of OECD data for log employment and the unemployment rate following a one-standard-deviation increase in the annual change of the EPS Total Index. Responses for employment are expressed as log deviations and can be interpreted approximately as percentage changes, while responses for the unemployment rate are in level. Shaded areas denote 90 and 68 percent confidence bands obtained from the IV Local Projection framework with country and year fixed effects and Driscoll-Kraay standard errors. The model is estimated under alternative sets of control variables, including GDP growth and the general CPI. Horizons are measured in years.*

Climate policy can influence income distribution and inequality through several channels: sectoral and macro-level labour market adjustments (Cappa et al., 2024), changes in the skill composition of the labour force (Bettarelli et al., 2024; Bray et al., 2022), shifts in energy prices affecting firms' labour demand (Dechezleprêtre et al., 2020), and the resulting household energy cost burdens (Hodok & Kozluk, 2024), among others. In this section, following Bettarelli et al. (2024) and Cappa et al. (2024), we focus on the macro employment transmission channel, highlighting the potential for climate and transition policies to generate new green jobs while maintaining an aggregate perspective, that is, without disentangling sectoral composition effects or skill content.

We also provide complementary evidence on additional transmission channels, including functional income distribution mechanisms at the macroeconomic level, proxied by the adjusted wage share, and the composition of green-transition employment by gender; these results are reported in Appendix A.9–A.10.

Figure 5 reports the results of the baseline model described in Section 4.2, where the outcome variables are the logarithm of total employment (in millions of persons) and the unemployment rate, following a one-standard-deviation shock to the Total EPS Index. The impulse responses point to a positive medium-run effect on employment. Log employment increases up to around horizon $h = 3$, with point estimates above zero and confidence bands indicating statistical significance at the 90% level over the short-to-medium term. Given the logarithmic specification, these responses can be interpreted approximately as percentage changes. Beyond the third horizon, the estimated effects become smaller and less precisely estimated, and the confidence intervals widen, calling for more cautious interpretation at longer horizons.

The right-hand panel shows the response of the unemployment rate, which exhibits sensible in magnitude decline at the impact (horizon $h = 1$) to a middle run (horizon $h = 3$), statistically significant at the 90% confidence level, before converging back towards values that are not statistically different from zero at subsequent horizons. Overall, the joint pattern of rising employment

and falling unemployment in the short run is consistent with a positive macro employment transmission channel following climate policy stringency shocks. At the same time, these aggregate results necessarily could mask the sectoral reallocation of the labour force induced by climate transition policies, which would require a sector-specific modelling framework to properly assess structural change effects.

5.2 Discussion

Our work contributes to the empirical literature examining the heterogeneous effects of climate policy and their asymmetric implications for income distribution. The results presented in the previous section provide nuanced evidence relative to existing studies, reflecting differences in identification strategy, the distributional dataset employed, the focus on high-income countries, and the methodological framework adopted. A key point of departure from much of the existing literature is that not all climate policies necessarily worsen income distribution. In our setting, the aggregate EPS Index and technology-support measures are associated with improvements across all inequality indicators considered, namely the Gini coefficient, the Palma ratio, and the S80/S20 ratio (Figure 3), as well as across the income-share measures reported in Figure 4 and Figure A.3.

By contrast, market-based and non-market policies display comparatively more regressive, although short-lived, effects. These findings are partly consistent with Bettarelli et al. (2024), who show that the distributional costs of climate-policy tightening arise primarily from market-based instruments, and with the evidence in Känzig (2023), suggesting that such effects may operate through higher energy-cost burdens for low-income households. In our framework, however, these adverse dynamics appear temporary. Moreover, in line with Metcalf and Stock (2023), we do not detect negative effects on aggregate employment, nor on functional income distribution as proxied by the adjusted wage share, thereby mitigating concerns about broad macroeconomic trade-offs associated with climate-policy implementation.

With respect to transmission channels, it should be noted that the panel mainly covers high-income countries. Within this context, the estimates do not indicate net job losses associated with climate-policy tightening. On the contrary, the results point to a moderate stimulus to employment dynamics, alongside partial confirmation from the estimated responses of the unemployment rate. These patterns are consistent with the theoretical and empirical arguments in Cappa et al. (2024), which emphasise the potential of green-job creation to generate multiplier-like employment effects through sectoral reallocation.

6 Conclusion and policy implications

The present paper has examined the heterogeneous effects of different climate change policies on income inequality in a panel of 29 high-income OECD countries over 1990–2020. To address endogeneity concerns, we employed an Instrumental Variables Local Projections (IV-LPs) framework. Two main conclusions emerge, alongside implications for policy design and avenues for future research.

First, our identification strategy, based on the interaction between a global, time-varying Climate Speech Index (CSI), constructed from the dataset by Campiglio et al. (2025), and a country-specific institutional component derived from the Central Bank Independence and Transparency (CBI) Index provided by Romelli (2022), offers a plausible source of exogenous variation in climate policy adoption. This institutional–communicative instrument isolates shocks to environmental policy stringency and builds on recent evidence emphasising the role of institutional settings in enabling effective climate action (Cologna et al., 2025; Nohrstedt & Parker, 2024; Peterson, 2021; Raikes et al., 2022a; Wappenhans et al., 2024).

Second, and most importantly, our results show that the distributional effects of climate policy are strongly policy-specific. At the aggregate level, we find no statistically significant evidence of adverse redistributive consequences associated with the overall EPS Index. On the contrary, the Total EPS measure is, on average, associated with lower income inequality, a declining unemployment rate, stable labour-share dynamics, and, in terms of the gender composition of employment, higher female labour-force participation.

Disaggregating by policy type, technology-support measures—such as public R&D spending and price-support mechanisms for renewable energy, which declined markedly after the Global Financial Crisis (Kruse et al., 2022), tend to deliver the most favourable distributional and labour-market outcomes. Taken together, these results suggest, albeit with appropriate caution, that climate and transition policies, especially technology-oriented instruments, can support a credible "just transition", jointly advancing climate objectives and progressive distributional outcomes. By contrast, market-based and non-market policies display comparatively more regressive, although short-lived, effects, consistent with concerns related to higher energy-cost burdens for lower-income households.

Even in these cases, however, the adverse effects appear to be at least partly offset over time at the aggregate level. From a policy perspective, this implies that revenues from potentially regressive market-based instruments, such as carbon taxes or emissions-permit auctions, can be recycled into technology-support programmes or targeted transfers to cushion short-run regressive impacts on vulnerable households during the decarbonisation process (Lamperti et al., 2025; Wieners et al., 2025).

These findings should be interpreted in light of the scope of the analysis. The estimates are derived from a sample of high-income, predominantly Western countries and may therefore mask heterogeneity across middle- and low-income economies, particularly in the Global South, where exposure to climate risks and transition costs is typically greater. Moreover, the aggregate nature of our estimates does not allow us to identify the sectoral composition of employment effects or differences in labour-force skill composition. These limitations point to promising avenues for future research, including more granular within-country analyses of distributional and labour-market impacts.

A Appendix

A.1 Disclosures

During the preparation of this work the author used Chat-GPT 5 and Grammarly in order to check grammar and improve the fluency of the text. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

A.2 Acknowledgment

I am very grateful to Giovanna Ciaffi, Stefano Di Bucchianico, Damiano Di Francesco, Mario Di Serio, Paola D'Orazio, Marco Sforza and Marco Sorge for their helpful comments on an early draft of the present paper. A special thanks goes to fellow explorer and comrade Alessio Ferraro. All errors and inaccuracies remain my sole responsibility.

A.3 Dataset

The dataset is composed of 30 high-income OECD countries over the years 1990 to 2020, as reported in Table A.1. We focus on high-income countries, in contrast with much of the existing literature, for two main reasons. The first is to reduce potential heterogeneity in the macroeconomic and institutional settings that could drive the results. The second relates to the availability of income distribution data from the World Income Inequality Database (WIID, hereafter), which are expressed in 2021 USD PPP net income per capita and abstract from family composition. This avoids comparability issues that would arise in a sample mixing high-, middle-, and low-income countries. Table A.2 reports all variables used in the analysis, together with brief descriptions and sources, while Table A.3 presents their summary statistics.

