INSTITUTE
OF ECONOMICS

Scuola Superiore
Sant'Anna

LEM | Laboratory of Economics and Management

Institute of Economics
Scuola Superiore Sant'Anna

Piazza Martiri della Libertà, 33 - 56127 Pisa, Italy
ph. +39 050 88.33.43
institute.economics@sssup.it

LEM
WORKING PAPER SERIES

Tackling emissions and inequality: policy insights from an agent-based model

Giacomo Ravaioli [a,b]
Francesco Lamperti [b,c]
Andrea Roventini [b,d]
Tiago Domingos [a]

[a] MARETEC, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
[b] Institute of Economics and L'EMbeDS, Scuola Superiore Sant'Anna, Pisa, Ital
[c] RFF-CMCC European Institute on Economics and the Environment, Milan, Italy
[d] OFCE-Sciences Po, France

2025/14 April 2025
ISSN(ONLINE): 2284-0400
DOI: 10.57838/sssa/tzz6-cc83

Tackling emissions and inequality: policy insights from an agent-based model

Giacomo Ravaioli[1,2,*], Francesco Lamperti[2,3], Andrea Roventini[2,4], Tiago Domingos[1]

[1] MARETEC − Marine, Environment and Technology Centre, LARSyS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, 1049-001 Lisbon, Portugal
[2] Institute of Economics and EMbeDS, Scuola Superiore Sant'Anna, Piazza Martiri della Libertà 33, 56127 Pisa, Italy
[3] RFF-CMCC European Institute on Economics and the Environment, via Bergognone 34, 20144 Milano, Italy
[4] OFCE-Sciences Po, France

*Corresponding author. E-mail address: giacomo.ravaioli@tecnico.ulisboa.pt

Abstract: Climate change and economic inequality are two critical and interlinked global challenges. The feasibility of jointly reducing greenhouse gas emissions and inequality has often been questioned. Here, we aim to test whether a properly designed mix of progressive and environmental fiscal policies can effectively reduce both while improving economic dynamics. We extend the DSK integrated-assessment agent-based model to combine an income class-based analysis of inequality with an improved accounting of emissions. We calibrate the model to the European Union and employ it to explore how fiscal policies can tackle the coevolution of income inequality and carbon emission. The results show that no single policy in our portfolio can simultaneously reduce inequality and emissions. Redistributing income increases aggregate consumption and hence emissions, whereas environmental taxes risk hampering economic growth and stability. In contrast, a combination of progressive fiscal policies, green subsidies to reduce carbon intensity of production and a mild carbon tax achieves both goals, while increasing employment, growth, stability and the consumption of low-income households. A potential trade-off emerges between increasing economic growth and reducing emissions, mediated by the extent to which green innovations lead to higher productivity. In conclusion, our results show that moving towards a sustainable and inclusive economy needs the co-design of distributive, innovation and mitigation policies.

Keywords: climate policies, inequality, mitigation, just transition, ecological macroeconomics, agent-based modelling

JEL classification: D31, E61, H23, Q43, Q54

1 Introduction

Climate change and economic inequality are two of the most pressing challenges of this century, and they are closely interlinked. Climate change disproportionately affects low-income households (Mumtaz and Theophilopoulou, 2024; Palagi et al., 2022; Piontek et al., 2021) and poorly designed climate policies can worsen inequality undermining climate action (Bettarelli et al., 2024; Bistline et al., 2024; Costantini et al., 2025; Känzig, 2023; Maestre-Andrés et al., 2019; Vona, 2023). Income is the main driver of individual emissions and its unequal distribution translates into high carbon and energy footprint inequality (Büchs and Schnepf, 2013; Chancel, 2022; Ivanova and Wood, 2020; Oswald et al., 2020; Sager, 2019). Nevertheless, the possibility of jointly reducing inequality and emissions has often been questioned, mainly on the basis that redistributing income is likely to increase consumption (Berthe and Elie, 2015; Dorn et al., 2024; Lamperti et al., 2025; Liobikienė, 2020; Sager, 2019). However, global scenarios showed that this would have only a limited impact on total carbon emissions (Millward-Hopkins and Oswald, 2021; Oswald et al., 2021; Rao and Min, 2018). Therefore, we want study whether there exist policy combinations able to jointly reduce inequality and emissions.

The academic literature has traditionally devoted limited attention to distributional issues in climate-economy modelling (Emmerling and Tavoni, 2021; Hardt and O'Neill, 2017; Rao et al., 2017). However, interest in this topic has recently increased: some studies included within-country economic inequality in mainstream integrated assessment models (IAMs), but applications are limited to assessing carbon pricing and alternative revenue recycling schemes (Budolfson et al., 2021, 2017; Emmerling et al., 2024; Malafry and Brinca, 2022). These models inform Intergovernmental Panel on Climate Change (IPCC) reports, but have been widely criticised for their limitations in addressing distributional issues, disequilibrium phenomena and uncertainty, in addition to downplaying demand-side impacts on the economy and failing to fully capture endogenous technological change and macrofinancial feedback loops (Dafermos et al., 2024; Farmer et al., 2015; Keen, 2020; Stern et al., 2022). These limitations highlight the need for alternative approaches.

In this paper, we employ an integrated assessment agent-based model (ABM) (Lamperti et al., 2018) calibrated on a high-income economy to study whether progressive and environmental fiscal policies can simultaneously reduce carbon emissions and personal economic inequality, while maintaining macroeconomic stability. Macroeconomic ABMs are bottom-up evolutionary simulations featuring multiple heterogenous agents, whose interaction in different markets leads to the emergence of economic aggregates and dynamics (Dawid and Delli Gatti, 2018; Dosi and Roventini, 2019; Fagiolo, 2016). More specifically, we extend the "Dystopian Schumpeter meeting Keynes" (DSK) ABM (Lamperti et al., 2018, 2019a, 2020, 2021; Reissl et al., 2024) along two directions. First, we introduce economic inequality by disaggregating the household sector into three classes differing by income, wealth and propensity to consume. Second, we model households' energy demand and improve the conceptualisation of the energy sector to obtain a more accurate accounting of energy flows and emissions across sectors. We then use the model to assess which policies can *jointly* reduce inequality and emissions, testing progressive fiscal policies, subsidies for low-carbon investment and carbon pricing. We assess the impact of each policy individually and then perform a scenario exploration across different policy parameters and combinations to assess a multitude of policy mixes. This leverages the potential of ABMs to assess synergies and feedback which are crucial in climate policy packages (Dafermos and Nikolaidi, 2019; Nieddu et al., 2024; Stechemesser et al., 2024; van den Bergh et al., 2021). Beyond inequality and emissions, our scenario exploration allows us to evaluate the impact of different policy combinations on key macro variables (e.g. GDP, unemployment, government debt, etc.), as well as on micro indicators (e.g. firm and bank failure rates). Finally, we also consider two additional dynamics that critically determine policy effectiveness: a green transition in the energy sector and green innovation leading to higher labour productivity, building on the DSK model's focus on endogenous technological change.

Our simulation results show that none of the tested policies can achieve our objectives in isolation. However, a mix of progressive and environmental fiscal policies can reduce inequality and emissions while increasing employment, economic stability, growth and the consumption of low-income households. These policies show complementary effects: redistributing income increases demand of low-income households, thus strengthening the economy, while incentivising green investment and introducing a carbon tax help dampen the resulting surge of emissions. Green industrial policies are also essential for reducing industrial emissions that a transition to renewable energy cannot tackle. A potential trade-off emerges between increasing economic growth and reducing emissions, mediated by the extent to which green innovations lead to higher productivity.

This study contributes to the emerging literature that applies alternative approaches to mainstream IAMs to analyse the relation between inequality and emissions. A recent example is Campigotto et al. (2024), which employs a system dynamics model to assess a wide range of policy mixes aimed at reducing both. Within this literature, ABMs play an important role. Being able to model the complexity of climate-economy systems (Dafermos et al., 2024; Farmer et al., 2015; Lamperti et al., 2019b), ABMs have been increasingly extended with energy and climate modules and used to address issues related to climate change, such as energy transition (Lamperti et al., 2020; Nieddu et al., 2024; Ponta et al., 2018) and its related transition risks (Ciola et al., 2024; Lamperti et al., 2021, 2019a), green technology diffusion (Hötte, 2020), climate damages (Czupryna et al., 2020; Lamperti et al., 2018) and net-zero emissions pathways (Lamperti et al., 2024). By naturally enabling the introduction of household heterogeneity, there have also been various applications of ABMs to topics related to the interactions of economic inequality and technical change (Dawid et al., 2018; Dawid and Hepp, 2022; Dawid and Neugart, 2023; Dosi et al., 2022; Fierro et al., 2022), fiscal and monetary policy (Dosi et al., 2015, 2013), and labour market policies (Dosi et al., 2018a, 2021, 2021), as well as the macroeconomic effects of inequality and redistribution (Caiani et al., 2019; Ciarli et al., 2019; Dosi et al., 2018b; Fierro et al., 2023; Palagi et al., 2023). Despite the calls for macroeconomic ABMs being suited to introduce inequality in climate modelling (Castro et al., 2020; Lamperti et al., 2019b), only a few studies have done so to date (Bazzana et al., 2024; Ciola et al., 2023; Rengs et al., 2020; Rizzati et al., 2024; Safarzynska and van den Bergh, 2022). Moreover, these few applications have primarily focused on the distributional impacts of climate change and policies, while none have explicitly examined the challenge of reducing inequality while accounting for its implications for emissions, as we do here.

The rest of the work is organised as follows. In Section 2, we describe the extended version of DSK model. Section 3 introduces the policies tested and the method to assess and combine them to generate policy mixes. Section 4 presents and discuss the results of all our experiments. Section 5 concludes.

2 The model

The core of the DSK ABM[1] (Lamperti et al., 2021, 2020, 2019a, 2018; Reissl et al., 2024) consists of two agent-based industrial sectors composed of Firms producing either consumption goods (C-firms) or capital goods (K-firms). K-firms produce machines that differ in labour productivity, energy productivity (i.e. real output produced per unit of energy used) and emissions per unit of energy used, using production techniques that differ in the same characteristics. K-firms spend for R&D activity, driving the emergence of new and improved capital machines and production techniques. This innovation process is the engine of growth of the model. K-firms sell capital machines to C-firms, which can switch supplier based on the technology they sell to reduce production costs. C-firms use capital machines to produce a homogenous consumption good. Both K- and C-firms also employ labour and use energy for their production. Households offer their labour to earn wages and receive dividends from Firms, Banks and the Energy Sector. Households spend their income to purchase

---

[1] The DSK model is grounded on the *Schumpeter meeting Keynes* (K+S) family of ABMs (Dosi et al., 2010, 2013, 2015), extended to address energy and climate-related issues.

energy from the Energy Sector and goods from C-firms. C-firms invest in new capital to expand their productive capacity based on the expected demand from Households. K-firms finance their production and R&D through retained earnings. C-firms' finance their production and investment also by applying for loans from a banking sector composed of multiple Banks. In addition to lending to C-firms, Banks keep deposits of Firms, Households and the Energy Sector and pay interest on them. Interbank payments are enabled by a Central Bank supplying reserves and setting the base interest rate. The Government offers bonds to Banks and the Central Bank to cover payments whenever its revenues are not sufficient. The Government spends to provide unemployment benefits, finance public spending, pay interest on outstanding bonds and bail-out failing Banks. To finance its activities, the Government collects taxes on Households' income and on the profits of Firms, Banks and the Energy Sector. The Energy Sector supplies final energy to K- and C-firms, Households and the Government, in the form of fossil fuels and electricity supplied through a combination of green non-carbon-emitting and brown plants, expanding its capacity to match energy demand and engaging in R&D. To supply energy, brown plants generate carbon emissions by converting fossil fuels purchased from an external fossil fuel sector. A climate module accounts for emissions from the Energy Sector and the production of K- and C-firms.

Figure 1 represents the DSK model with the extensions introduced in this paper: Households are disaggregated into three income-based classes with different labour and capital income and demanding goods and energy; the Government contributes to final demand by purchasing goods and energy; an improved accounting of energy and emission flows is introduced. The following sections describe these parts of the model, while Appendix A.1 reports the sequence of events and Appendix A.2, A.3 and A.4 report the aspects of the Energy Sector, technological change and Firms' and Banks' failure that are relevant for understanding the policies we implement and our results, despite not being modified. Table S.1 andTable S.2 in Appendix A.5 report the balance sheet and the transaction flow matrices constituting the accounting structure of the model. For a detailed description of the rest of the model and how the stock-flow consistency is ensured, see Reissl et al. (2024).