Table A.1: Panel of Countries considered in the Dataset

Countries		
Australia	Austria	Belgium
Canada	Chile	Czechia
Denmark	Estonia	Finland
France	Germany	Greece
Hungary	Iceland	Ireland
Italy	Japan	Republic of Korea
Luxembourg	Netherlands	Norway
Poland	Slovak Republic	Slovenia
Spain	Sweden	Switzerland
United Kingdom	United States	

Table A.2: Variables Used in the IV-Local Projections Framework

Variable	Description	Source
Climate Policy Variables		
Environmental Policy Stringency (EPS) Index	Composite indicator measuring the stringency of environmental and climate-related regulations and policy.	OECD
Market-based EPS	Sub-index capturing taxes, trading schemes, and market incentives for decarbonisation.	OECD
Non-market EPS	Sub-index capturing command-and-control regulations (standards, prohibitions).	OECD
Technology-based EPS	Sub-index capturing public R&D in clean energy and support for renewable technologies (solar, wind).	OECD
Income Inequality and Distribution		
Gini Index	Net income inequality measure (0-100), PPP-adjusted to 2021 USD.	WIID
Palma Ratio	Ratio of the income share of the top 10% to that of the bottom 40%, PPP-adjusted to 2021 USD.	WIID
S80/S20 Ratio	Ratio of income earned by the richest 20% to that of the poorest 20%, PPP-adjusted to 2021 USD.	WIID
Bottom 5% income share	Share of net income accruing to the bottom 5% of the national income distribution, PPP-adjusted to 2021 USD.	WIID
Bottom 40% income share	Share of net income accruing to the bottom 40% of the national income distribution, PPP-adjusted to 2021 USD.	WIID
Top 5% income share	Share of net income accruing to the top 5% of the national income distribution, PPP-adjusted to 2021 USD.	WIID
Q1	Share of net income accruing to the first quintile (bottom 20%) of the national income distribution, PPP-adjusted to 2021 USD.	WIID
Q2	Share of net income accruing to the second quintile (20-40%) of the national income distribution, PPP-adjusted to 2021 USD.	WIID
Q3	Share of net income accruing to the third quintile (40-60%) of the national income distribution, PPP-adjusted to 2021 USD.	WIID
Q4	Share of net income accruing to the fourth quintile (60-80%) of the national income distribution, PPP-adjusted to 2021 USD.	WIID
Q5	Share of net income accruing to the fifth quintile (top 20%) of the national income distribution, PPP-adjusted to 2021 USD.	WIID
Macroeconomic Variables		
Real GDP Growth	Annual real GDP growth rate.	WIID
Real GDP Growth	Annual real GDP growth rate. Used as an alternative measure in robustness checks.	World Bank
Inflation	Consumer price inflation (annual %).	World Bank

Continued on next page

Table A.2 – *Continued from previous page*

Variable	**Description**	**Source**
Inflation	Consumer price inflation (annual %). Used as an alternative measure in robustness checks.	OECD
Unemployment Rate	Share of unemployed workers in the labour force (annual).	World Bank
Adjusted Wage Share MC	Labour compensation as a share of GDP at market cost, adjusted for self-employment by imputing mixed income to labour.	AMECO
Adjusted Wage Share FC	Labour compensation as a share of GDP at factor cost, adjusted for self-employment by imputing mixed income to labour.	AMECO
Instrumental Variables		
Climate Speech Index	Annual count of climate-related speeches by central banks, weighted by text length.	Campiglio et al. (2025)
CBI Index	Central Bank Independence index capturing formal institutional setting.	Romelli (2022)

Table A.3: Summary Statistics of Variables Used in the IV-Local Projections Model

Variable	Obs	Mean	Std	Min	Max	Source
Climate Policy Variables						
EPS Index	434	2.496928	1.045843	0	4.888889	OECD
Market-based EPS	434	1.384793	0.9001549	0	4.166666	OECD
Non-market EPS	434	4.09735	1.716951	0	6	OECD
Technology-based EPS	434	2.008641	1.373332	0	6	OECD
Income Inequality and Distribution						
Gini Index	434	32.37834	5.155361	20.19	54.96	WIID
Palma Ratio	434	1.298018	0.4633055	0.69	4.19	WIID
S80/S20 Ratio	434	5.590737	2.006112	2.75	17.72	WIID
Bottom 5% income share	434	1.073226	0.3207169	0.22	2.24	WIID
Bottom 40% income share	434	20.34779	2.645168	10.61	27.32	WIID
Top 5% income share	434	15.84894	2.984403	10.39	32.02	WIID
Q1	434	7.63023	1.335778	3.39	11.68	WIID
Q2	434	12.71742	1.35599	7.22	15.66	WIID
Q3	434	16.88016	1.104554	11.26	19.16	WIID
Q4	434	22.51834	0.743585	18.11	24.13	WIID
Q5	434	40.25362	4.078455	31.71	60.02	WIID
Macroeconomic Variables						
Real GDP Growth	434	1.541353	2.985782	-11.37407	23.44369	WIID
Real GDP Growth	434	2.196991	3.020928	-10.94007	24.61557	World Bank
Inflation	434	2.556542	3.930034	-4.447547	46.09856	World Bank
Inflation	434	2.548781	3.852687	-4.447547	42.85	OECD
Unemployment Rate	434	7.305235	3.431347	1.482	26.708	World Bank
Wage Share (MC)	418	61.67675	5.560616	34.04	74.11	AMECO
Wage Share (FC)	418	54.97935	5.309336	32.59	66	AMECO
Instrumental Variables						
Climate Speech Index	434	0.000048	0.0000979	0	0.0003628	Campiglio et al. (2025)
CBI Index	434	0.7387433	0.1529729	0.3665	0.9071	Romelli (2022)

A.3.1 Income Inequality and Distribution data

Income inequality and distributional data are retrieved from the latest version of the UNU-WIDER World Income Inequality Database UNU-WIDER, 2025, a comprehensive compilation of established sources providing the longest possible time coverage. To ensure international comparability of inequality indices and, crucially, income shares across countries, we restrict the sample to observations expressed in net (disposable) per capita income, in 2021 PPP-adjusted US dollars. Net income in WIID refers to total income received (employee income, self-employment income, rental income excluding rents on land, property income, and current transfers received) minus current transfers paid (employees' social contributions and direct taxes). From the originally considered group of OECD countries, we had to exclude Portugal and New Zealand because no observations expressed in 2021 USD PPP terms were available in the WIID database.

A.4 Instrumental Variable

A.4.1 Climate Speech Index (CSI)

We construct our climate-salience index using the dataset collected by Campiglio et al. (2025), which contains 35,487 speeches by global central banks from 131 countries over the period 1986 to December 2023, and is freely available[8]. To obtain a simple and

[8] https://cbspeeches.com/

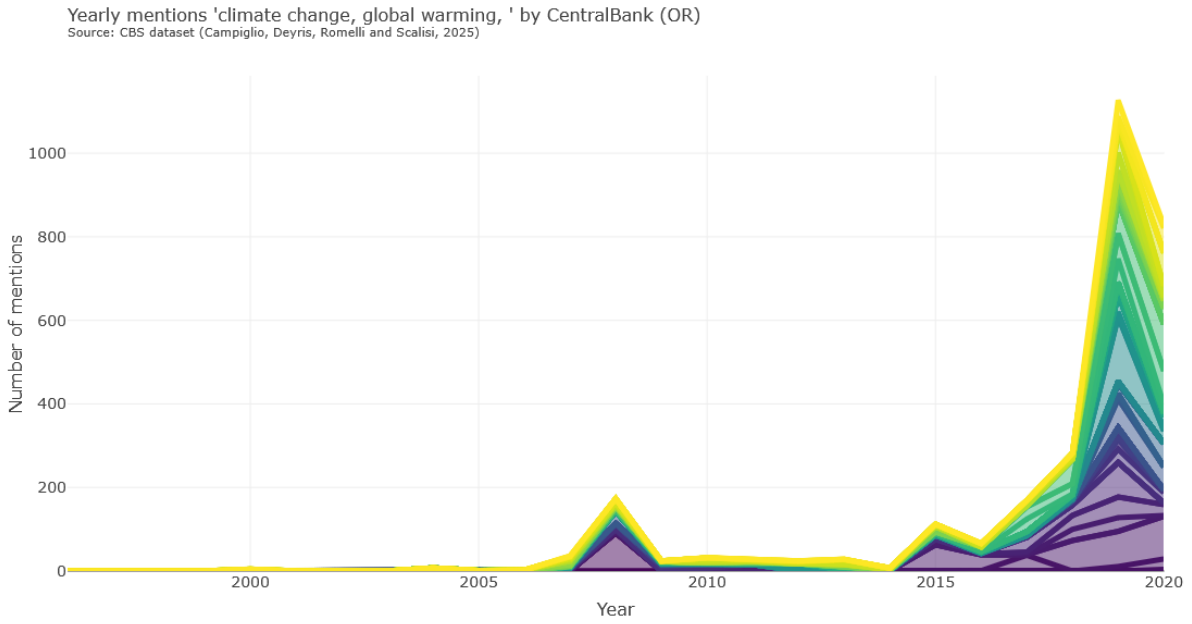


Figure A.1: Annual mentions of 'climate change' and 'global warming' in central bank speeches, 1990–2020 (OR condition, minimum one mention). Colours represent different Central Banks. Source: CBS Dataset Campiglio et al. (2025).

transparent indicator, we count the number of occurrences of the expressions "climate change" or "global warming"[9] in speeches within the Bank for International Settlements network for each year between 1 January 1990 and 31 December 2020. The annual count is then normalised by the total number of words in all speeches delivered in that year, yielding a frequency-based measure of climate salience. Figure A.1 shows the stacked area plot of the raw number of mentions for each central bank entity. Two clear breaks emerge: a noticeable rise around the Paris Agreement in 2015, and a sharp, persistent increase after 2018, coinciding with the creation and expansion of the Network for Greening the Financial System (NGFS). These institutional shifts appear to have played a key role in driving the rapid uptake of climate-related terminology in central bank communication.

A.4.2 Central Bank Independence Index (CBI)

The Central Bank Independence (CBI) Index is provided by Romelli (2022) and is publicly available[10]. The dataset covers 155 countries over the period 1923–2023 and provides historical measures of de jure central bank independence. The CBI is constructed as the average score across six dimensions, based on answers to 42 questions, with values ranging from 0 (no independence) to 1 (full independence). The six dimensions capture: (i) government and central bank board arrangements,n(ii) monetary policy objectives,(iii) procedures for conflict resolution, (iv) limitations on lending to the government,(v) financial independence, and(vi) reporting and disclosure rules.

[9] This choice reflects the terminology used in different periods. While "climate change" and related expressions are dominant today, earlier public debates frequently employed alternative wording such as "global warming" (Campiglio et al., 2025).