2.1 Model description

2.1.1 Households

The Household sector consists of three aggregate classes, which represent households in the Bottom 60%, Middle 30% and Top 10% of the income distribution. Household classes differ by income, wealth and propensity to consume and correspond to different hierarchical positions within Firms[2]. Each Household class cl can have four income sources: wages ($W_{cl,t}$), dividends ($Div_{cl,t-1}$), unemployment benefits ($UB_{cl,t}$) and interest payments on Bank deposits ($iD_{cl,t}$). Households pay taxes to the Government out of their wage ($Tax^{w}_{cl,t}$), dividends ($Tax^{div}_{cl,t}$) and deposits ($Tax^{dep}_{cl,t}$). Each household class cl disposable income is:

$$YD_{cl,t} = W_{cl,t} + Div_{cl,t-1} + UB_{cl,t} + iD_{cl,t} - Tax^{w}_{cl,t} - Tax^{div}_{cl,t} - Tax^{dep}_{cl,t}. \tag{1}$$

At the end of each period, the uniform nominal wage rate of Bottom 60% Households $w_{BI,t}$ is updated as:

$$w_{BI,t} = w_{BI,t-1} \cdot \left(1 + \min\left(\overline{\omega}, \max\left(-\overline{\omega}, \pi^{*} + \psi_1 \hat{\pi}_t + \psi_2 \widehat{Pr}_t - \psi_3 \hat{u}_t\right)\right)\right) \tag{2}$$

where:

- $\overline{\omega}$ is an exogenous parameter that limits the change in wage rate in each period.
- π^{*} is the fixed inflation target of the Central Bank.
- $\hat{\pi}_t$ is the deviation of the inflation rate from the inflation target.
- $\widehat{Pr}_t$ is a weighted average of current and past changes in average productivity across C- and K-firms.

---

[2] Our income classes can also be conceived as the ones identified in other ABMs as Caiani et al. (2019) and Ciarli et al. (2019): Bottom 60% Households correspond to blue-collar workers, Middle 30% Households to professionals/researchers/white-collar workers and Top 10% Households to executive/managers. However, since in our model Households' roles within Firms do not actually differ, we preferred to characterise them through their income, which is their key differentiation.

- $\hat{u}_t$ is the change in unemployment rate respect to t – 1.
- ψ_1, ψ_2 and ψ_3 are exogenous weights.

The uniform wage rates of Middle 30% and Top 10% Households are fixed multiples of Bottom 60% Households' wage rate, being respectively set as $w_{MI,t} = w_{BI,t} \cdot wr_{MI,BI}$ and $w_{TI,t} = w_{BI,t} \cdot wr_{TI,BI}$, where $wr_{MI,BI}$ and $wr_{TI,BI}$ are the exogenous ratios of Middle 30% and Top 10% Households' wage rate to Bottom 60% Households' wage rate. Each household class supplies at its nominal wage rate any amount of labour demanded up to a maximum $LS_{cl,t}$, which represents the current aggregate labour force of the class evolving with an exogenous rate as $LS_{cl,t} = (1 + g_L) \cdot LS_{cl,t-1}$. The amount of labour employed $L_{cl,t}$ depends on the labour demand of each Firm and the Energy Sector. The number of Bottom 60% Households each C- and K-firm demands for production depends on its desired output and the labour productivity of its capital vintages. Each K-firm and the Energy Sector additionally demand Households for R&D activities, determined dividing their desired R&D expenditure by Households' nominal wages. Firms' hire Households for both production and R&D following a hierarchical structure (Caiani et al., 2019; Ciarli et al., 2019), which we assume fixed and corresponding to population shares: for every six Bottom 60% Households hired, Firms hire three Households from the Middle 30% and one from the Top 10%. This implies that the unemployment rates of household classes ($U_{cl,t} = (1 - L_{cl,t})/LS_{cl,t}$) are equal between them and to the aggregate unemployment rate ($U_t = \sum_{cl}\left(1 - L_{cl,t}\right) / \sum_{cl} LS_{cl,t}$). This also implies that for each Bottom 60% Household employed Firms pay a total wage $w_{H,t} = w_{BI,t} + w_{MI,t}\, LS_{MI,t}/LS_{BI,t} + w_{TI,t}\, LS_{TI,t}/LS_{BI,t}$ to Households. The labour income of each class is given by $W_{cl,t} = L_{cl,t} \cdot w_{cl,t}$, where $L_{cl,t}$ is the number of Households of class cl employed in the current timestep. The fixed wage rate and labour demand ratios between classes determine the share of labour income going to each household class. Thus, in our model these parameters exogenously determine pre-tax labour income inequality, which remains fixed.

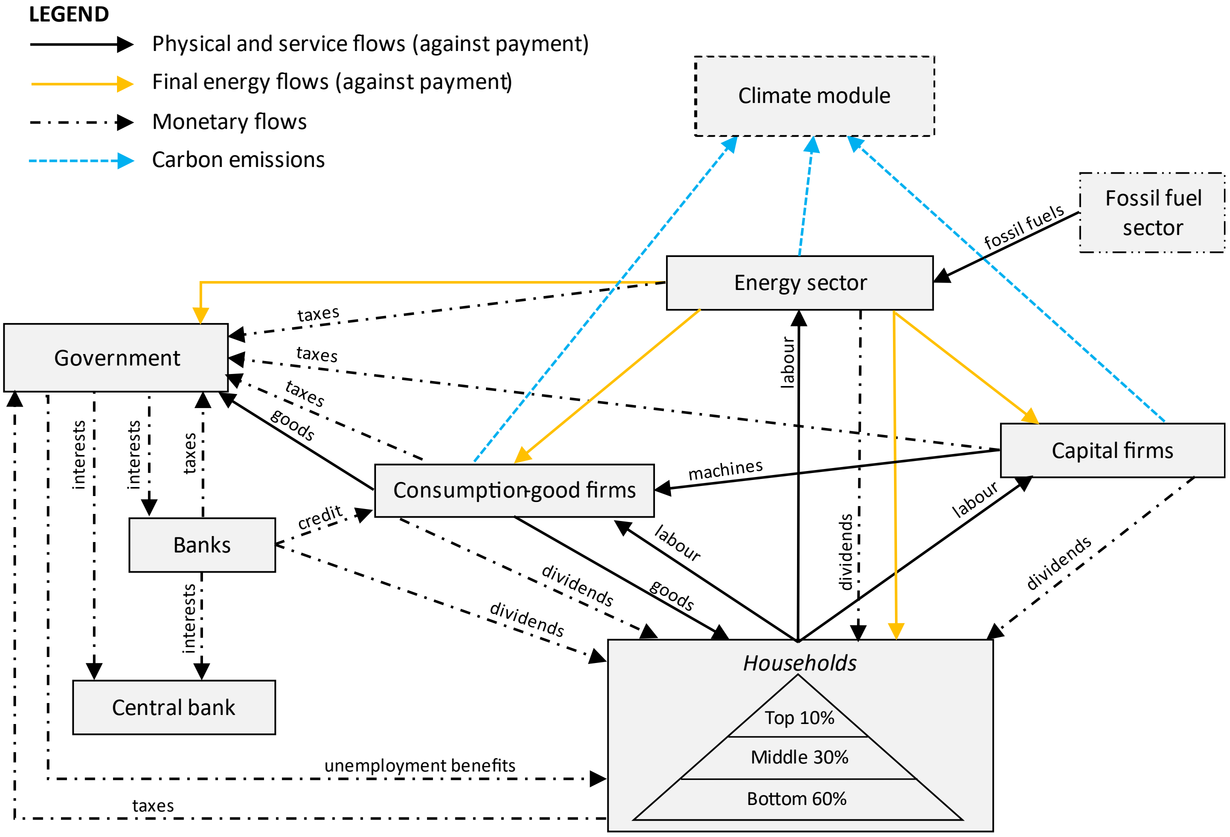

Figure 1: schematic representation of the model, with all agents and main flows. Flows are represented as arrows going from the providing to the receiving agent(s). Solid lines represent flows of goods or services, among which yellow ones represent flows of energy, to which correspond monetary flows in the opposite direction. Dot-dashed lines represent monetary flows. Blue dashed lines represent flows of carbon emissions. For a representation of all flows and stocks, refer to Table S.1 and Table S.2 in Appendix A.5.

Households receive dividends from C- and K-firms, Banks and the Energy Sector. Total dividends are determined through a sector-specific dividend payout rate out of net profits. The share of dividends paid by each sector to each household class is proportional to their ownership share of the sector. The shares of ownership of Banks and the Energy Sector are exogenously set during the initialisation of the simulation and remain constant throughout it. K- and C-firms are subject to a process of exit and entry, with Households providing the startup capital of entering Firms from their deposits and receiving a share of ownership proportional to their contribution. We assume that Bottom 60% Households do not have any ownership of Banks and the Energy Sector and do not contribute to the entry of new Firms, therefore not receiving dividends. Middle 30% and the Top 10% Households instead provide for the startup capital of entering Firms proportionally to their shares of total Households deposits. Therefore, their ownership shares and the dividends they receive evolve endogenously.

The Government pays unemployment benefits to each household class as $G_{cl,t} = \mu \cdot w_{cl,t} \cdot (LS_{cl,t} - L_{cl,t})$, where μ is the exogenous unemployment benefit rate as a share of each class wage rate. The Government also collect taxes on labour income, capital income and wealth as $Tax^{w}_{cl,t} = \tau^{w}_{cl} \cdot W_{cl,t}$, $Tax^{div}_{cl,t} = \tau^{div} \cdot Div_{cl,t-1}$ and $Tax^{dep}_{cl,t} = \tau^{dep} \cdot D_{cl,t}$, where τ^{w}_{cl} is the exogenous tax rate on wages that can differ between household classes, τ^{div} and τ^{dep} are the exogenous tax rate respectively out of dividends and deposits and $D_{cl,t}$ are the deposits of the household class. Finally, Households can also receive interest payments on their deposits from Banks, given by the product of the interest rate on deposits and the amount of Bank deposits they held at the end of the previous period: $iD_{cl,t} = r_{d,t-1} \cdot D_{cl,t-1}$. We set $r_{d,t-1}$ to 0 in the baseline calibration, thus dividends constitute the only capital income of Households.

Households demand consumption goods from C-firms and energy from the Energy Sector. Their desired expenditure in each depends on their target expenditure and their consumption habits. The target total expenditure of each household class is given by:

$$C^{tot}_{tg,cl,t} = \alpha_{cl,1}\left(W_{cl,t} - Tax^{w}_{cl,t}\right) + \alpha_{cl,2}\left(iD_{cl,t} + Div_{cl,t-1} - Tax^{div}_{cl,t-1}\right) + \alpha_{cl,3}D_{cl,t-1} + UB_{cl,t}. \tag{3}$$

The exogenous average propensities to consume out of labour income ($\alpha_{cl,1}$), capital income ($\alpha_{cl,2}$) and deposits ($\alpha_{cl,3}$) vary between household classes, decreasing along the income distribution (Dynan et al., 2004; Lamarche et al., 2020). The target expenditure in energy is determined as an exogenous energy expenditure share ($EnExpSh_{cl}$) of actual total expenditure in the previous period ($C^{tot}_{cl,t-1}$), as $C^{E}_{tg,cl,t} = EnExpSh_{cl} \cdot C^{tot}_{cl,t-1}$. Energy expenditure shares decrease along the income distribution as well (Bistline et al., 2024; Costantini et al., 2025). Since in the EU retail prices of electricity for Households are higher than for industry (Rademaekers et al., 2020), we introduce an exogenous parameter (ϕ_E) representing the ratio between energy price paid by Households and by C- and K- Firms. Thus, the target energy demand of each household class is $E_{tg,cl,t} = C^{E}_{tg,cl,t} / (p_{e,t-1} \cdot \phi_E)$, where $p_{e,t-1}$ is the energy price set by the Energy Sector in the previous timestep for industry (see Appendix A.2). The actual energy demanded and actual expenditure in energy are then respectively calculated as

$$E_{cl,t} = \gamma \cdot E_{cl,t-1} + (1-\gamma) \cdot E_{tg,cl,t}, \tag{4}$$

$$C^{E}_{cl,t} = E_{cl,t} \cdot p_{e,t-1} \cdot \phi_E, \tag{5}$$

where γ is a consumption smoothing parameter that capture persistency in Households' consumption behaviour (Havranek et al., 2017). The target expenditure in consumption goods of each household class is the residual total target expenditure not spent in energy: $C^{C}_{tg,cl,t} = C^{tot}_{tg,cl,t} - C^{E}_{cl,t}$. The desired expenditure in consumption goods in real terms is also subject to persistency:

$$C^{C}_{d,cl,t} = \left(\gamma \cdot \frac{C^{C}_{cl,t-1}}{CPI_{t-1}} + (1-\gamma) \cdot \frac{C^{C}_{tg,cl,t}}{CPI_t}\right) \cdot CPI_t. \tag{6}$$

where $C^C_{cl,t-1}$ is the actual expenditure for consumption goods of Households in the previous timestep. Household classes' desired total nominal expenditure is finally calculated as $C^{tot}_{d,cl,t} = C^E_{cl,t} + C^C_{d,cl,t}$. If it is higher than its current stock of deposits, the desired expenditure for consumption goods of each household class is then reduced to the maximum amount that can be financed out of deposits. This assumes that Households cannot borrow for consumption[3]. Finally, the actual expenditure for consumption goods of Households $C^C_{cl,t}$ is determined by Households' interaction with consumption good Firms, after having determined Government desired expenditure as well (see Section 2.1.2). If Households must reduce their demand due to insufficient supply, we assume that the demand of each household class is reduced proportionally. Households save the income not spent as Bank deposits.

2.1.2 Government

The Government engages in various fiscal policies: it pays unemployment benefits to Households ($UB_t = \sum_{cl} UB_{cl,t}$), it purchases energy and consumption goods ($C_{G,t}$) and it collects a total amount of taxes Tax_t from wages, dividends and deposits of Households and from profits of C- and K-firms, Banks and the Energy Sector. The Government also implements environmental fiscal policies (described in Section 3.1) that imply both collection of taxes ($TaxE_t$) and payment of subsidies ($SubE_t$). In addition, the Government transfers $T_{g,t}$ to entering Firms when Households cannot afford to finance their start-up capital and bails-out failing Banks ($Bail_t$). The Government issues bonds to Banks and the Central Bank to finance its spending when it's higher than its revenues and pays interests on them (iGB_t). The Government must also repay a fixed share ξ_{GB} of outstanding bonds (GB_{t-1}) each period. The Central Banks transfers all its profits to the Government (Tch_t) or gets compensated by the Government for any losses. The public sector borrowing requirement is therefore:

$$PSBR_t = UB_t + C_{G,t} + T_{g,t} + Bail_t + iGB_t + \xi_{GB} GB_{t-1} - Tax_t - TaxE_t + SubE_t - Tch_t. \qquad (7)$$

If $PSBR_t > 0$, the Government issues new bonds, while if $PSBR_t < 0$ the Government repays bonds in addition to the required amount. The stock of current outstanding bonds GB_t corresponds to the Government's public debt.

Public consumption is modelled as demand of consumption goods from C-firms and energy from the Energy Sector. Desired Government spending is a fixed fraction of GDP in the previous period GDP_{t-1}:

$$C^{tot}_{d,G,t} = g^* \cdot GDP_{t-1}, \qquad (8)$$

here g^* is the exogenous target public spending to GDP ratio. The split of public spending between energy and consumption goods happens as for Households. Actual public spending in energy is determined as $C^E_{G,t} = \overline{EnExpSh_{cl}} \cdot C^{tot}_{G,t-1}$, where $\overline{EnExpSh_{cl}}$ is the average energy expenditure share of household classes and $C^{tot}_{G,t-1}$ is the actual total public spending in the previous period. Thus, the energy demand from the Government equals to $E_{G,t} = C^E_{G,t} / (p_{e,t-1} \cdot \phi_E)$. Desired public spending for consumption goods is equal to $C^C_{d,G,t} = C^{tot}_{d,G,t} - C^E_{G,t}$. The total desired expenditure in consumption goods (from both Households and the Government) is then $C^C_{d,tot,t} = C^C_{d,G,t} + \sum_{cl} C^C_{d,cl,t}$. If the total supply of consumption goods by C-firms is higher than $C^C_{d,tot,t}$, the actual expenditure in consumption goods of the Government $C^C_{G,t}$ and each household class $C^C_{cl,t}$ is equal to the corresponding desired value. Otherwise, the actual expenditure is equal to the desired one reduced by the unmet total desired demand, with reductions proportional to each agent expenditure shares. The total actual expenditure of Government is equal to $C_{G,t} = C^C_{G,t} + C^E_{G,t}$.

---

[3] We assume that only demand for consumption goods is reduced in case of financial constraints on expenditure, while energy expenditure remains pre-determined based on the desired total expenditure and energy price in the previous timestep. We made this choice to solve the circularity issue that energy price depends on households' energy demand, which depends on households' income, which depends on energy sector dividends and R&D salaries, which depends on energy price.

2.1.3 Carbon emissions

The climate module sums the carbon emissions from the different sectors and reports the total yearly value[4]. In addition to the benchmark DSK, the climate module is also responsible for accounting emissions to Households and the Government beyond those of the energy sector and industries. The production of C- and K-firms generates emissions both directly, through in-firm conversion of fossil fuels, and indirectly, by purchasing final energy in the form of electricity. We will refer to the former as direct industrial emissions ($\mathfrak{E}_{I,t}^{dir}$) and to the latter as indirect industrial emissions ($\mathfrak{E}_{I,t}^{indir}$). The Energy Sector emits to supply electricity through brown plants, but not to supply fossil fuels since we neglect emissions linked to fossil fuels refineries, which are anyway very small compared to the ones from fossil fuel conversion to electricity in the power sector. We also assume that emissions related to energy use of Households and the Government ($\mathfrak{E}_{H,t}$ and $\mathfrak{E}_{G,t}$) are only caused by their use of electricity, neglecting energy-related direct emissions from Households[5]. We can decompose total emissions $\mathfrak{E}_t$ as:

$$\mathfrak{E}_t = \mathfrak{E}_{I,t}^{dir} + \mathfrak{E}_{E,t} = \mathfrak{E}_{I,t}^{dir} + \mathfrak{E}_{I,t}^{indir} + \mathfrak{E}_{H,t} + \mathfrak{E}_{G,t}, \tag{9}$$

where $\mathfrak{E}_{E,t}$ are the total emissions from the Energy Sector, and:

$$\mathfrak{E}_{I,t}^{dir} = \sum_c Q_{c,t}\frac{EF_{c,t}^e}{EE_{c,t}^e} + \sum_k Q_{k,t}\frac{EF_{k,t}}{EE_{k,t}} = \sum_c Q_{c,t}CI_{c,t}^e + \sum_k Q_{k,t}\frac{EF_{k,t}}{EE_{k,t}}, \tag{10}$$

$$\mathfrak{E}_{I,t}^{indir} = \left[\sum_c Q_{c,t}\frac{1}{EE_{c,t}^e} + \sum_k Q_{k,t}\frac{1}{EE_{k,t}}\right]\cdot\left(\frac{\mathfrak{E}}{E}\right)_{E,t} = \left[\sum_c Q_{c,t}\frac{CI_{c,t}^e}{EF_{c,t}^e} + \sum_k Q_{k,t}\frac{1}{EE_{k,t}}\right]\cdot\left(\frac{\mathfrak{E}}{E}\right)_{E,t}, \tag{11}$$

$$\mathfrak{E}_{H,t} = \sum_{cl} E_{cl,t}\cdot\left(\frac{\mathfrak{E}}{E}\right)_{E,t}, \tag{12}$$

$$\mathfrak{E}_{G,t} = E_{G,t}\cdot\left(\frac{\mathfrak{E}}{E}\right)_{E,t}. \tag{13}$$

$Q_{c,t}$ and $Q_{k,t}$ are the output of the C-firm c and K-firm k. $EE_{c,t}^e$ and $EF_{c,t}^e$ are respectively the effective energy productivity and the effective carbon emissions per final energy unit used of the C-firm c. We also express the equations in terms of the effective carbon intensity of the C-firm $CI_{c,t}^e$, a function of the carbon intensity of C-firms' capital vintages which will be the object of some of the policies and scenarios assessed[6]. The carbon intensity of a capital vintage represents the emissions per unit of real output produced and is equal to the ratio between its emissions per unit of output and its energy productivity. $EE_{k,t}$ and $EF_{k,t}$ are respectively the energy productivity and the carbon emissions per energy unit of the production technique currently used by the K-firm k. Increases of $EE_{c,t}^e$ and $EE_{k,t}$ can result from energy efficiency increase or electrification – since substituting electricity for fossil fuels decreases final energy demanded, thanks to the higher efficiency of conversion of electricity into useful energy. Reductions of $EF_{c,t}^e$ and $EF_{k,t}$ proxy processes of electrification (since the denominator includes all final energy use, both in the form of electricity and of

---

[4] The climate module of the benchmark DSK model can also account for temperature increase, assuming the exogenous trend of emissions outside the EU, and model climate damages. In this work all climate damages are turned off, given our focus on emissions in EU which have a limited influence on total emissions and therefore on global temperature increase, and our consideration of comparative scenarios until 2050.

[5] Direct residential emissions are related to transportation, heating and cooling services when the relative end-use devices use fossil fuels and are not electrified. Our model does not include end-use devices owned by households, and therefore we could not capture changes in their energy efficiency and emission intensity and in their electrification, which would drive changes in direct residential emissions.

[6] C-firms' $EE_{c,t}^e$, $EF_{c,t}^e$ and $CI_{c,t}^e$ (as well as their effective labour productivity) depend on the capital machines they own that are used for production in the current timestep. Before producing, C-firms rank their capital machines in order of increasing unit cost of production and activate them until reaching the desired level of output. $EE_{c,t}^e$ can therefore be calculated as $EE_{c,t}^e = \sum_{\kappa\in\Phi_{\kappa,c,t}} EE_{\kappa,t}\frac{\mathrm{K}_{\kappa,c,t}}{\mathrm{K}_{c,t}}$, where $\Phi_{\kappa,c,t}$ is the set of capital machines that the Firm activates in the current period, $EE_{\kappa,t}$ is the energy productivity of the capital vintage κ, $\mathrm{K}_{\kappa,c,t}$ is the productive capacity of machines of technology κ that the C-firm has available in the current period, and $\mathrm{K}_{c,t}$ is the current total productive capacity of the Firm. The formula is the same for $EF_{c,t}^e$ and $CI_{c,t}^e$.

fossil fuels), of decreased emissions in the conversion of fossil fuels in industry, and of shifts between fossil fuels sources (e.g. coal to natural gas). $\left(\frac{\mathfrak{E}}{E}\right)_{E,t}$ are the emissions produced by the Energy Sector to supply a unit of electricity. Their evolution captures changes in the share of energy supplied by green plants in the Energy Sector.

2.2 Model calibration and validation

We calibrate the model in order to achieve a fairly low growth rate of real GDP and roughly constant inequality, energy use and emissions in line with the projections of the SSP2 scenario under current policies for the European Union (EU) (see Appendix A.6 for a description of the re-calibration procedure and refer to Reissl et al. (2024) for an extensive description of the benchmark model calibration and initialisation). In the baseline calibration and scenario, we keep the share of energy supplied from green plants fixed at 20%, the value at the initial timestep. This assumption allows us to assess the effects of our policies independently from the speed at which energy supply transitions to renewable sources. The future speed of the energy transition is in fact unsure, with current trends differing from the ones in line with climate targets (IRENA, 2020), and difficult to determine and model due to many technical and political constraints (Fodstad et al., 2022; Hofbauer et al., 2022). Together with our improved accounting of emissions, this also allows us to focus the analysis on industrial emissions, which are knowingly hard to abate. However, since the share of green energy crucially determines the emission intensity of energy supplied and thus indirect emissions from industry, Households and the Government, we also assess a scenario in which this share increases (see Section 3.3).

Figure 2 shows the time series of selected variables generated by our model (see Figure S.1 in Appendix A.6 for the time series of additional variables). It confirms that our model exhibits exponential growth of output and consumption, while income inequality and yearly emissions remain roughly constant, as confirmed by the growth rates reported in Table 1. Table 1 shows that we obtain values of unemployment rate, residential share of energy demand, public debt to GDP and income shares of household classes in line with current values for the EU, as well as Households' average propensities to consume out of income decreasing with the income of class[7]. In addition, as common for the models of the K+S family and in macroeconomic ABMs literature (Dosi et al., 2010; Fagiolo et al., 2019; Lamperti et al., 2018), we ensure that our model captures realistic business cycle dynamics, such as cross-correlations of filtered macroeconomic time series, and a variety of microeconomic stylised facts on firms' heterogeneity, all reported in Appendix A.6.

---

[7] Note that the values of the propensities to consume out of income we obtain are partially endogenous to the model: we exogenously set the propensities to consume out of labour income ($\alpha_{cl,1}$), capital income ($\alpha_{cl,2}$) and deposits ($\alpha_{cl,3}$), but the propensities to consume out of income depend also on the each Household class labour income, capital income and deposits.