[10] https://cbidata.org/

A.4.3 First-stage diagnostics

Consistent with the benchmark in Jordà et al. (2015), this section reports unconditional first-stage regressions aimed at assessing the potential of Z as a valid external instrument, where Z is obtained by

$$Z_{it} = \text{CSI}_t \times \text{CBI}_i, \tag{4}$$

where CSI_t is the global, time-varying Climate Speech Index (common to all countries in year t), and CBI_i is the country-specific, time-invariant Central Bank Independence index, obtained by the average on period 1990-2020. To this end, we estimate a parsimonious model relative to the full IV–LPs specification and regress the annual change in the EPS Index and its subcomponents on Z, controlling for real GDP growth and the unemployment rate. Table A.4 presents the results. In this simplified setting, the instrument exhibits only a modest ability to predict changes in the aggregate EPS Index across the panel. By contrast, the market-based and non-market sub-indices yield comfortably large F-statistics, exceeding the conventional threshold of 10. No statistically significant association is found for the technological-support sub-index in this unconditional static specification. This pattern is unsurprising, as we are working with composite indices whose aggregate dynamics may dilute the variation captured more clearly within specific EPS subcomponents.

Formal instrument relevance is assessed within the full IV-LPs framework (Section A.7), which incorporates country and year fixed effects, the dynamic lag structure, and Driscoll–Kraay standard errors.

Table A.4: Bivariate first-stage panel regressions of EPS and sub-indices on the instrument

	(1) ΔEPS total	(2) ΔEPS market	(3) ΔEPS non-market	(4) ΔEPS tech
Z	-0.113	0.405***	-0.734***	-0.011
	(0.076)	(0.082)	(0.083)	(0.189)
GDP Growth	-0.002	0.002	0.002	-0.011*
	(0.002)	(0.003)	(0.004)	(0.004)
Unemployment	-0.003	-0.002	0.000	-0.007*
	(0.002)	(0.001)	(0.003)	(0.003)
Constant	0.110***	0.052***	0.158***	0.120***
	(0.015)	(0.014)	(0.024)	(0.023)
Observations	926	926	926	926
R^2	0.004	0.013	0.011	0.010
Adjusted R^2	0.000	0.010	0.007	0.007
First-stage F-statistic	2.204	24.269	78.533	0.003

Country-based cluster-robust standard errors in parentheses. Fixed effects omitted.
Note: The instrument has been scaled by 1000 for readability.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

A.4.4 Instrument-Outcome Orthogonality Test

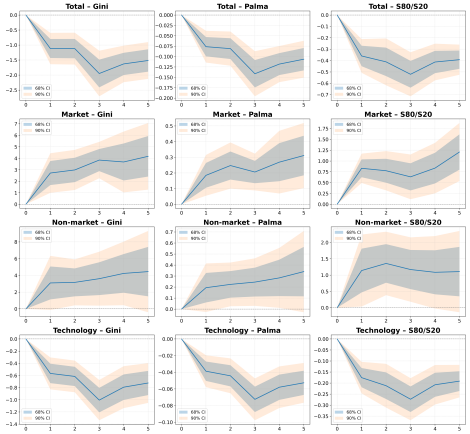
As a further diagnostic check, we regress the main inequality indicators (Gini, Palma, and S80/S20 indices) directly on the instrument, controlling for country and year fixed effects as well as macroeconomic dynamics. As reported in Table A.5, the coefficients are small and statistically insignificant across all specifications, providing supportive evidence that the instrument is not mechanically correlated with our outcome variables.

Table A.5: First-stage regressions of Instrument on Inequality measures

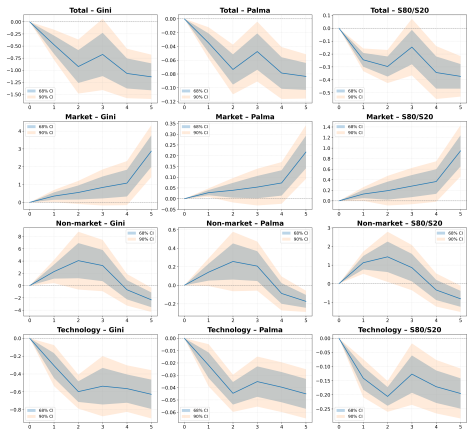
	(1) Gini	(2) Palma	(3) S80/S20
Z	-2.259	-0.289	-0.910
	(3.864)	(0.309)	(1.375)
GDP Growth	0.091	0.012	0.039
	(0.120)	(0.013)	(0.054)
Unemployment	0.099	0.005	0.047
	(0.123)	(0.008)	(0.042)
Constant	31.594***	1.253***	5.221***
	(1.628)	(0.120)	(0.580)
Observations	434	434	434
R^2	0.010	0.012	0.013
Adjusted R^2	0.003	0.005	0.006
First-stage F-statistic	0.342	0.877	0.437

Country-based cluster-robust standard errors in parentheses. Fixed effects omitted.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

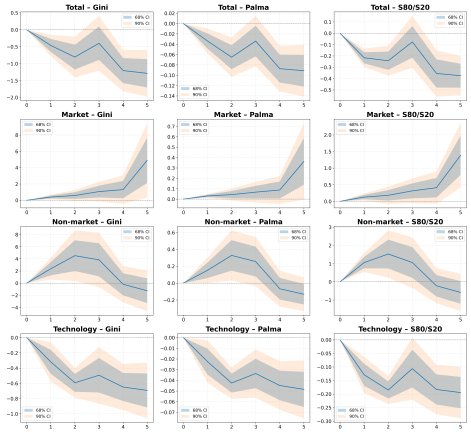
A.5 Robustness Exercises



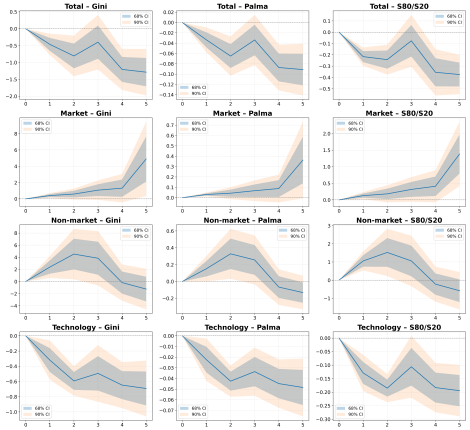
(a) Excluding the last five years (sample 1990–2015).



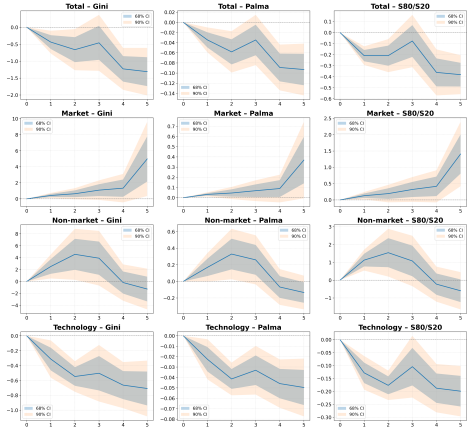
(b) Excluding the first five years (sample 1995–2020).



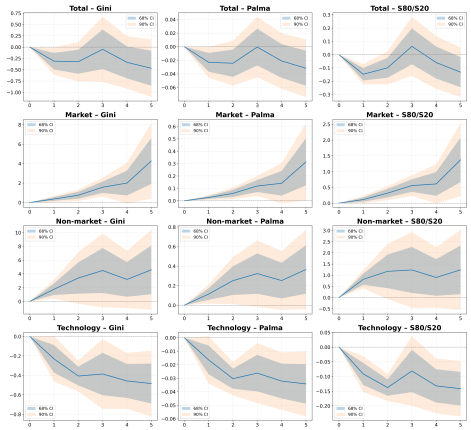
(c) Excluding the first ten years (sample 2000–2020).



(d) Excluding the most equal countries (Denmark and Slovak Republic).



(e) Excluding moderately unequal countries (Italy and Spain).



(f) Excluding the most unequal countries (Chile and the United States).

Figure A.2: *Robustness checks on the baseline IV–LP impulse responses of inequality measures to EPS shocks. Panels (a)-(c) report cumulative IRFs under alternative time-window restrictions. Panels (d)-(f) trim the cross-country sample by excluding the most equal, moderately unequal, and most unequal countries by average Gini levels.*

A.6 Static Two-way Fixed Effect Model Table Estimates

Table A.6: **Static TWFE-IV Estimates for Income Inequality Indices. EPS Total scenario.** Country and year FE included. Driscoll–Kraay SEs in parentheses.

	(1) Gini	(2) Palma	(3) S80/S20	(4) Bottom40	(5) Top5
Structural shock					
ΔEPS Total	-1.458	-0.135*	-0.780***	0.710	-1.121
	(0.821)	(0.0585)	(0.212)	(0.396)	(0.835)
Lagged dependent variable					
L.Inequality	0.697***	0.706***	0.740***	0.714***	0.551***
	(0.0774)	(0.0701)	(0.0751)	(0.0699)	(0.0686)
L2.Inequality	0.121	0.0866	0.0403	0.112	0.155*
	(0.0891)	(0.0860)	(0.0916)	(0.0842)	(0.0674)
Controls					
L.ΔEPS Total	-0.293	-0.0302	-0.172	0.133	-0.105
	(0.358)	(0.0222)	(0.117)	(0.195)	(0.190)
L2.ΔEPS Total	-0.525	-0.0429	-0.186*	0.237	-0.460*
	(0.280)	(0.0220)	(0.0914)	(0.126)	(0.227)
L.Unemp	0.0578	0.00114	0.00996	-0.0551	0.0165
	(0.0902)	(0.00651)	(0.0281)	(0.0412)	(0.0844)
L2.Unemp	-0.0102	0.00170	-0.000947	0.0308	-0.0124
	(0.0927)	(0.00693)	(0.0309)	(0.0423)	(0.0858)
L.GDP growth	-0.0328	-0.00199	-0.0136	0.0200	0.00653
	(0.0249)	(0.00168)	(0.00810)	(0.0120)	(0.0208)
L2.GDP growth	0.0475*	0.00222*	0.00900	-0.0246**	0.0227
	(0.0189)	(0.00101)	(0.00476)	(0.00885)	(0.0120)
Observations	226	226	226	226	226

Notes: This table reports static two-way fixed effects (TWFE) instrumental-variable estimates for inequality outcomes. The climate policy shock is measured by the first difference of the EPS Total index and is instrumented using the interaction between country-specific mean CBIE exposure and climate shocks, including two lags of the instrument. All specifications include country and year fixed effects, two lags of the dependent variable, and lagged controls. Driscoll–Kraay standard errors are reported in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

A.7 Tables Estimates

A.7.1 Main Model

Table A.7: **IV Local Projections for Gini Inequality Index. EPS Total scenario.**
Coefficient estimates for $h = 0$ to $h = 5$. Country and year FE included. Driscoll-Kraay SEs in parentheses.

	(1) $h=0$	(2) $h=1$	(3) $h=2$	(4) $h=3$	(5) $h=4$	(6) $h=5$
Structural shock						
ΔEPS Total	-1.458*	-3.975***	-3.001	-4.750***	-4.484***	-2.105*
	(0.821)	(1.422)	(1.891)	(1.571)	(1.172)	(1.244)
Lagged dependent variable						
L.Gini	-0.303***	-0.315**	-0.346***	-0.441***	-0.663***	-0.666***
	(0.077)	(0.139)	(0.108)	(0.144)	(0.078)	(0.118)
L2.Gini	0.121	-0.041	-0.094	-0.072	0.064	0.017
	(0.089)	(0.174)	(0.128)	(0.151)	(0.096)	(0.106)
Controls						
L.ΔEPS	-0.293	-1.292**	-0.798	-0.922	-1.201	-0.168
	(0.358)	(0.561)	(0.610)	(0.671)	(0.772)	(0.560)
L2.ΔEPS	-0.525*	-0.767*	-0.464	-0.838*	-0.493	-0.119
	(0.280)	(0.445)	(0.651)	(0.483)	(0.606)	(0.486)
L.Unemp	0.058	-0.026	-0.065	-0.420**	-0.454***	-0.310***
	(0.090)	(0.118)	(0.123)	(0.185)	(0.118)	(0.063)
L2.Unemp	-0.010	0.074	0.110	0.433**	0.468***	0.302***
	(0.093)	(0.110)	(0.129)	(0.204)	(0.132)	(0.071)
L.GDP	-0.033	-0.022	0.005	-0.091*	-0.136***	-0.039
	(0.025)	(0.034)	(0.022)	(0.047)	(0.037)	(0.043)
L2.GDP	0.048**	0.012	-0.026	-0.067***	0.054	-0.007
	(0.019)	(0.023)	(0.019)	(0.021)	(0.071)	(0.037)
Observations	226	208	191	177	164	153
K-P F-stat	8.376	33.817	16.113	8.638	18.886	12.378
Hansen J	4.352	4.306	4.743	4.294	3.807	3.703
p-value J	0.113	0.116	0.093	0.117	0.149	0.157
AR F	6.134	5.353	8.239	7.208	16.059	14.262
AR p-val	0.003	0.005	0.001	0.001	0.000	0.000
Wald χ^2	3.150	7.810	2.519	9.145	14.630	2.864
Wald p-val	0.076	0.005	0.112	0.002	0.000	0.091

Notes: The Hansen J test assesses the null hypothesis that the instruments are valid (overidentification). The Anderson–Rubin test evaluates the joint null that the coefficient on the endogenous regressor is zero and that the instruments are relevant, providing inference robust to weak instruments. The Wald test examines the null hypothesis that the cumulative response of the outcome to an EPS shock is equal to zero at the reported horizon.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.8: **IV Local Projections for Palma Ratio. EPS Total scenario.**
Coefficient estimates for horizons $h = 0$ to $h = 5$. Country and year FE included. Driscoll–Kraay standard errors in parentheses.

	(1) $h = 0$	(2) $h = 1$	(3) $h = 2$	(4) $h = 3$	(5) $h = 4$	(6) $h = 5$
Structural shock						
ΔEPS Total	-0.135**	-0.314***	-0.211*	-0.312***	-0.318***	-0.167*
	(0.058)	(0.093)	(0.114)	(0.099)	(0.080)	(0.091)
Lagged dependent variable						
L.Palma	-0.294***	-0.347***	-0.419***	-0.535***	-0.703***	-0.721***
	(0.070)	(0.134)	(0.124)	(0.139)	(0.073)	(0.100)
L2.Palma	0.087	-0.073	-0.075	-0.009	0.068	0.040
	(0.086)	(0.148)	(0.126)	(0.141)	(0.091)	(0.082)
Controls						
L.ΔEPS	-0.030	-0.097***	-0.051	-0.054	-0.090	-0.013
	(0.022)	(0.037)	(0.043)	(0.050)	(0.055)	(0.040)
L2.ΔEPS	-0.043*	-0.062*	-0.037	-0.063*	-0.040	-0.012
	(0.022)	(0.035)	(0.045)	(0.032)	(0.041)	(0.035)
L.Unemp	0.001	-0.008	-0.006	-0.030**	-0.032***	-0.021***
	(0.007)	(0.008)	(0.009)	(0.013)	(0.009)	(0.004)
L2.Unemp	0.002	0.011	0.009	0.031**	0.034***	0.022***
	(0.007)	(0.008)	(0.009)	(0.015)	(0.010)	(0.005)
L.GDP	-0.002	-0.003	0.000	-0.006	-0.010***	-0.003
	(0.002)	(0.002)	(0.001)	(0.003)	(0.003)	(0.003)
L2.GDP	0.002**	0.000	-0.001	-0.005***	0.004	-0.000
	(0.001)	(0.002)	(0.001)	(0.002)	(0.005)	(0.002)
Observations	226	208	191	177	164	153
K-P F-stat	9.075	35.998	16.699	9.164	17.835	12.580
Hansen J	3.961	4.252	4.981	4.536	3.958	3.551
p-value J	0.138	0.119	0.083	0.104	0.138	0.169
AR F	4.054	5.094	7.868	5.622	22.926	20.035
AR p-val	0.017	0.007	0.001	0.005	0.000	0.000
Wald χ^2	5.332	11.311	3.445	9.856	15.735	3.336
Wald p-val	0.021	0.001	0.063	0.002	0.000	0.068

Notes: The Hansen J test assesses the null hypothesis that the instruments are valid (overidentification). The Anderson–Rubin test evaluates the joint null that the coefficient on the endogenous regressor is zero and that the instruments are relevant, providing inference robust to weak instruments. The Wald test examines the null hypothesis that the cumulative response of the outcome to an EPS shock is equal to zero at the reported horizon.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.9: **IV Local Projections for S80/S20 Inequality Index. EPS Total scenario.**
Coefficient estimates for horizons $h = 0$ to $h = 5$. All models include country and year fixed effects. Driscoll-Kraay standard errors in parentheses.

	(1) $h = 0$	(2) $h = 1$	(3) $h = 2$	(4) $h = 3$	(5) $h = 4$	(6) $h = 5$
Structural shock						
ΔEPS Total	-0.780***	-1.148***	-0.753	-1.322**	-1.280***	-0.504
	(0.212)	(0.354)	(0.535)	(0.528)	(0.386)	(0.457)
Lagged dependent variable						
L.S80/S20	-0.260***	-0.341***	-0.479***	-0.538***	-0.710***	-0.852***
	(0.075)	(0.109)	(0.119)	(0.152)	(0.092)	(0.155)
L2.S80/S20	0.040	-0.074	-0.080	-0.064	-0.022	0.042
	(0.092)	(0.159)	(0.141)	(0.154)	(0.118)	(0.118)
Controls						
L.ΔEPS	-0.172	-0.370**	-0.171	-0.264	-0.324	0.003
	(0.117)	(0.175)	(0.181)	(0.212)	(0.286)	(0.224)
L2.ΔEPS	-0.186**	-0.205	-0.120	-0.194	-0.122	0.013
	(0.091)	(0.132)	(0.200)	(0.167)	(0.194)	(0.177)
L.Unemp	0.010	-0.001	-0.011	-0.125**	-0.157***	-0.130***
	(0.028)	(0.041)	(0.037)	(0.053)	(0.034)	(0.022)
L2.Unemp	-0.001	0.009	0.013	0.113**	0.138***	0.106***
	(0.031)	(0.039)	(0.042)	(0.058)	(0.038)	(0.022)
L.GDP	-0.014*	-0.009	-0.000	-0.027*	-0.038***	-0.018
	(0.008)	(0.014)	(0.007)	(0.015)	(0.013)	(0.015)
L2.GDP	0.009*	0.003	-0.008	-0.022***	0.003	-0.013
	(0.005)	(0.007)	(0.007)	(0.008)	(0.028)	(0.012)
Observations	226	208	191	177	164	153
K-P F-stat	8.034	32.497	15.744	9.503	15.896	11.374
Hansen J	3.113	5.113	5.085	4.163	3.771	3.632
p-value J	0.211	0.078	0.079	0.125	0.152	0.163
AR F	9.113	8.011	12.010	14.810	19.488	18.747
AR p-val	0.000	0.001	0.000	0.000	0.000	0.000
Wald χ^2	13.570	10.544	1.979	6.269	11.000	1.219
p-value Wald	0.000	0.001	0.160	0.012	0.001	0.270

Notes: The Hansen J test assesses the null hypothesis that the instruments are valid (overidentification). The Anderson–Rubin test evaluates the joint null that the coefficient on the endogenous regressor is zero and that the instruments are relevant, providing inference robust to weak instruments. The Wald test examines the null hypothesis that the cumulative response of the outcome to an EPS shock is equal to zero at the reported horizon.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.10: **IV Local Projections for Gini Index. EPS Market scenario.**
Coefficient estimates for horizons $h = 0$ to $h = 5$. All models include country and year fixed effects. Driscoll-Kraay standard errors in parentheses.