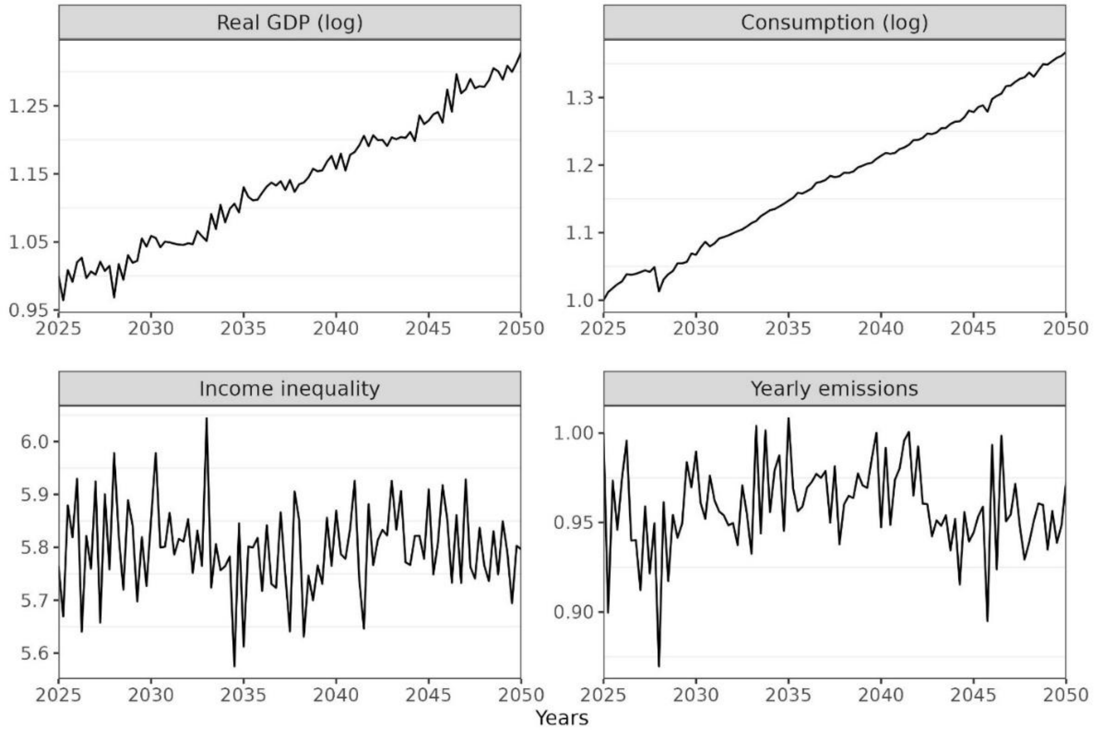

Figure 2: time series of selected variables for one run of the model, randomly selected. Real GDP and consumption are in logarithmic scales. Values for real GDP, consumption and yearly emissions are normalised to the value they have in the year 2025. Income inequality is measured as the net income ratio of a household in the Top 10% to one in the Bottom 60%.

Table 1: values of selected variables obtained from our model simulations. Values are averaged over 300 Monte Carlo runs and 100 timesteps, after a discarded burn-in period of 200 timesteps. Growth rates are calculated as geometric average of yearly values. Bottom 60%, Middle 30% and Top 10% refer to Household income classes. Average propensities to consume are out of income and are calculated dividing expenditure by net income of each Household class.

Statistic	**Value**
GDP growth rate	1.26 %
Energy demand growth rate	≈ 0.0 % (-0.03%)
Emissions growth rate	≈ 0.0 % (-0.05%)
Unemployment rate	6.39 %
Public debt to GDP ratio	119 %
Residential share of energy demand	25.5 %
Bottom 60% income share	31.1 %
Middle 30% income share	39.4 %
Top 10% income share	29.5 %
Average propensity to consume of Bottom 60%	0.99
Average propensity to consume of Middle 30%	0.94
Average propensity to consume of Top 10%	0.80

3 Experiments' design

The first step of our analysis is to study the effects of individual policies, to determine whether any can in isolation reduce inequality and emissions without causing detrimental economic effects. Section 3.1 describes the four progressive fiscal policies and three environmental fiscal policies we tested. In Section 3.2, such policies are implemented in combination to assess the economic implications of pursuing greater reductions in inequality and emissions, and to identify possible synergistic combinations. Finally, we analyse a policy mix in the two additional scenarios in Section 3.3, one with an increasing share of energy supplied from green plants and one with green innovation increasing labour productivity.

In all experiments, we implement policies after the model burn-in period of 200 quarterly timesteps (50 years) and run the simulations for 100 more (25 years), averaging the results over Monte Carlo runs, and compare the results to the baseline no-policy scenario. We select two main indicators to assess policies' effectiveness in reducing inequality and emission: the ratio of the net income of a household in the Top 10% to one in the Bottom 60%, and the level of yearly emissions at the end of the simulation (i.e. after 25 years from policies' introduction). To assess how policies influence macroeconomic performance, we use a set of additional indicators: the unemployment rate; the public debt to GDP ratio; the average number of C-firms and Banks failing in each timestep – as indicators of economic instability; the yearly growth rate of GDP; the real consumption of both energy and goods of Households in the Bottom 60% of the income distribution at the end of the simulation[8]. For all indicators whose value is not reported at the end of the simulation, we refer to the average value over the 100 timesteps following policies' introduction. In addition, we track and report some additional indicators at the end of the simulation to help understand policy effects: industrial, both direct and indirect, residential and government yearly emissions; total final energy demand and aggregate consumption of goods; the average (weighted on Firms' output shares) effective labour productivity and effective carbon intensity of C-firms[9].

3.1 Single policies

We select and design seven fiscal policies[10], each characterised by a single policy parameter (see Appendix B.1 for their detailed description). Four are progressive fiscal policies that modify the tax rates on labour and/or capital income of the different household classes. The first two redistribute the tax burden from lower to higher income Households, without modifying the total tax burden at the time of policies implementation – which can however change endogenously in the following periods. Therefore, these two policies allow us to isolate the effects of changing income inequality from changes in total net income of Households. These are:

- Progressive income tax: we increase the progressivity of tax rates on wages while keeping the total amount of labour income taxes collected unchanged. The policy parameter determines the progressivity of the new labour income tax scheme, by determining the resulting tax rates on each household income group.
- Shift taxes to capital: we increase the tax rate on dividends and decrease the tax rate on wages for all household classes while keeping both the sum of capital and labour income taxes collected and the

---

[8] To calculate this indicator, we discount Households' nominal consumption by a consumer price index that considers the change in prices of both goods and energy, weighted by their share in expenditure for the specific Household class.

[9] We report these indicators only for C-firms, because in our model the consumption good sector contributes to a much higher share of value added (83% vs. 5%), employment (94% vs 5%) and emissions (24% vs 8%) than the capital goods sector. For the same reason, we target to vintages characteristics', rather than their production process, subsidies and taxes targeting carbon intensity of production (see Section 3.1) and the additional scenario in which green innovation leads to higher labour productivity (see Section 3.3).

[10] We generically refer to the policies we test as fiscal, meaning that they use or increase public resources by modifying or introducing taxes or subsidies.

progressivity of the labour income tax scheme unchanged. The policy parameter represents the fraction of total Households' income taxes collected that is shifted from labour to capital income.

The other two progressive fiscal policies change the total tax burden on Households, modifying the tax rate on wages of specific household classes:

- Higher tax Top 10%: we increase the tax rate on labour income of Top 10% Households. The policy parameter is the increase of the tax rate, expressed as a fraction of labour income.
- Lower tax Bottom 60%: we reduce the tax rate on labour income of Bottom 60% Households. The policy parameter is the decrease of the tax rate, expressed as a fraction of labour income.

We introduce three environmental fiscal policies:

- Green capital subsidies: the Government subsidises C-firms for purchasing capital vintages with low carbon intensity. The maximum subsidy is offered to the vintages with the lowest carbon intensity and is determined as a fraction of the average price across K-firms, with this fraction being the policy parameter. The subsidy offered per machine decreases linearly with increasing carbon intensity and it is zero for vintages with higher carbon intensity than the market average.
- Dirty capital taxation: the Government taxes C-firms for purchasing capital vintages with high carbon intensity. The maximum tax is imposed on the vintages with the highest carbon intensity and is determined as a fraction of the average price across K-firms, with this fraction being the policy parameter. The tax imposed on each machine decreases linearly with decreasing carbon intensity and it is zero for vintages with lower carbon intensity than the market average.
- Carbon tax: the Government collects a tax on carbon emissions from the Energy Sector, C- and K-firms. The carbon tax is indexed on inflation and grows exponentially with time in real terms. The policy parameter is the initial tax rate.

To assess the effects of policies in isolation, we select one value of the policy parameter and simulate 300 Monte Carlo runs. We ensure comparability by selecting the parameter value so that each progressive fiscal policy in isolation reduces inequality by 10%, and that each environmental policy in isolation reduces emissions by 10%. We perform for each policy a sensitivity analysis over its policy parameter, whose results are reported in Appendix B.3.

3.2 Policy mixes

We construct policy mixes as all possible combinations of individual policies. To limit their number, we assume that two policy pairs can only be implemented alternatively: we either increase the tax rate on Top 10% Households or reduce the tax rate on Bottom 60% Households, and we either subsidise greener capital or tax dirtier capital. Policies can also be implemented with different values of their parameter (reported in Table S. in Appendix C), selected so that each progressive and environmental fiscal policy in isolation achieves pre-determined reductions of respectively inequality (5% and 10%) and emissions (5%, 10% and 15%). We obtain a total of 765 policy mixes, and we evaluate their effects by averaging results over 50 Monte Carlo runs for each.

We then identify successful policy mixes that reduce inequality and emissions by at least 5%, while not increasing unemployment, public debt to GDP and economic instability. We analyse the results to see how pursuing greater reductions of inequality and emission through policy mixes impacts on GDP growth and the consumption of Bottom 60% Households. For each indicator pair, we identify "efficient" policy mixes with respect to which no other policy mix improves both outcomes simultaneously[11]. The shape of the "efficiency

---

[11] In this work, we consider as desirable a reduction of emissions and inequality, and an increase in consumption of low-income households and GDP growth. Though green growth remains the main pillar underpinning climate objectives and policy-making, how to achieve it together with inequality reduction is still unclear. Recent literature has raised concerns about the feasibility of green

frontier" obtained connecting efficient policy mixes highlights eventual trade-offs between improving indicators. In addition, we check if there are successful policy mixes that also increase both GDP growth and the consumption of Bottom 60% Households. We identify one "Selected Policy Mix" for further analysis, choosing it among the ones that are efficient in reducing both emissions and inequality. Finally, to determine which policies are more effective, we calculate the frequency with which policies are implemented in successful policy mixes.

3.3 Additional scenarios

We assess the effects of the Selected Policy Mix in two additional scenarios. In the first green energy transition scenario, we impose an exogenous linear increase in the share of energy supplied from green plants in the Energy Sector (which we will refer to as "green share"), from 20% at the time of policies implementation to 70% at the end of the simulation. If we assume that our simulations start in 2025 and ends in 2050, 20% is just below the share of renewable generation of final energy supply in EU as of 2025, while 70% is the ambitious but realistic target share for EU in 2050 that, according to the International Renewable Energy Agency (IRENA), would meet the goals of the Paris agreement (IRENA, 2020). We implement this transition by forcing the Energy Sector to invest in new green plants until meeting the increasing green share target at each timestep.

In the second scenario, we assume that green innovations lead to higher labour productivity. In the model's technological change process, the characteristics of new capital vintages discovered by K-firms are determined independently through a stochastic process (see Appendix A.2): their energy productivity and emissions per unit of energy, and thus carbon intensity, do not influence their labour productivity, and vice versa. However, evidence suggests that green innovation leads to higher labour productivity (Aldieri et al., 2021; Woo et al., 2014). We introduce this dynamic in its most extreme form, by implementing a perfect negative correlation between the change in labour productivity and carbon intensity of new capital vintages. To achieve this, we maintain the stochastic process of innovating K-firms to determine the change in labour productivity of discovered vintages relative to the current one. However, we then assume that the direction and magnitude of change of energy productivity and of emissions per unit of energy (and thus of carbon intensity) are fully determined by changes in labour productivity. We ensure that innovated vintages with higher (lower) labour productivity always exhibit also higher (lower) energy productivity and lower (higher) emissions per energy unit, and so lower (higher) carbon intensity. To ensure comparability of policy effects across scenarios, we recalibrate this scenario to replicate baseline trends of labour productivity, energy productivity and energy-related emission intensity when no policies are implemented[12]. Appendix D.1 details the exact implementation of this scenario.

4 Results

4.1 Single policies

Figure 3 reports the effects of introducing each policy individually as compared to the baseline scenario (see also Figure S.6 in Appendix B.2 for additional indicators). Environmental fiscal policies incentivise Firms to

---

growth in high-income countries, i.e. the possibility of sustaining economic growth while respecting climate targets (Haberl et al., 2020; Hickel and Kallis, 2020; Jackson and Victor, 2019; Vogel and Hickel, 2023), and even the carbon footprint of low-income households has been deemed as too (Chancel, 2022). However, a high carbon footprint does not automatically translate into high well-being and (energy) poverty is still an issue in high-income countries (Baltruszewicz et al., 2023), for which the consumption of Bottom 60% Households is the best proxy we have in the model. For these reasons, our paper aims to understand to which extent higher economic growth and consumption of low-income households are compatible with reducing emissions and inequality.