	(1) $h = 0$	(2) $h = 1$	(3) $h = 2$	(4) $h = 3$	(5) $h = 4$	(6) $h = 5$
Structural shock						
ΔEPS Market	2.133***	2.563	3.906*	5.722**	8.940***	4.736***
	(0.586)	(1.675)	(2.320)	(2.478)	(2.720)	(1.599)
Lagged dependent variable						
L.Gini	-0.198**	-0.345*	-0.091	-0.099	-0.176	-0.343*
	(0.088)	(0.185)	(0.191)	(0.188)	(0.163)	(0.203)
L2.Gini	0.082	0.127	-0.155	-0.159	0.071	0.090
	(0.071)	(0.135)	(0.139)	(0.210)	(0.214)	(0.144)
Controls						
L.ΔEPS	0.442**	-0.155	0.321	1.330	2.200*	2.047***
	(0.175)	(0.721)	(0.975)	(0.984)	(1.199)	(0.545)
L2.ΔEPS	-0.245*	-0.466	0.294	0.229	1.214**	0.576**
	(0.141)	(0.552)	(0.531)	(0.601)	(0.526)	(0.247)
L.Unemp	0.129**	0.267**	0.124	-0.221*	-0.253**	-0.301***
	(0.053)	(0.118)	(0.098)	(0.118)	(0.121)	(0.107)
L2.Unemp	-0.079*	-0.189*	-0.076	0.234**	0.317***	0.294***
	(0.046)	(0.107)	(0.098)	(0.115)	(0.112)	(0.092)
L.GDP	-0.009	0.040	0.026	-0.069**	-0.142***	-0.101*
	(0.013)	(0.027)	(0.029)	(0.032)	(0.039)	(0.054)
L2.GDP	0.068***	0.069***	0.022	0.006	0.131	-0.011
	(0.020)	(0.025)	(0.025)	(0.033)	(0.119)	(0.045)
Observations	226	208	191	177	164	153
K-P F-stat	14.876	11.509	21.497	11.940	3.335	2.004
Hansen J	1.580	1.851	1.791	0.924	1.048	2.755
p-value J	0.454	0.396	0.408	0.630	0.592	0.252
AR F	4.420	5.343	7.892	4.962	10.470	14.452
AR p-val	0.012	0.005	0.001	0.008	0.000	0.000
Wald χ^2	13.238	2.342	2.834	5.332	10.800	8.776
p-value Wald	0.000	0.126	0.092	0.021	0.001	0.003

Notes: The Hansen J test assesses the null hypothesis that the instruments are valid (overidentification). The Anderson–Rubin test evaluates the joint null that the coefficient on the endogenous regressor is zero and that the instruments are relevant, providing inference robust to weak instruments. The Wald test examines the null hypothesis that the cumulative response of the outcome to an EPS shock is equal to zero at the reported horizon.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.11: **IV Local Projections for Palma Inequality Index. EPS Market scenario.**
Coefficient estimates for horizons $h = 0$ to $h = 5$. All models include country and year fixed effects. Driscoll-Kraay standard errors in parentheses.

	(1) $h = 0$	(2) $h = 1$	(3) $h = 2$	(4) $h = 3$	(5) $h = 4$	(6) $h = 5$
Structural shock						
ΔEPS Market	0.143***	0.181	0.250	0.379*	0.733***	0.287*
	(0.038)	(0.149)	(0.199)	(0.208)	(0.230)	(0.150)
Lagged dependent variable						
L.Palma	-0.230***	-0.354*	-0.185	-0.220	-0.184	-0.486**
	(0.075)	(0.182)	(0.195)	(0.182)	(0.165)	(0.194)
L2.Palma	0.075	0.084	-0.106	-0.093	0.080	0.133
	(0.065)	(0.134)	(0.113)	(0.181)	(0.197)	(0.097)
Controls						
L.ΔEPS	0.022*	-0.018	0.010	0.075	0.166*	0.123**
	(0.011)	(0.054)	(0.070)	(0.073)	(0.088)	(0.050)
L2.ΔEPS	-0.025**	-0.039	0.012	0.010	0.090**	0.030*
	(0.010)	(0.041)	(0.038)	(0.041)	(0.038)	(0.016)
L.Unemp	0.006*	0.013	0.005	-0.017**	-0.020**	-0.021***
	(0.004)	(0.010)	(0.007)	(0.008)	(0.010)	(0.006)
L2.Unemp	-0.003	-0.008	-0.001	0.019**	0.027***	0.021***
	(0.003)	(0.009)	(0.007)	(0.009)	(0.009)	(0.005)
L.GDP	-0.000	0.002	0.002	-0.004	-0.012***	-0.007*
	(0.001)	(0.002)	(0.002)	(0.003)	(0.003)	(0.004)
L2.GDP	0.004***	0.004**	0.001	0.000	0.014	0.000
	(0.001)	(0.002)	(0.002)	(0.003)	(0.009)	(0.003)
Observations	226	208	191	177	164	153
K-P F-stat	13.924	11.037	17.584	10.662	3.619	1.857
S-Y 5% crit.	18.370	18.370	18.370	18.370	18.370	18.370
Hansen J	1.937	2.324	1.871	1.037	1.466	2.993
p-value J	0.380	0.313	0.392	0.595	0.480	0.224
AR F	3.591	5.015	7.344	4.239	9.257	28.414
AR p-val	0.026	0.007	0.001	0.015	0.000	0.000
Wald χ^2	14.465	1.479	1.572	3.312	10.191	3.666
Wald p-val	0.000	0.224	0.210	0.069	0.001	0.056

Notes: The Hansen J test assesses the null hypothesis that the instruments are valid (overidentification). The Anderson–Rubin test evaluates the joint null that the coefficient on the endogenous regressor is zero and that the instruments are relevant, providing inference robust to weak instruments. The Wald test examines the null hypothesis that the cumulative response of the outcome to an EPS shock is equal to zero at the reported horizon.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.12: **IV Local Projections for S80/S20 Inequality Index. EPS Market scenario.**
Coefficient estimates for horizons $h = 0$ to $h = 5$. All models include country and year fixed effects. Driscoll–Kraay standard errors in parentheses.

	(1) $h = 0$	(2) $h = 1$	(3) $h = 2$	(4) $h = 3$	(5) $h = 4$	(6) $h = 5$
Structural shock						
ΔEPS Market	0.707***	0.820	1.329*	1.790**	3.030***	0.871
	(0.241)	(0.680)	(0.731)	(0.798)	(0.820)	(0.718)
Lagged dependent variable						
L.S80/S20	-0.124	-0.264	-0.176	-0.171	-0.159	-0.695**
	(0.106)	(0.190)	(0.184)	(0.150)	(0.189)	(0.288)
L2.S80/S20	-0.025	-0.014	-0.167	-0.154	0.021	0.145
	(0.087)	(0.140)	(0.167)	(0.234)	(0.278)	(0.115)
Controls						
L.ΔEPS	0.109	-0.078	0.125	0.415	0.751*	0.453*
	(0.069)	(0.226)	(0.304)	(0.328)	(0.416)	(0.260)
L2.ΔEPS	-0.071	-0.140	0.101	0.125	0.446***	0.068
	(0.054)	(0.198)	(0.175)	(0.170)	(0.171)	(0.103)
L.Unemp	0.043**	0.098*	0.035	-0.077**	-0.112**	-0.138***
	(0.020)	(0.051)	(0.036)	(0.037)	(0.045)	(0.026)
L2.Unemp	-0.032*	-0.081*	-0.035	0.063*	0.108***	0.105***
	(0.017)	(0.045)	(0.037)	(0.037)	(0.037)	(0.023)
L.GDP	-0.005	0.014	0.004	-0.022**	-0.048***	-0.031*
	(0.004)	(0.014)	(0.011)	(0.011)	(0.011)	(0.018)
L2.GDP	0.019***	0.018*	0.004	-0.001	0.035	-0.017
	(0.006)	(0.010)	(0.010)	(0.013)	(0.039)	(0.013)
Observations	226	208	191	177	164	153
K-P F-stat	16.214	10.400	19.535	12.108	3.489	1.690
Hansen J	2.270	2.124	1.658	1.166	1.709	3.463
p-value J	0.321	0.346	0.436	0.558	0.426	0.177
AR F	8.902	7.877	10.647	6.674	13.813	16.086
AR p-val	0.000	0.001	0.000	0.002	0.000	0.000
Wald χ^2	8.611	1.454	3.308	5.031	13.656	1.472
Wald p-val	0.003	0.228	0.069	0.025	0.000	0.225

Notes: The Hansen J test assesses the null hypothesis that the instruments are valid (overidentification). The Anderson–Rubin test evaluates the joint null that the coefficient on the endogenous regressor is zero and that the instruments are relevant, providing inference robust to weak instruments. The Wald test examines the null hypothesis that the cumulative response of the outcome to an EPS shock is equal to zero at the reported horizon.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.13: **IV Local Projections for Gini Index. EPS Non–Market scenario.**
Coefficient estimates for horizons $h = 0$ to $h = 5$. All models include country and year fixed effects. Driscoll–Kraay standard errors in parentheses.

	(1) $h = 0$	(2) $h = 1$	(3) $h = 2$	(4) $h = 3$	(5) $h = 4$	(6) $h = 5$
Structural shock						
ΔEPS Non–Market	3.479	7.571*	2.222	-5.193*	-3.838*	1.490
	(2.469)	(4.541)	(3.356)	(2.810)	(2.307)	(2.399)
Lagged dependent variable						
L.Gini	-0.318**	-0.473**	-0.424***	-0.573***	-0.680***	-0.787***
	(0.136)	(0.196)	(0.115)	(0.154)	(0.112)	(0.097)
L2.Gini	-0.054	-0.205	-0.179	0.285	0.323**	0.086
	(0.181)	(0.296)	(0.169)	(0.227)	(0.127)	(0.148)
Controls						
L.ΔEPS	1.175	2.213*	0.678	-1.493**	-1.153*	0.679
	(0.789)	(1.184)	(0.907)	(0.721)	(0.656)	(0.661)
L2.ΔEPS	0.532	1.096	0.334	-0.886**	-0.397	0.538
	(0.412)	(0.667)	(0.497)	(0.419)	(0.377)	(0.340)
L.Unemp	0.364**	0.575**	0.207	-0.480**	-0.462**	-0.129
	(0.182)	(0.241)	(0.210)	(0.238)	(0.187)	(0.196)
L2.Unemp	-0.346	-0.613**	-0.209	0.612**	0.528**	0.078
	(0.216)	(0.286)	(0.253)	(0.281)	(0.214)	(0.233)
L.GDP	0.065	0.138	0.067	-0.128**	-0.132***	0.045
	(0.040)	(0.090)	(0.060)	(0.059)	(0.042)	(0.128)
L2.GDP	0.059**	0.088***	0.007	-0.036	0.004	-0.002
	(0.024)	(0.030)	(0.026)	(0.031)	(0.082)	(0.037)
Observations	226	208	191	177	164	153
K-P F-stat	4.654	5.489	1.547	3.775	3.935	3.593
Hansen J	1.874	1.918	4.392	3.687	2.351	4.360
p-value J	0.392	0.383	0.111	0.158	0.309	0.113
AR F	4.931	5.304	8.310	5.354	13.562	17.527
AR p-val	0.007	0.005	0.001	0.006	0.000	0.000
Wald χ^2	1.985	2.780	0.438	3.415	2.769	0.386
Wald p-val	0.159	0.095	0.508	0.065	0.096	0.535

Notes: The Hansen J test assesses the null hypothesis that the instruments are valid (overidentification). The Anderson–Rubin test evaluates the joint null that the coefficient on the endogenous regressor is zero and that the instruments are relevant, providing inference robust to weak instruments. The Wald test examines the null hypothesis that the cumulative response of the outcome to an EPS shock is equal to zero at the reported horizon.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.14: **IV Local Projections for Palma Inequality Index. EPS Non–Market scenario.**
Coefficient estimates for horizons $h = 0$ to $h = 5$. All models include country and year fixed effects. Driscoll–Kraay standard errors in parentheses.

	(1) $h = 0$	(2) $h = 1$	(3) $h = 2$	(4) $h = 3$	(5) $h = 4$	(6) $h = 5$
Structural shock						
ΔEPS Non–Market	0.198	0.491	0.058	-0.385**	-0.268*	0.157
	(0.170)	(0.299)	(0.213)	(0.191)	(0.145)	(0.161)
Lagged dependent variable						
L.Palma	-0.318**	-0.489**	-0.465***	-0.618***	-0.705***	-0.816***
	(0.146)	(0.205)	(0.091)	(0.177)	(0.111)	(0.098)
L2.Palma	-0.090	-0.311	-0.103	0.385	0.365**	0.038
	(0.232)	(0.387)	(0.170)	(0.257)	(0.148)	(0.182)
Controls						
L.ΔEPS	0.069	0.146*	0.021	-0.110**	-0.085**	0.064
	(0.053)	(0.083)	(0.057)	(0.051)	(0.043)	(0.046)
L2.ΔEPS	0.032	0.075	0.010	-0.069**	-0.030	0.048**
	(0.029)	(0.047)	(0.031)	(0.030)	(0.025)	(0.024)
L.Unemp	0.021	0.035**	0.008	-0.038**	-0.033***	-0.004
	(0.013)	(0.017)	(0.013)	(0.017)	(0.012)	(0.013)
L2.Unemp	-0.019	-0.038*	-0.007	0.049**	0.039***	0.000
	(0.015)	(0.021)	(0.017)	(0.020)	(0.014)	(0.016)
L.GDP	0.003	0.009	0.003	-0.009**	-0.009***	0.005
	(0.003)	(0.006)	(0.004)	(0.004)	(0.003)	(0.009)
L2.GDP	0.003**	0.006**	0.001	-0.003	0.001	0.000
	(0.001)	(0.002)	(0.002)	(0.002)	(0.006)	(0.002)
Observations	226	208	191	177	164	153
K-P F-stat	4.253	4.947	1.619	3.352	3.397	3.153
Hansen J	1.909	2.381	4.577	3.358	2.405	4.017
p-value J	0.385	0.304	0.101	0.187	0.301	0.134
AR F	2.925	5.002	8.017	4.528	13.188	28.458
AR p-val	0.052	0.007	0.001	0.012	0.000	0.000
Wald χ^2	1.368	2.698	0.073	4.073	3.422	0.960
Wald p-val	0.242	0.101	0.787	0.044	0.064	0.327

Notes: The Hansen J test assesses the null hypothesis that the instruments are valid (overidentification). The Anderson–Rubin test evaluates the joint null that the coefficient on the endogenous regressor is zero and that the instruments are relevant, providing inference robust to weak instruments. The Wald test examines the null hypothesis that the cumulative response of the outcome to an EPS shock is equal to zero at the reported horizon.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.15: **IV Local Projections for Gini Index. EPS Technology scenario.**
Coefficient estimates for horizons $h = 0$ to $h = 5$. All models include country and year fixed effects. Driscoll–Kraay standard errors in parentheses.

	(1) $h = 0$	(2) $h = 1$	(3) $h = 2$	(4) $h = 3$	(5) $h = 4$	(6) $h = 5$
Structural shock						
ΔEPS Technology	-0.735***	-1.303***	-1.282***	-1.303***	-1.210***	-0.547*
	(0.269)	(0.273)	(0.404)	(0.361)	(0.291)	(0.315)
Lagged dependent variable						
L.Gini	-0.236***	-0.258*	-0.277***	-0.412***	-0.654***	-0.673***
	(0.088)	(0.132)	(0.104)	(0.122)	(0.079)	(0.130)
L2.Gini	0.047	-0.107	-0.200*	-0.133	0.074	0.048
	(0.096)	(0.149)	(0.120)	(0.129)	(0.075)	(0.117)
Controls						
L.ΔEPS	-0.201	-0.279*	-0.027	0.080	0.048	-0.042
	(0.141)	(0.145)	(0.124)	(0.202)	(0.256)	(0.118)
L2.ΔEPS	-0.272***	-0.256*	-0.284	-0.246	-0.340*	-0.282**
	(0.083)	(0.143)	(0.246)	(0.232)	(0.190)	(0.128)
L.Unemp	0.077	0.045	-0.035	-0.299*	-0.339***	-0.298***
	(0.102)	(0.090)	(0.109)	(0.154)	(0.102)	(0.090)
L2.Unemp	-0.042	-0.022	0.055	0.290*	0.333***	0.271***
	(0.101)	(0.089)	(0.116)	(0.165)	(0.107)	(0.091)
L.GDP	-0.026	-0.014	0.001	-0.071	-0.113***	-0.034
	(0.024)	(0.021)	(0.017)	(0.045)	(0.026)	(0.046)
L2.GDP	0.041**	0.032*	-0.007	-0.032	0.064	-0.014
	(0.017)	(0.017)	(0.020)	(0.021)	(0.078)	(0.040)
Observations	226	208	191	177	164	153
K-P F-stat	15.805	56.856	37.162	24.115	39.684	51.408
S-Y 5% crit.	18.370	18.370	18.370	18.370	18.370	18.370
Hansen J	2.106	2.654	4.446	4.294	4.088	3.651
p-value J	0.349	0.265	0.108	0.117	0.129	0.161
AR F	6.934	6.052	7.510	9.021	13.239	13.012
AR p-val	0.001	0.003	0.001	0.000	0.000	0.000
Wald χ^2	7.460	22.765	10.078	13.008	17.264	3.029
Wald p-val	0.006	0.000	0.002	0.000	0.000	0.082

Notes: The Hansen J test assesses the null hypothesis that the instruments are valid (overidentification). The Anderson–Rubin test evaluates the joint null that the coefficient on the endogenous regressor is zero and that the instruments are relevant, providing inference robust to weak instruments. The Wald test examines the null hypothesis that the cumulative response of the outcome to an EPS shock is equal to zero at the reported horizon.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.16: **IV Local Projections for Palma Inequality Index. EPS Technology scenario.**
Coefficient estimates for horizons $h = 0$ to $h = 5$. All models include country and year fixed effects. Driscoll–Kraay standard errors in parentheses.