[12] The three parameters multiplying $\mathfrak{I}_{1,k,t}$, $\mathfrak{I}_{2,k,t}$ and $\mathfrak{I}_{3,k,t}$ resulted to have values of respectively 0.98, 0.58 and 0.12. We recalibrated this scenario to reproduce the baseline trend in absence of policies because we were not interested in studying the effects of this scenarios against the baseline, but in studying the effects of introducing our policies in these two different scenarios. I.e., we were not interested in the question of "what happens if green innovation leads to higher productivity?", but in "If green innovation leads to higher productivity, do the effects of our policies change?".

reduce their energy demand and direct industrial emissions, but do not significantly impact inequality and risk hampering economic dynamics. Subsidies for greener capital and taxes on dirtier capital reduce industrial emissions by decreasing the average carbon intensity of capital machines (see Eqs. (10) and (11) for the link between machines' characteristics and industrial emissions). Such policies achieve this by reducing the relative price of low-emission capital vintages, thus increasing the likelihood that C-firms will adopt them (see Eq. (S.23) in Appendix B.1). More specifically, these policies increase C-firms' energy productivity, which decreases both direct and indirect industrial emissions, and reduce emissions per unit of energy used in industry, which further lowers direct industrial emissions. However, as Firms prioritise low-emission vintages, overall labour productivity grows at a slower rate, leading to lower GDP growth and thus reduced consumption of Bottom 60% Households compared to the baseline[13]. The unemployment rate remains similar to the baseline, with the effects of lower labour productivity and GDP growth balancing out. The amount of subsidies paid or taxes collected is low enough to not significantly impact the ratio between public debt and GDP. Lower output further decreases emissions, but it also reduces C-firms' profits increasing their failure rate. These effects are particularly relevant for taxes on dirtier capital, which also increase C-firms' failures by decreasing their deposits and net worth (whereas subsidies have an opposite compensating effect). However, with lower deposits C-firms' become more reliant on external credit to finance their production and investment, which in turn increases loans and profits for Banks, limiting their defaults when taxes are introduced.

Our results for the carbon tax align with previous work highlighting its regressive effects, risks for economic stability and inadequacy to meet climate targets in isolation (Dafermos and Nikolaidi, 2019; Känzig, 2023; Lackner et al., 2025; Lamperti et al., 2024; Nieddu et al., 2024; Rengs et al., 2020). A carbon tax increases the cost of energy use and industrial emissions, raising production costs more significantly for machines with higher carbon intensity (see Eq. (S.27) in Appendix B.1). This biases C-firms' choices against high-emission machines, decreasing carbon intensity and industrial emissions. At the same time, higher energy prices lower residential and government energy demand, making carbon pricing the only environmental policy tested that reduces residential and government emissions[14]. As Eqs. (12) and (13) show, residential and government emissions do not depend on Firms' carbon intensity; thus, subsidies and taxes on capital machines can affect them only indirectly by altering income and energy demand. However, higher energy prices disproportionately impact Bottom 60% Households due to their higher energy expenditure share, reducing their consumption more than the other environmental policies. Higher taxes on production increase the number of defaulting Firms and thus Banks, which along with lower consumption increases unemployment. The carbon tax revenues decrease public debt to GDP.

The outcome of progressive fiscal policies depends on their effect on Households' expenditure, as higher total expenditure directly increases demand for goods and energy. Redistributing income by increasing the progressivity of the labour income tax scheme or by shifting taxation from labour to capital income raises Households' total expenditure, since propensities to consume decrease with income. However, the effects on consumption and energy demand appear limited, probably because the propensities to consume of Household classes (see Table 1) are too similar, with those of the Middle 30% and especially the Top 10% being higher than observed in reality (Eurostat, 2024a)[15]. In contrast, reducing the tax rate on the wages of

---

[13] Since in the baseline scenario GDP and consumption are growing exponentially (see Section 2.2), having lower consumption of Bottom 60% Households compared to the baseline does not imply that consumption decreases during the simulation compared to the initial period, but that it grows at a lower rate, as GDP does.

[14] Our consumption model overestimates the reductions in energy demand due to an increase in energy price: since Households aim to allocate a fixed share of their total expenditure to energy (see Section 2.1.1), if energy price increases by 10% Households' demand for energy decreases by 10%, implying an own-price elasticity of energy demand equal to -1, which is lower than what found in the literature for the EU (Csereklyei, 2020; Pellini, 2021). Still, the direction of change remains correct.

[15] To sustain consumption and match unemployment levels, we could not further reduce Households' propensities to consume (see Appendix A.6 for more details). In our model deposits are only used to finance the entry of new firms, as we do not model financial assets or real estate markets where high-income households could invest their deposits and increase demand.

Bottom 60% Households leads to a significant increase in goods and energy demand. Higher demand translates into higher GDP growth and, together with lower inequality, higher consumption of Bottom 60% Households. Higher demand also reduces unemployment and the number of failing Firms and Banks. Lower unemployment decreases Government spending on benefits, which, in the case of tax cuts for Bottom 60% Households, can fully offset lower tax revenues. These positive effects of redistribution on economic dynamics are consistent with a wage-led growth regime and previous ABMs findings (Caiani et al., 2019; Dosi et al., 2015, 2013). However, total emissions rise due to increased demand for goods and energy, which spurs industrial (see Eqs. (10) and (11)) and residential (see Eq. (12)) emissions. This confirms that redistributing income without complementary environmental policies risks increasing emissions. Raising the tax rate on the wages of Top 10% Households reduces inequality while curbing consumption and thus emissions, but at the cost of higher unemployment and lower growth. Table 2 summarises the effects of all policies, considering also the results of the sensitivity analyses reported in Appendix B.3. In isolation, none of the tested fiscal policies jointly reduces emissions and inequality without adverse economic consequences.

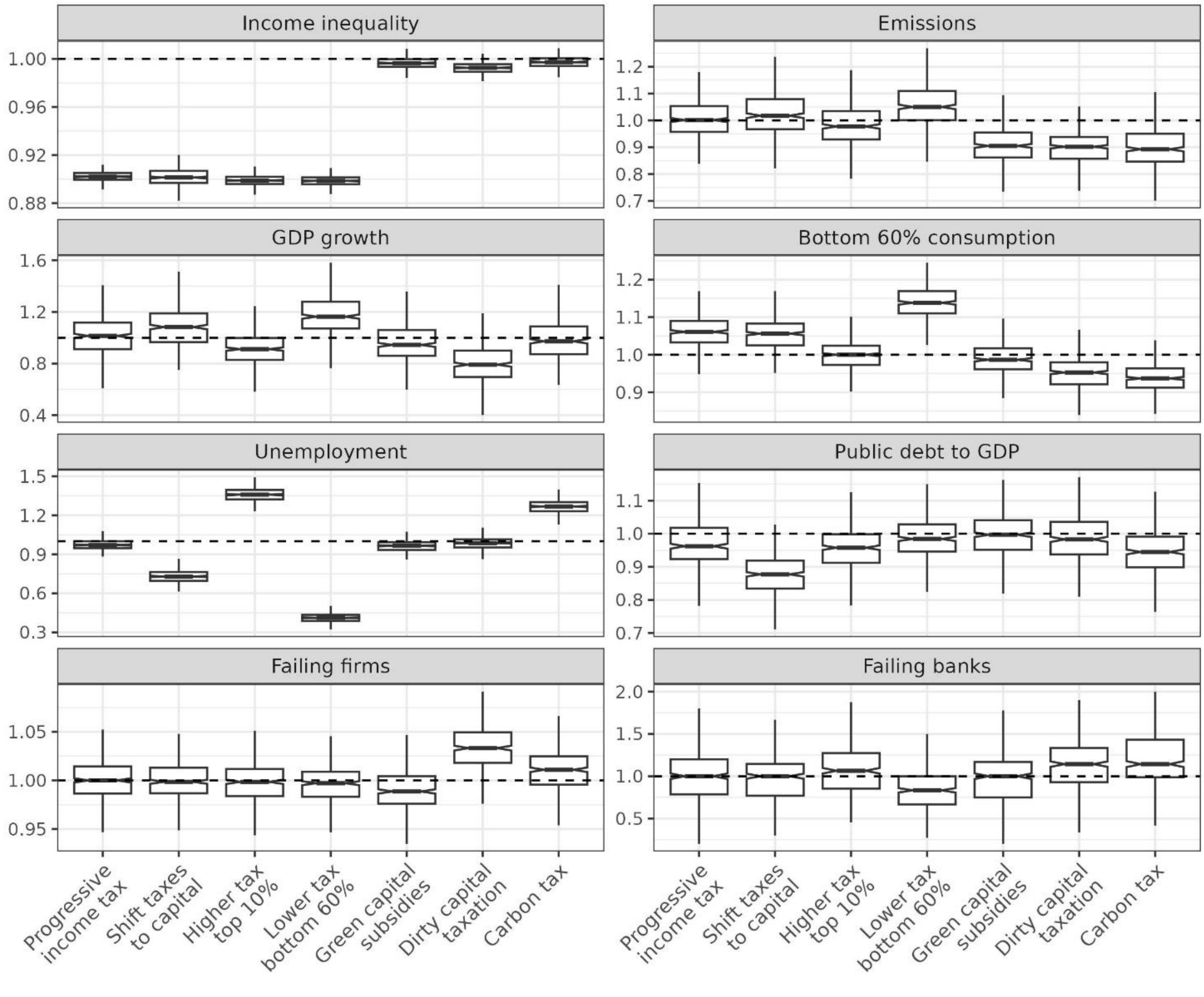

Figure 3: effect on selected indicators (on top of each boxplot) of introducing policies (reported in the x-axis) individually. Boxplots are obtained over 300 Monte Carlo runs. We report different y-axis and exclude outliers for clearer visualization. Indicators are normalised to the value they assume in the baseline scenario, reported as black dashed lines.

Income inequality is measured as the net income ratio of a household in the Top 10% to one in the Bottom 60%. Emissions are measured as the yearly emissions at the end of the simulation. Bottom 60% consumption refers to the expenditure in real terms of both energy and goods of Bottom 60% Households at the end of the simulation. Failing firms and banks are measured as the average number of respectively C-firms and Banks failing each timestep. Apart from Emissions and Bottom 60% consumption, all indicators are averaged over the 100 timesteps after policies introduction. Policies: "Progressive income tax" increases the progressivity of taxes on Households' labour income, without changing their total amount; "Shift taxes to capital" shifts a fraction of taxes from labour to capital income of Households, without changing their total amount; "Higher capital Top 10%" increases the tax rate on labour income of Top 10% Households; "Lower tax Bottom 60%" decreases the tax rate on labour income of Bottom 60% Households; "Green capital subsidies" offers subsidies for capital machines with lower carbon intensity than market average; "Dirty capital taxation" imposes taxes on machines with higher carbon intensity than market average; "Carbon tax" imposes a tax on emissions from the Energy Sector and Firms.

Table 2: effects of individual policies on selected indicators as compared to their trends in the baseline. An upward arrow indicates an increase in the value of the indicator due to the introduction of the policy, a rightward arrow indicates a negligible effect, and a downward arrow indicates a decrease. The effects are based on a sensitivity analysis on each policy's parameter, and two arrows separated by a slash imply different effects with an increasing value of the policy parameter. The colour of the arrows indicates if the direction of change of the indicator is desirable (green) or not (red), while yellow is used for negligible effects. The caption of Figure 3 describes the indicators and policies.

	Emissions	**Income inequality**	**Unempl-oyment**	**Economic instability**	**Public debt to GDP**	**GDP growth**	**Bottom 60% consumption**
Progressive income tax	→/↑	↓	↓	→	↓	→/↑	↑
Shift taxes to capital	→/↑	↓	↓	→	↓	→/↑	↑
Higher tax Top 10%	↓	↓	↑	→	↓	→/↓	→
Lower tax Bottom 60%	↑	↓	↓	↓	→/↓	↑	↑
Green capital subsidies	↓	→	↓	→/↓	→/↑	↓	↓
Dirty capital taxation	↓	→	→/↓	↑	→/↓	↓	↓
Carbon tax	↓	→	↑	↑	↓	→/↓	↓

4.2 Policy mixes

Figure 4a shows instead that, when properly combined, progressive and environmental fiscal policies succeed in reducing both inequality and emissions by 5% without increasing unemployment, public debt to GDP and economic instability (see also Figure S.14 in Appendix C). Most successful policy mixes also increase the consumption of Bottom 60% Households compared to the baseline (Figure 4d and e), while a minority increases economic growth (Figure 4b and c). The efficiency frontiers in Figure 4b and d show that policy mixes most effective in reducing inequality are those best able to spur GDP growth and Bottom 60% Households' consumption. On the contrary, Figure 4c shows that aiming for greater emissions reductions limits the potential for boosting GDP growth, while prioritising economic growth reduces the achievable emissions reduction. Thus, a trade-off emerges between tackling emissions and increasing growth (see also Campigotto et al. 2024). Still, there are some successful policy mixes that increase both GDP growth and the Bottom 60% Households' consumption (marked with blue crosses in Figure 4). However, while these do not reduce emissions by more than 14%, other successful policy mixes achieve reductions exceeding 23%, further emphasizing the aforementioned trade-off.

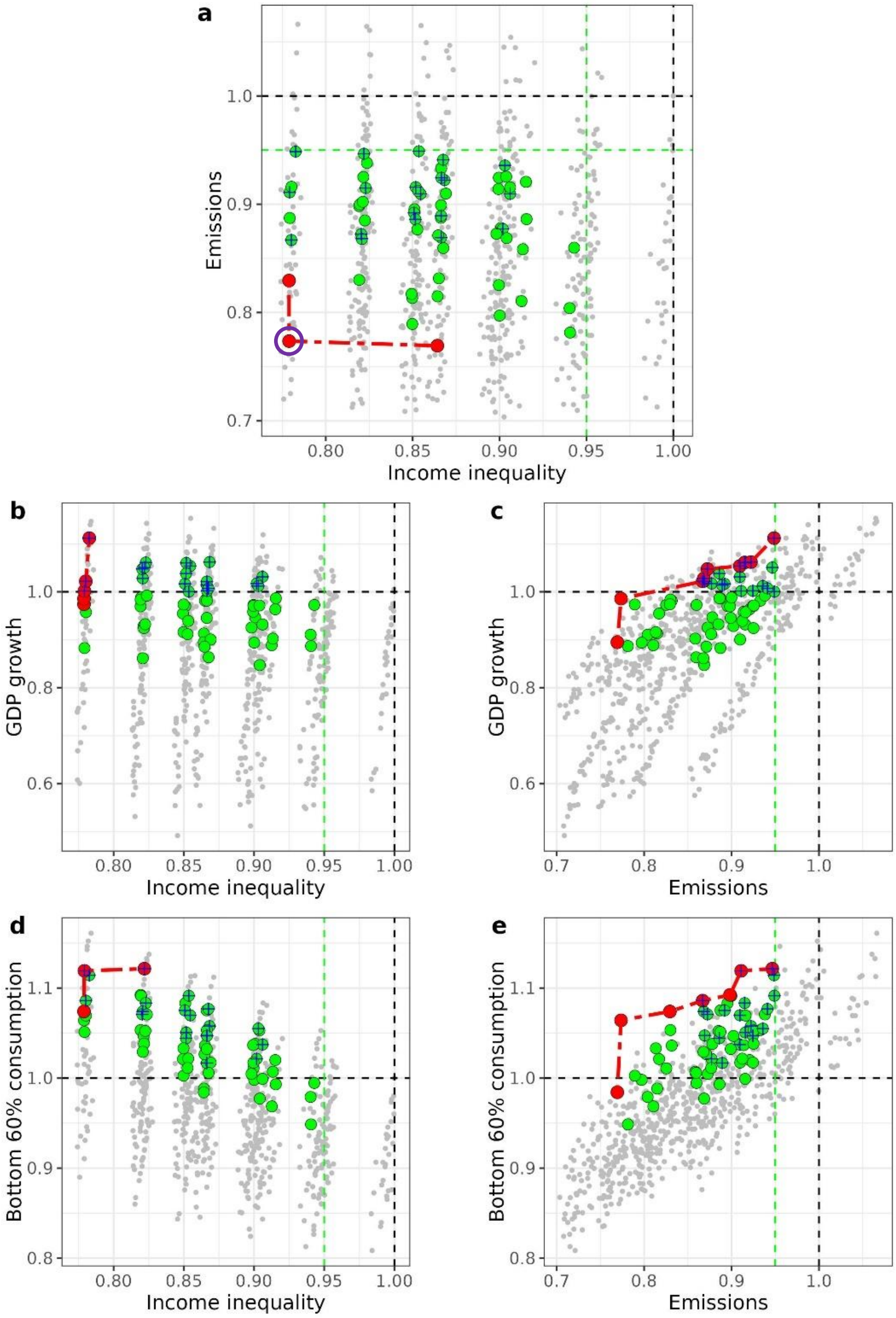

Figure 4: effect of policy mixes. Each dot in the scatter plots represents the outcome of one policy mix on the indicators reported in the axes (note the different scales). Green-filled dots represent successful policy mixes in reducing inequality and emissions by at least 5% without increasing unemployment, public debt to GDP and frequency of Firms and Banks failing compared to the baseline no-policy scenario. Green dashed lines represent the 5% targets. Red-filled dots represent "efficient" successful policy mixes with respect to which no other improves the outcome on both indicators in the graph (so that different policy mixes are efficient in different scatter plots), assuming as desired a decrease of Emissions and Income inequality and an increase of GDP growth and Bottom 60% consumption. We define the dashed red lines connecting them as "efficiency" frontiers. The red dot circled in purple in Figure a) is the Selected Policy Mix. Green and red dots with blue crosses inside are successful policy mixes that also increase both GDP growth and the Bottom 60% consumption. Grey smaller dots represent all unsuccessful policy mixes. All values are averaged over 50 MC runs and normalised to the baseline scenario values - reported as black dashed lines. Figure a) shows the effects of introducing all policy mixes on inequality, measured as the net income ratio of a household in the top 10% to one in the bottom 60% of the income distribution (averaged over 100 timesteps after policies introduction), and emissions, measured as the yearly values at the end of the simulation. Figures b) to e) show the effects on GDP growth (averaged over 100 timesteps after policies introduction) and on the consumption in real terms of energy and goods of Bottom 60% Households at the end of the simulation (on the y-axis), against the effects on inequality and emission (on the x-axis).

Among the successful policy mixes on the efficiency frontier for reducing inequality and emissions (Figure 4a), we choose the one circled in purple as the Selected Policy Mix, since the other two efficient policy mixes achieve similar reductions for one indicator but a smaller reduction for the other[16]. The outcome of the Selected Policy Mix is further analysed in the following Section 4.3. The Selected Policy Mix features most tested policies (see Table 3 and Table S.6 in Appendix C for its policy parameter values), including high subsidies for green capital and both progressive policies redistributing the tax burden between household classes. Additionally, it introduces a mild carbon tax to finance a decrease of labour income tax for Bottom 60% Households without increasing emissions, to further increase low-income households' consumption and reduce inequality. Table 3 shows that, like the Selected Policy Mix, successful policy mixes generally require the activation of multiple policies. Thus, ambitious reductions of emissions and inequality require a combination of different policies to reap the potential synergies across interventions. These findings extend previous insights for climate policies (Lamperti et al., 2024; Stechemesser et al., 2024; van den Bergh et al., 2021) to mixes also including progressive fiscal policies, confirming the importance of evaluating policies using models that can capture the complexity of the climate-economy system (Dafermos et al., 2024; Stern et al., 2022). Table 3 further indicates that progressive fiscal policies stimulating Bottom 60% Households' consumption are more frequent in the successful policy mixes than only increasing taxation on high-income households. Despite rising emissions, higher consumption increases employment and economic stability, enabling the implementation of more aggressive environmental policies that offset the increase in emissions. All successful policy mixes include subsidies for greener capital, which are essential to reach our targets thanks to their positive effects on employment and stability. Taxes alone, whether on dirty capital or carbon emissions, are insufficient. This also applies to a carbon tax with revenue recycling (proxied by lowering taxes on Bottom 60% Households), which contrary to what mainstream IAMs find (Budolfson et al., 2021; Emmerling et al., 2024) does not appear to be a panacea for climate change and inequality. A tax rate high enough to sufficiently reduce emissions would harm stability and employment (see also Lamperti et al. 2024). Nevertheless, almost half of successful policy mixes feature a carbon tax, highlighting its contribution if included in a more comprehensive policy mix.

Table 3: policy mixes reducing emissions and inequality without hampering economic dynamics. The first row reports which percentage of the successful policy mixes (the ones reducing both inequality and emissions by at least 5% and not increasing unemployment, public debt to GDP and economic instability) each policy is implemented in. The second row reports which policies are implemented (represented with a green tick) or not (red cross) in the Selected Policy Mix. The caption of Figure 3 describes the policies.

	Progressive income tax	**Shift taxes to capital**	**Higher tax Top 10%**	**Lower tax Bottom 60%**	**Green capital subsidies**	**Dirty capital taxation**	**Carbon tax**
Frequency (%) in successful policy mixes	70.1	80.6	16.4	59.7	100.0	0.0	46.3
Selected Policy Mix	✓	✓	✗	✓	✓	✗	✓

---

[16] Choosing one of the other efficient policy mixes would imply to impose a high difference in value between same percentual reduction of inequality and emission.

4.3 Selected policy mix and additional scenarios

Figure 5 reports the effects of the Selected Policy Mix across the different scenarios presented in Section 3.3. In the baseline scenario, it reduces both inequality and emissions by over 20% (see black and golden circular dots in Figure 5a) and increases the consumption of Bottom 60% Households by 5% (Figure 5c). It also lowers unemployment and public debt to GDP by over 20%, without increasing economic instability (see Figure S.15a and b in Appendix D.2). Figure 5a further shows that the reduction of inequality achieved through the Selected Policy Mix remains similar under an energy transition and when green innovation increases labour productivity. However, both scenarios weaken its effectiveness in reducing emissions.

Without introducing any policy, a transition from 20% to 70% of green energy share decreases emissions by almost 40% (see circular and square black dots in Figure 5a). This reduction is entirely due to lower emissions from energy supply, while the increase in green share has a negligible effect on direct industrial emissions (Figure 5b and Figure S.15f in Appendix D.2). An increase in green energy share in fact directly lowers the emissions per unity of energy supplied by the Energy Sector – which remains constant in the baseline scenario with a fixed share –, thus reducing residential, government and indirect industrial emissions (see Eqs. (11) to (13)). Instead, the green energy share has no influence on direct industrial emissions (see Eq. (10)), making our policies essential for reducing them during a transition to renewables. However, the reduction of indirect industrial emissions due to the Selected Policy Mix's halves, since lower emissions per unit of supplied energy reduce the effect of energy demand reductions on total emissions (see Eq. (11)). Still, in the transition to green energy supply scenario, our policies lower emissions by 15%, for a total reduction compared to the baseline of over 55%. In addition, the reduction in final energy demand driven by higher energy productivity (see Figure S.15e in Appendix D.2) lowers the additional capacity of green plants required to increase the green energy share, simplifying and reducing the impact of decarbonising energy supply.

If greener capital vintages are always more productive, the Selected Policy Mix achieves a smaller reduction in emissions (see black and golden triangular dots in Figure 5a), with industrial emissions declining only marginally (Figure 5b). This occurs because C-firms always choose capital vintages with lower carbon intensity even without subsidies, as these vintages also have higher labour productivity. Therefore, policies that alter production costs no longer influence Firms' choices. However, subsidies still accelerate the replacement of machines with less carbon intensive ones, leading to lower carbon intensity (see Figure S.15c in Appendix D.2). Carbon intensity decreases also because in this scenario our policies enhance labour productivity and thus the growth rate of GDP, which stimulates innovation (see black and golden triangular dots in Figure 5c). Additionally, the carbon tax is still effective in reducing residential and government emissions (see Figure S.15c in Appendix D.2). As a result, in this scenario the Selected Policy Mix reduces inequality and increases GDP and consumption of Bottom 60% Households, while still lowering emissions – albeit less than in the baseline.

These two additional scenarios represent extreme cases, as current energy plans and policies are expected to reach less than 40% of green share in 2050 in the EU (IRENA, 2020), and the negative correlation between labour productivity and carbon intensity of new machines remains debated and is certainly not perfect (Aldieri et al., 2021; Woo et al., 2014). Therefore, we can assume that the actual effects of our policies fall between their impact in the baseline scenario and in the one combining energy transition and correlation (rhomboid dots in Figure 5). This implies that, across all scenarios, our policies reduce inequality, unemployment, public debt to GDP and economic instability while increasing the consumption of Bottom 60% Households (see also Figure S.15a and b in Appendix D.2). The results confirm a trade-off between increasing economic growth and reducing emissions while lowering inequality – as already observed for policy mixes in Section 4.2 –, mediated by the extent to which green innovation leads to higher productivity. Nonetheless, our policies can reduce emissions while increasing GDP growth, except in extreme cases.