	(1) $h = 0$	(2) $h = 1$	(3) $h = 2$	(4) $h = 3$	(5) $h = 4$	(6) $h = 5$
Structural shock						
ΔEPS Technology	-0.050**	-0.096***	-0.082***	-0.082***	-0.083***	-0.042*
	(0.020)	(0.021)	(0.026)	(0.025)	(0.021)	(0.023)
Lagged dependent variable						
L.Palma	-0.238***	-0.308**	-0.367***	-0.523***	-0.698***	-0.715***
	(0.077)	(0.127)	(0.117)	(0.113)	(0.063)	(0.112)
L2.Palma	0.021	-0.138	-0.174	-0.074	0.066	0.056
	(0.090)	(0.131)	(0.119)	(0.116)	(0.078)	(0.103)
Controls						
L.ΔEPS	-0.012	-0.019*	-0.004	0.006	0.002	-0.002
	(0.009)	(0.010)	(0.009)	(0.014)	(0.017)	(0.009)
L2.ΔEPS	-0.019***	-0.025**	-0.021	-0.016	-0.024*	-0.020**
	(0.006)	(0.012)	(0.018)	(0.016)	(0.013)	(0.010)
L.Unemp	0.004	-0.002	-0.003	-0.022**	-0.024***	-0.020***
	(0.007)	(0.006)	(0.008)	(0.010)	(0.007)	(0.006)
L2.Unemp	-0.002	0.003	0.005	0.022*	0.025***	0.019***
	(0.007)	(0.006)	(0.008)	(0.011)	(0.007)	(0.006)
L.GDP	-0.001	-0.002	0.000	-0.004	-0.008***	-0.002
	(0.002)	(0.002)	(0.001)	(0.003)	(0.002)	(0.003)
L2.GDP	0.002**	0.002*	-0.000	-0.002*	0.005	-0.001
	(0.001)	(0.001)	(0.002)	(0.001)	(0.005)	(0.003)
Observations	226	208	191	177	164	153
K-P F-stat	16.265	61.067	37.777	24.066	35.568	39.831
S-Y 5% crit.	18.370	18.370	18.370	18.370	18.370	18.370
Hansen J	1.817	2.725	4.825	4.519	4.389	3.534
p-value J	0.403	0.256	0.090	0.104	0.111	0.171
AR F	4.399	5.447	7.118	6.731	11.575	22.795
AR p-val	0.012	0.005	0.001	0.002	0.000	0.000
Wald χ^2	6.202	20.545	10.110	10.475	16.346	3.291
Wald p-val	0.013	0.000	0.001	0.001	0.000	0.070

Notes: The Hansen J test assesses the null hypothesis that the instruments are valid (overidentification). The Anderson–Rubin test evaluates the joint null that the coefficient on the endogenous regressor is zero and that the instruments are relevant, providing inference robust to weak instruments. The Wald test examines the null hypothesis that the cumulative response of the outcome to an EPS shock is equal to zero at the reported horizon.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.17: **IV Local Projections for S80/S20 Inequality Index. EPS Technology scenario.**
Coefficient estimates for horizons $h = 0$ to $h = 5$. All models include country and year fixed effects. Driscoll–Kraay standard errors in parentheses.

	(1) $h = 0$	(2) $h = 1$	(3) $h = 2$	(4) $h = 3$	(5) $h = 4$	(6) $h = 5$
Structural shock						
ΔEPS Technology	-0.275***	-0.416***	-0.329**	-0.351***	-0.334***	-0.107
	(0.077)	(0.076)	(0.128)	(0.119)	(0.099)	(0.116)
Lagged dependent variable						
L.S80/S20	-0.186**	-0.274***	-0.406***	-0.519***	-0.738***	-0.899***
	(0.079)	(0.103)	(0.111)	(0.124)	(0.098)	(0.158)
L2.S80/S20	-0.051	-0.180	-0.184	-0.121	-0.007	0.098
	(0.094)	(0.138)	(0.124)	(0.126)	(0.086)	(0.122)
Controls						
L.ΔEPS	-0.086*	-0.093**	0.003	0.042	0.013	-0.009
	(0.046)	(0.046)	(0.032)	(0.055)	(0.082)	(0.039)
L2.ΔEPS	-0.070**	-0.057	-0.042	-0.029	-0.086	-0.062
	(0.029)	(0.039)	(0.074)	(0.086)	(0.065)	(0.054)
L.Unemp	0.015	0.005	-0.004	-0.093**	-0.129***	-0.133***
	(0.028)	(0.032)	(0.033)	(0.042)	(0.029)	(0.030)
L2.Unemp	-0.010	-0.006	0.002	0.076*	0.104***	0.103***
	(0.030)	(0.031)	(0.036)	(0.044)	(0.031)	(0.029)
L.GDP	-0.010	-0.012	-0.001	-0.021	-0.031***	-0.018
	(0.007)	(0.010)	(0.006)	(0.014)	(0.010)	(0.016)
L2.GDP	0.008*	0.008	-0.003	-0.012	0.005	-0.017
	(0.005)	(0.008)	(0.009)	(0.008)	(0.029)	(0.013)
Observations	226	208	191	177	164	153
K-P F-stat	11.650	51.712	39.866	27.938	40.061	50.868
S-Y 5% crit.	18.370	18.370	18.370	18.370	18.370	18.370
Hansen J	1.491	4.380	4.974	4.329	4.205	3.613
p-value J	0.475	0.112	0.083	0.115	0.122	0.164
AR F	9.808	7.380	11.579	21.371	16.278	16.762
AR p-val	0.000	0.001	0.000	0.000	0.000	0.000
Wald χ^2	12.624	29.950	6.585	8.682	11.260	0.852
Wald p-val	0.000	0.000	0.010	0.003	0.001	0.356

Notes: The Hansen J test assesses the null hypothesis that the instruments are valid (overidentification). The Anderson–Rubin test evaluates the joint null that the coefficient on the endogenous regressor is zero and that the instruments are relevant, providing inference robust to weak instruments. The Wald test examines the null hypothesis that the cumulative response of the outcome to an EPS shock is equal to zero at the reported horizon.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