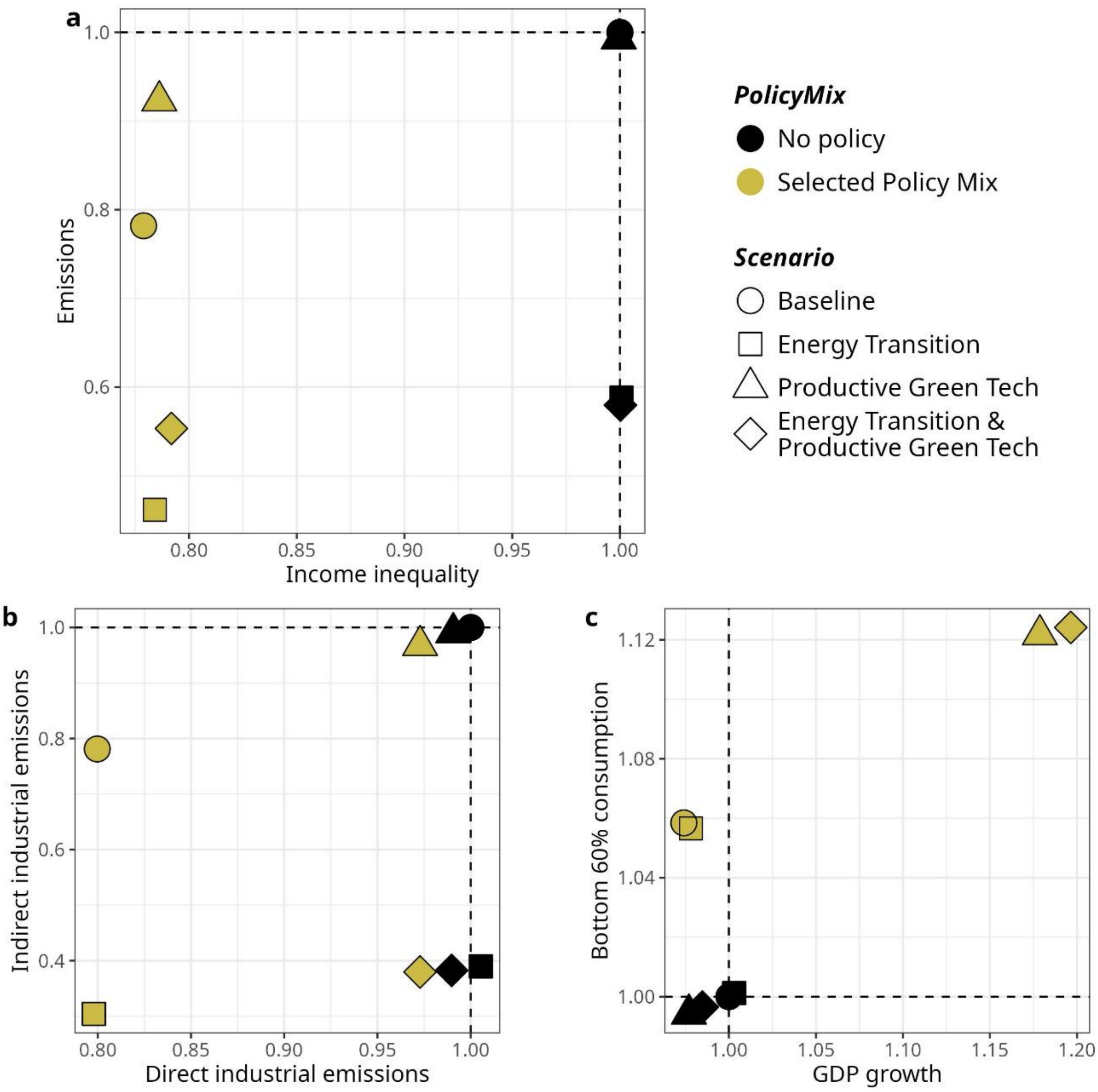

Figure 5: effect on selected indicators of introducing the Selected Policy Mix under different scenarios. Each dot represents the average value of the indicators on the y-axis and x-axis under no policy or the Selected Policy Mix (identified by the dot's colour) and a scenario (identified by the dot's shape), averaged over 300 Monte Carlo runs run for 100 quarterly timesteps. "Energy Transition" refers to the scenario in which share of energy supplied from green plants increases linearly to a value of 70% at the end of the simulation. "Productive Green Tech" refers to the scenario where we assume that green innovation leads to higher labour productivity. Indicators are normalised to the value they assume in the baseline scenario with no policy mix implemented, which are reported as black dashed lines. Figure a) and Figure c) show the effects respectively on emissions and inequality and on GDP growth and the real consumption of Bottom 60% Households, measured as described in the caption of Figure 4. Figure b) shows the effects on direct and indirect industrial emissions, measured as the yearly values at the end of the simulation.

5 Conclusions

In this work, we show how to jointly reduce greenhouse gas emissions and economic inequality with a mix of policies that do not hamper economic growth and stability. More specifically, we extend the DSK climate macroeconomic agent-based model (Lamperti et al., 2021, 2020, 2019a, 2018; Reissl et al., 2024) with an income class-based analysis of inequality and an improved accounting of emissions. We then use the model to test progressive fiscal policies modifying tax rates on labour and capital income, green industrial policies subsidising or taxing capital vintages based on their carbon intensity of production, and carbon pricing.

Our results show that no single policy can decrease both emissions and inequality without hampering economic dynamics. Progressive fiscal policies stimulate consumption, boosting growth and benefitting low-income households, but at the cost of higher emissions. Environmental taxes pose risks to employment and stability, while subsidies for green investment are less disruptive and more effective in reducing carbon intensity and thus emissions, but they adversely affect public debt and growth. However, when such policies are combined, the increase in consumption due to progressive policies strengthens economic dynamics, enabling the implementation of more aggressive environmental policies that achieve greater emissions reductions. Additionally, our policies complement the decarbonisation of energy supply, by abating direct industrial emissions that a transition to renewable energy cannot target. They also lower energy demand, decreasing the required capacity of green energy plants to install and indirect industrial emissions – though the latter effect weakens as energy supply becomes cleaner. This underscores the importance of capturing synergies between multiple policy instruments and scenarios, assessing policy mixes with an agent-based model which captures the complexity of climate-economy systems.

Across all considered scenarios, a properly designed mix of fiscal policies can reduce emissions and inequality, while also reducing unemployment, public debt to GDP and economic instability and increasing growth and consumption of low-income households. However, our findings reveal a potential trade-off between cutting emissions and stimulating GDP growth. Policies designed to drive output growth are indeed less effective in cutting emissions. The extent to which green innovation increases labour productivity appears to be a key mediating factor: the more green technologies enhance productivity, the more our policies boost growth (and the consumption of low-income households), but the less they reduce emissions.

This work can be extended in two complementary directions. First, we should further investigate the interlinkages between residential energy demand, industrial dynamics and the energy transition, coupling the modifications implemented here with the endogenous modelling of the energy transition already present in other versions of the DSK model (Lamperti et al., 2024, 2020; Reissl et al., 2024). This would also allow us to assess broader policy mixes combining progressive and green industrial fiscal policies with policies targeting the energy sector, which, alongside non-price-based instruments such as command-and-control policies, could reduce or even reverse the trade-off between reducing emissions and increasing growth highlighted above, as found by Lamperti et al. (2024).

The other direction for future research involves a fine-grained disaggregation of the household sector. If combined with a proper labour market model as included in other ABMs (Dosi et al., 2021, 2021, 2018a), this would allow us to study the effects of our policies and scenarios on labour market inequality and assess pre-distributive policies. Moreover, together with the re-activation of endogenous climate damages already featured in the DSK model (Lamperti et al., 2018), this would allow us to evaluate the distributional impact of climate change in addition to the one of climate policies. Finally, further disaggregating low- and high-income households would allow us to better study the co-evolution of inequality, growth and emissions with poverty, as well as the disproportionate impact of the wealthiest individuals (Gössling and Humpe, 2023; Nielsen et al., 2021; Tian et al., 2024; Wiedmann et al., 2020). All these modifications would eventually enable the assessment of policy interventions and of increasing economic growth in relation to climate targets, which we abstract from in this paper to focus on comparative scenarios.

Acknowledgments

G.R. and T.D. acknowledge support by FCT/MCTES (PIDDAC) through projects UIDB/50009/2025, UIDP/50009/2025 and LA/P/0083/2020; G.R. also acknowledges support by Fundação para a Ciência e Tecnologia through project 2021.07144.BD; T.D. also acknowledges support from the Horizon Europe project “MAPS” (contract n. 101137914). F.L. and A.R. acknowledge support from the Italian Ministry of Research, PRIN 2022 project "ECLIPTIC" and PRIN 2022 PNRR project "NEWS"; F.L. also acknowledges support from the European Union (ERC, FIND - Finance and Innovation to couple Negative emissions and sustainable Development, Grant Agreement n. 101117427). The authors also thank Severin Reissl, Luca Eduardo Fierro and Gianluca Pallante for their help with model development.

Appendix A The model

A.1 Sequence of events

In each period of the simulation, the events unfold in the following order:

1. Banks pay interest on the deposits their customers held at the end of the previous period.
2. C-firms receive capital machines purchased in the previous period.
3. K- and C-firms calculate their unit cost and update their prices.
4. Banks set the maximum credit they are willing to extend and the interest rate on loans.
5. K-firms advertise their vintages and C-firms may update their supplier.
6. C-firms determine their desired production based on expected demand.
7. C-firms decide which worn-out machines to scrap and which not worn-out machines to replace.
8. C-firms determine desired expansion investment based on desired production and scrapped machines.
9. C-firms calculate their effective production costs based on desired production and capital machines used.
10. C-firms determine the eventual desired borrowing for production and investment, scale back desired investment if necessary and then calculate desired investment costs.
11. Banks allocate credit to C-firms; credit-rationed C-firms scale back production and investment; C-firms that cannot roll over loans become inactive and are prepared to exit.
12. K- and C-firms calculate the labour required for production.
13. Total labour demand is determined as the sum of demand for production by K- and C-firms and of demand for R&D from K-firms and the Energy Sector from the previous period. If labour supply is insufficient to cover demand, K- and C-firms scale back production.
14. Production takes place. Realised production determines energy demand and emissions from industry.
15. Households and the Government determine their demand and expenditure for energy.
16. Based on total energy demand, the Energy Sector invests to expand its capacity, engages in R&D activities, determines the price of energy and supplies it.
17. C-firms pay for investment.
18. K- and C-firms and the Energy Sector pay wages and the Government pays unemployment benefits to unemployed Households (if any).
19. C-firms scrap machines.
20. C-firms' ex-ante market shares are determined; C-firms with low market shares become inactive and are prepared to exit.
21. K-firms determine their profits and pay for energy, taxes and dividends. K-firms that cannot pay for energy become inactive and are prepared to exit.
22. Households pay taxes. Households and the Government determine their desired expenditure for goods' consumption, which is allocated to C-firms based on their market shares.
23. K- and C-firms determine their profits.
24. C-firms pay energy, principal and interest on loans and taxes. C-firms that cannot pay or that have negative net worth become inactive and are prepared to exit.
25. The Energy Sector determines its profits and pays fossil fuels and taxes; the fossil fuel sector pays dividends to Households.
26. The nominal wage of all household classes is updated.
27. New Firms replace exiting K- and C-firms.
28. Banks determine their profits and pay taxes and dividends; the Government bails-out Banks with negative net worth.
29. The Government determines its budget and covers its deficit by selling bonds to Banks and the Central Bank.
30. The Central Bank sets the policy rate for the following period.

31. Banks calculate net inflows and outflows of reserves and, if necessary, take advances from the Central Bank.
32. Endogenous technical change takes place in K-firms.
33. The climate module accounts for all emissions in the current period.
34. The fossil fuel sector updates its price and the Energy Sector updates its mark-up.

A.2 Energy Sector

The Energy Sector sells energy to C- and K-firms, Households and the Government. The Energy Sector embeds all industries delivering final energy, thus both the power sector supplying electricity and the industries refining and supplying fossil fuels ready to be burnt at the end use point. Electricity is supplied through a mix of "green" and "brown" power plants employing technologies differing by emissions per energy unit supplied and costs. Green plants represent renewable power plants which do not produce carbon emissions when supplying electricity. They employ only capital, and their production cost is zero. Brown plants supply electricity by converting fossil fuels supplied by an external sector, generating carbon emissions. Therefore, the exogenous price of fossil fuels determines brown plants' production cost, while their expansion is costless, contrary to green plants. We assume that fossil fuels are instead supplied "for free" by the Energy Sector together with electricity, neglecting refining processes. To determine the price of energy, the Energy Sector follows a "merit-order" principle (Sensfuß et al., 2008): green plants that supply for free are activated first; if they are not sufficient to cover total energy demand, brown plants are activated progressively from the one with the lowest supply cost, until meeting the total amount of energy demanded. The energy price for industry is determined as a mark-up over the unit cost of the last (and most expensive) plant activated.

Whenever energy demand is higher than the total capacity of all plants available, the Energy Sector instantaneously expands its capacity to satisfy demand. In the model version used in this work, the share of capacity expansion in green and brown plants is determined by the target share of green energy supplied in the current period, which depends on the exogenous target share at the end of the simulation. For building new green plants, the Energy Sector employs labour, which is also the only input required for R&D activities for innovation. Innovation, resulting from R&D, affects the characteristics of both green and brown plants available for future capacity expansion. Innovated green plants present different capacity expansion costs, while innovated brown plants present different emissions per unit of energy and unit cost of production. The main novelty introduced in this work is the supply of energy to Households and the Government, which for the Energy Sector only translates into additional energy demand as described in Sections 2.1.1 and 2.1.2.

A.3 Technological change

The process of technological change is driven by K-firms, which aim to improve their production technique to offer capital machines with lower production costs to C-firms. Each K-firm produces a single capital vintage κ, which is defined by the output produced per unit of labour employed (its labour productivity Pr_{κ}), the real output produced per unit of energy used (energy productivity EE_{κ}), and the emission per unit of energy used (EF_{κ}), when C-firms employ it for production. We also define, since will be the object of some of the policies and scenarios assessed, the carbon intensity of a vintage (CI_{κ}), which represents emissions per unit of real output produced and is equal to $CI_{\kappa} = EF_{\kappa}/EE_{\kappa}$. Each capital vintage has an associated production technique, identified by three corresponding characteristics determining the inputs required and the emissions when K-firms produce machines of that vintage ($Pr_{k,t}$, $EE_{k,t}$ and $EF_{k,t}$).