A.8 Quantile Model

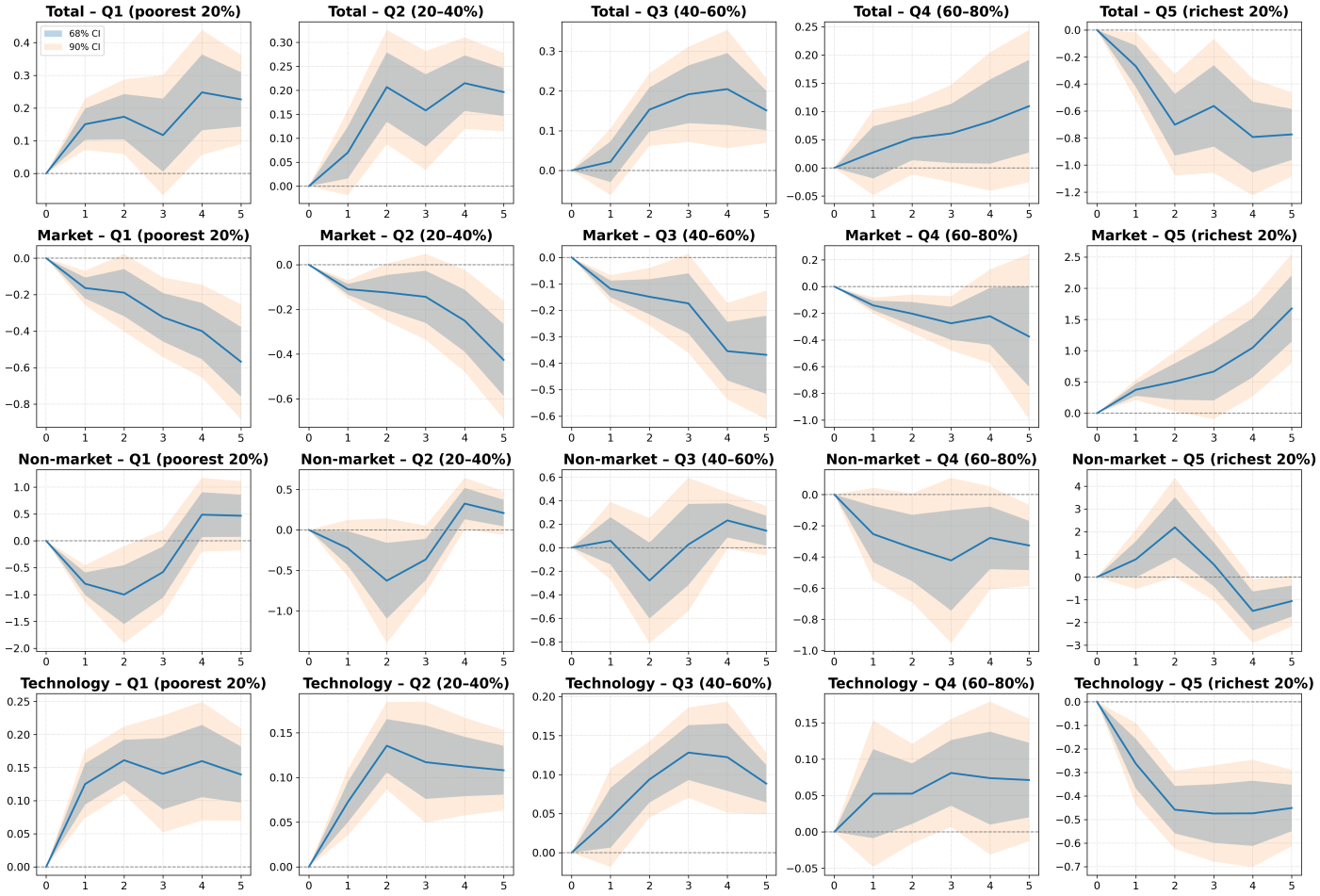


Figure A.3: *Impulse-response functions of income quantile shares (net income, PPP-adjusted, 2021 USD) to a one-standard-deviation shock in the annual change of the EPS Index and its market-based, non-market, and technology-support components. Rows correspond to EPS pillars, while columns report responses for quantile from the poorest (Q1) to the richest (Q5). Income shares are expressed in percentage points of total net income at 2021 PPP US; impulse responses therefore represent level changes (in percentage points) at each horizon. Shaded areas denote 90 and 68 percent confidence bands obtained from the IV Local Projection framework with country and year fixed effects and Driscoll-Kraay standard errors. Standard macroeconomics controls included. Horizons are measured in years.*

A.9 Macroeconomic channel: Unemployment and wage-share responses

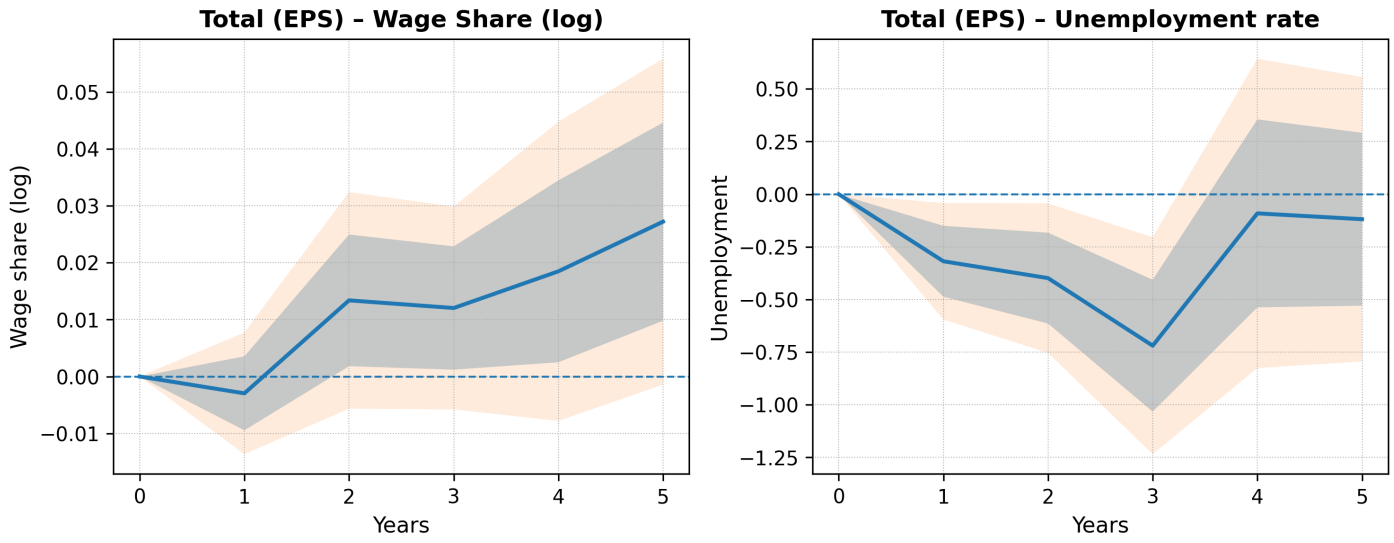


Figure A.4: *Impulse responses of the unemployment rate (top row, World Bank data) and the (log) adjusted wage share (bottom row, AMECO data; Chile excluded) to a one-standard-deviation shock in the annual change of the EPS Index and its subcomponents. Each column reports responses for a specific policy dimension. Unemployment rate responses are expressed in percentage points, while the wage share is expressed in log deviations and can be interpreted approximately as percentage changes. Shaded areas denote 90 and 68 percent confidence bands obtained from the IV Local Projection framework with country and year fixed effects and Driscoll-Kraay standard errors. Standard macroeconomics controls included. Horizons are measured in years.*

A.10 Gender-differentiated employment responses

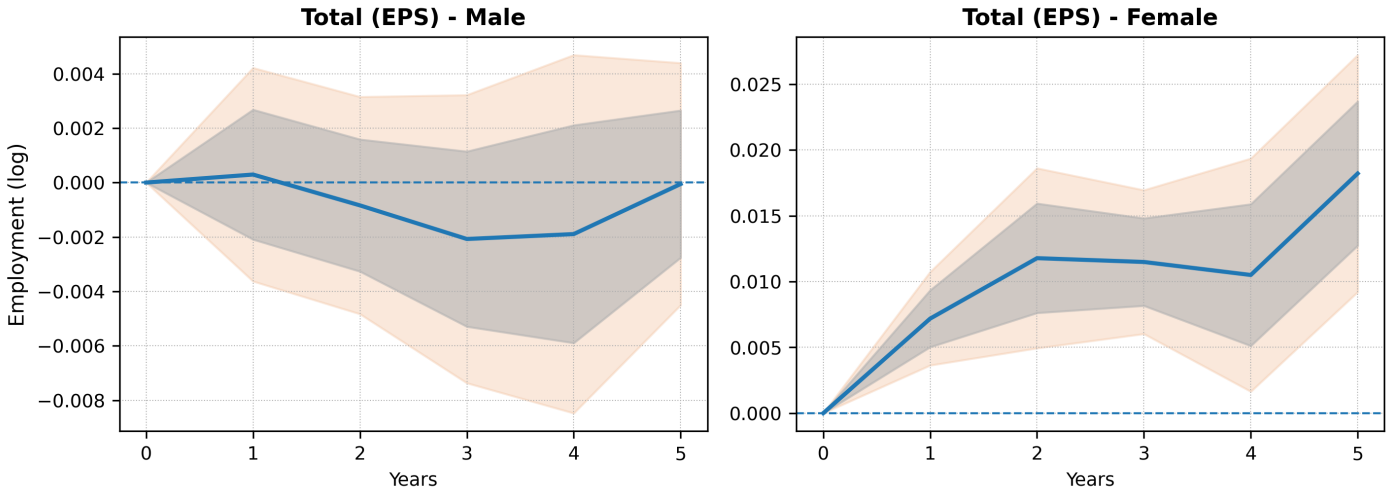


Figure A.5: *Impulse responses of (log) male and female employment (OECD data), to a one-standard-deviation shock in the annual change of the EPS Index. Responses are expressed in log deviations and can be interpreted approximately as percentage changes. Shaded areas represent 90 and 68 percent confidence bands obtained from the IV Local Projection framework with country and year fixed effects and Driscoll-Kraay standard errors. Standard macroeconomics such as GDP Growth and inflations controls are included. Horizons are measured in years.*

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Conclusions

The papers contained in this PhD thesis represent both a point of departure and a step towards further research. Although they do not constitute an end point, they offer preliminary yet meaningful findings and open promising avenues for future work at the intersection of macro-finance, inequality and the low-carbon transition.

The first paper systematises the transmission channels linking the low-carbon transition to income inequality. Two main mechanisms are identified: (i) a real-economy channel driven by energy-price dynamics and distributional burdens on households and productive sectors; and (ii) a macro-financial channel operating through agents' expectations regarding the speed and credibility of decarbonisation. The results highlight the need for bold and coordinated policy packages, rather than fragmented interventions, to address economic, environmental, and social outcomes in a coherent manner. The paper also outlines several underexplored areas in the existing literature and proposes directions for further research.

The second contribution provides, to our knowledge, the first attempt to link the low-carbon transition with green securitisation within an AB-SFC framework. Under the chosen parametrisation, the model shows that achieving a comprehensive green retrofit of private dwellings may be hindered by credit-rationing mechanisms, particularly for lower-income households facing high levels of indebtedness. As a result, the pace of retrofit investment falls short of the levels required to meet climate commitments, suggesting that fiscal, redistributive, and financial measures are necessary to expand access to green credit and avoid regressive outcomes.

The third and final paper offers an empirical validation of the preceding theoretical and modelling framework. Building on recent evidence regarding the role of institutions in enabling effective climate-policy implementation, it introduces a novel instrument based on climate-related central-bank communication combined with country-specific institutional characteristics. The results indicate substantial heterogeneity in the distributional effects of environmental policy: market-based measures generate regressive but relatively short- to medium-term effects, while technology-support policies display more positive redistributive patterns. These findings suggest that a fair socio-economic transition can be facilitated by recycling revenues from market-based instruments, such as carbon taxation,

into technology-support programmes or targeted transfers for vulnerable households.

Overall, the thesis underscores the importance of coherent, distributive and redistributive policy design for a "just" and financially stable low-carbon transition. While the conclusions remain preliminary, they provide analytical foundations and empirical evidence that can support future research, policy design, and model development in this complex and evolving field.