K-firms spend a fixed fraction of their revenues to employ labour to innovate or imitate competitors, with the likelihood of being successful in each increasing with how much they spend. If successful in imitation, K-firms can start producing the technology of a competitor selected based on a measure of their technological proximity[17]. A successful innovation results in a new capital vintage κ_{in}, whose characteristics are determined through a stochastic process as:

$$Pr_{\kappa_{in}} = (1 + \Im_{1,k,t})Pr_{\kappa}, \tag{S.1}$$

$$EE_{\kappa_{in}} = (1 + \Im_{2,k,t})EE_{\kappa}, \tag{S.2}$$

$$EF_{\kappa_{in}} = (1 + \Im_{3,k,t})EF_{\kappa}, \tag{S.3}$$

where $\Im_{1,k,t}$ is the relative change in labour productivity of the innovated vintage with respect to the current one, and is obtained as a random draw from a beta distribution with exogenous shape parameters b_3^K and b_4^K rescaled on the exogenous interval (b_5^K, b_6^K). Similarly, $\Im_{2,k,t}$ ($\Im_{3,k,t}$) is obtained as a random draw from a beta distribution with shape parameters b_7^K (b_{11}^K) and b_8^K (b_{12}^K) rescaled on the interval (b_9^K, b_{10}^K) ((b_{13}^K, b_{14}^K)). Simultaneously, a successful innovation results in a new technique to produce the new capital vintage, whose characteristics ($Pr_{in,k,t}$, $EE_{in,k,t}$ and $EF_{in,k,t}$) are obtained with the same stochastic process. The re-scaling intervals are not strictly positive, which implies that the innovated vintage and production technique might have worse characteristics than the current one.

Once innovated and imitated vintages' characteristics are determined, K-firms decide which vintage to produce. To decide if to adopt a new technology or continue to produce the current one, each K-firm compares them through a measure of their attractiveness calculated as:

$$A_{\kappa,t} = p_{k,t} + uc_{\kappa,t} \cdot b, \tag{S.4}$$

where $p_{k,t}$ is the price that the K-firm would charge for one machine of vintage κ, $uc_{\kappa,t}$ is the unit cost of production for C-firms using vintage κ and b is an exogenous fixed payback parameter. $p_{k,t}$ and $uc_{\kappa,t}$ depend on the characteristics of respectively the production technique and the capital vintage, being calculated as:

$$p_{k,t} = (1 + \mu^K) \cdot uc_{k,t} = (1 + \mu^K)\left(\frac{w_{H,t}}{Pr_{k,t}} + \frac{p_{e,t-1}}{EE_{k,t}}\right), \tag{S.5}$$

$$uc_{\kappa,t} = \frac{w_{H,t}}{Pr_{\kappa,t}} + \frac{p_{e,t-1}}{EE_{\kappa,t}} = \frac{w_{H,t}}{Pr_{\kappa,t}} + \frac{p_{e,t-1}}{EF_{\kappa,t}} CI_{\kappa,t}, \tag{S.6}$$

where μ^K is the (homogenous) mark-up of K-firms and $uc_{k,t}$ is the unit cost of production using the associated technology. K-firms will produce the vintage having a lower value of $A_{\kappa,t}$, since C-firms use the same measure of attractiveness to compare K-firms when deciding to switch the capital supplier. This implies that K-firms might decide to adopt (and C-firms might decide to switch to a supplier selling) capital vintages that are inferior in some characteristics to the current one, if the others improve sufficiently to justify it – or if wages and energy prices change significantly.

A.4 C-firms and Banks failure

A C-firm fails and exits the model if either: it cannot finance any production, being too constrained in the credit market; its market share becomes very small; it is not able to satisfy payment obligations on energy, principal and interests on loans or taxes; its net worth at the end of the timestep is negative. C-firms never fail on payments for wages or investment, since they scale back production and investment if not able to fully finance them. When a C-firm exits, at the end of the timestep a new C-firm enters the model, receiving a transfer from Households' deposits as described in Section 2.1.1 and an initial stock of second-hand capital machines.

---

[17] For a detailed description of K-firms' spending on innovation and imitation, how this influences their likelihood of being successful and the imitation process please refer to Reissl et al. (2024). Here, we focus on the processes of innovation and of Firms' choice on which technology to produce, being these the ones influenced by our policies and scenarios.

Banks fail only if their net worth is negative at the end of the period, in which case they are bailed out by the Government. The change in net worth of a Bank is determined by its profits (net of taxes and dividends when positive), which depend on the Bank's interest income (on loans, bonds and reserves) and expenditures (on deposits and advances) and possible losses from failing C-firms.

A.5 Stock-flow consistency tables

Table S.1: balance sheet matrix. Hous.: Households; Gov.: Government; CB: Central Bank

	Hous.	**C-Firms**	**K-firms**	**Banks**	**Gov.**	**CB**	**Energy**	**Fossil**	$\sum$
Bank Deposits	$+D_h$	$+D_c$	$+D_k$	$-D$			$+D_e$		0
Gov. Bonds				$+GB_b$	$-GB$	$+D_{cb}$			0
Loans		$-L$		$+L$					0
CB Reserves				$+R_b$		$-R$		$+R_f$	0
CB Advances				$-A$		$+A$			0
Fixed Capital		$+K$					$+K_e$		$K + K_e$
Inventories		$+Inv$							Inv
$\sum$	NW_h	NW_c	NW_k	NW_b	NW_g	NW_{cb}	NW_e	NW_f	$K + K_e + Inv$

Table S.2: transaction flow matrix. Hous.: Households; Gov.: Government; CB: Central Bank; Int.: interests on.

	Hous.	**C-Firms**	**K-firms**	**Banks**	**Gov.**	**CB**	**Energy**	**Fossil**	$\sum$
Consumption	$-C_h$	$+C$			$-C_g$				0
Investment		$-I$	$+I$						0
Benefits	$+UB$				$-UB$				0
Taxes	$-Tax_h$	$-Tax_c$	$-Tax_k$	$-Tax_b$	$+Tax$		$-Tax_e$		0
Wages	$+W$	$-W_c$	$-W_k$				0		0
Fuel							$-FF$	$+FF$	0
Energy	$-E_h$	$-E_c$	$-E_k$		$-E_g$		$+E$		0
Dividends	$+Div$	$-Div_c$	$-Div_k$	$-Div_b$			$-Div_e$	$-Div_f$	0
Int. Loans		$-iL$		$+iL$					0
Int. Deposits	$+iD_h$	$+iD_c$	$+iD_k$	$-iD$			$+iD_e$		0
Int. Gov. Bonds				$+iGB_b$	$-iGB$	$+iGB_{cb}$			0
Int. Reserves				$+iR$		$-iR$			0
Int. Advanced				$-iA$		$+iA$			0
Transfers CB					$+T_{cb}$	$-T_h$			0
Transfer Entry	$-T_h$	$+T_c$	$+T_k$	$-T_b$	$-T_g$				0
Bailout				$+Bail$	$-Bail$				0
Δ Deposits	$-\Delta D_h$	$-\Delta D_c$	$-\Delta D_k$	$+\Delta D$			$-\Delta D_e$		0
Δ Gov. Bonds				$+\Delta GB_b$	$+\Delta GB$	$-\Delta GB_{cb}$			0
Δ Loans		$+\Delta L$		$-\Delta L$					0
Δ Reserves				$-\Delta R_b$		$+\Delta R$		$-\Delta R_f$	0
Δ Advances				$+\Delta A$		$-\Delta A$			0
$\sum$	0	0	0	0	0	0	0	0	

A.6 Model calibration and validation

To disaggregate Households into three income-based classes we started from the baseline parametrization of the benchmark DSK model presented in Reissl et al. (2024) and we followed a procedure similar to the one of Caiani et al. (2019). Since we assumed that production is proportional to the number of employed Bottom 60% Households (see Section 2.1.1), we set their initial number equal to the total number of Households in the benchmark version, in order to keep the same value of initial labour productivity. We then set the initial number of Middle 30% and Top 10% Households based on their population shares. We aimed at matching initial income shares to values roughly in line with the EU, with 30% of income going to Bottom 60% Households, 40% to Middle 30% Households and 30% to Top 10% Households (these are the same shares used by Caiani et al. (2019), and are similar for instance with the ones of France (Garbinti et al., 2018)). We pre-set ownership of the Energy Sector and Banks, initial ownership of C- and K- Firms and initial deposit shares of Bottom 60%, Middle 30% and Top 10% Households increasing with the income of the classes to 0%, 30% and 70%. These shares determine also equal initial shares of capital income, given that the dividends of each sector are split between household classes based on their ownership shares (see Section 2.1.1). We did not change the initial amount of total dividends, and we aimed at keeping total wages paid by Firms unchanged respect to the benchmark version, therefore not changing Households' total initial income as well. Therefore, from these decisions and by having already set capital income and total income shares of each Households class, we calculated their labour income and finally the initial wage of Bottom 60% Households (w_{BI}) and the wage ratios between classes ($wr_{MI,BI}$ and $wr_{TI,BI}$).

We set a value of the ratio between energy price paid by Households and by Firms (ϕ_E) of 2, which is roughly in line with EU data since 2008 (Rademaekers et al., 2020), and we aimed at matching a share of final energy demanded by Households realistic for the EU, which was of 25.8% in 2022 (Eurostat, 2024b). In order to properly capture the effects of redistributing income on aggregate demand of energy and goods, and thus emissions, we imposed to obtain target energy expenditure share of Households ($EnExpSh_{cl}$) and propensities to consume out of disposable income decreasing with increasing income of the class (Bistline et al., 2024; Costantini et al., 2025; Dynan et al., 2004; Lamarche et al., 2020). We set the average propensity to consume out of deposits (α_3) to 1% for all Households classes. Decreasing the average propensity to consume of Households and diverting a portion of their demand to energy lowered the value of aggregate consumption and thus of employment compared to the previous calibration. We therefore tuned the values of target energy expenditure shares, propensities to consume our of labour ($\alpha_{cl,1}$) and capital ($\alpha_{cl,2}$) income, unemployment rate as a share of each class wage rate (μ), target public spending to GDP ratio (g^*) and tax rate on wages (τ_{cl}^{w}), on dividends (τ^{div}) and on deposits (τ^{dep}) with the aim to bring aggregate consumption and thus unemployment rate back to the previous level, while ensuring to have realistic values of these parameters and public debt to GDP for the EU. Table S.3 reports the values of the parameters resulting from the new calibration, while the other model parameters have the same values reported in Reissl et al. (2024). Figures S.1, S.2 and S.3 and Table S.4 report additional outcomes of the model calibration, while Table S.5 reports the main stylised facts that our model replicates.

Table S.3: values for parameters that we introduced or that we changed respect to the calibration of the DSK model in Reissl et al. (2024). Bottom 60%, Middle 30% and Top 10% refer to household income classes. APC: average propensity to consume. Symbols are reported only for parameters that appear in equations in this paper.

Symbol	Description	Value
$wr_{MI,BI}$	Ratio of Middle 30% to Bottom 60% wage rate	2.4
$wr_{TI,BI}$	Ratio of Top 10% to Bottom 60% wage rate	4.1
μ	Unemployment benefit rate as a share of class wage rate	0.8
τ^{div}	Tax rate on Households' dividends	0.30
τ^{w}_{BI}	Tax rate on wages for Bottom 60%	0.25
τ^{w}_{MI}	Tax rate on wages for Middle 30%	0.30
τ^{w}_{TI}	Tax rate on wages for Top 10%	0.35
τ^{dep}	Tax rate on Households' deposits	0.02
	Tax rate on Firms' profits	0.2
	Tax rate on Banks' profits	0.2
	Tax rate on Energy Sector's profits	0.2
	Energy Sector dividends' payment rate	0.79
g^{*}	Target public spending to GDP ratio	0.3
$\alpha_{BI,1}$	Bottom 60% APC out of labour income	1.0
$\alpha_{MI,1}$	Middle 30% APC out of labour income	0.95
$\alpha_{TI,1}$	Top 10% APC out of labour income	0.85
$\alpha_{BI,2}$	Bottom 60% APC out of capital income	1.0
$\alpha_{MI,2}$	Middle 30% APC out of capital income	0.85
$\alpha_{TI,2}$	Top 10% APC out of capital income	0.65
α_{3}	Households APC out of wealth	0.01
$EnExpS\mathrm{h}_{BI}$	Energy expenditure share of Bottom 60%	0.07
$EnExpS\mathrm{h}_{MI}$	Energy expenditure share of Middle 30%	0.05
$EnExpS\mathrm{h}_{TI}$	Energy expenditure share of Top 10%	0.03
ϕ_{E}	Ratio between energy price paid by Households and by Firms	2
γ	Consumption smoothing parameter	0.7

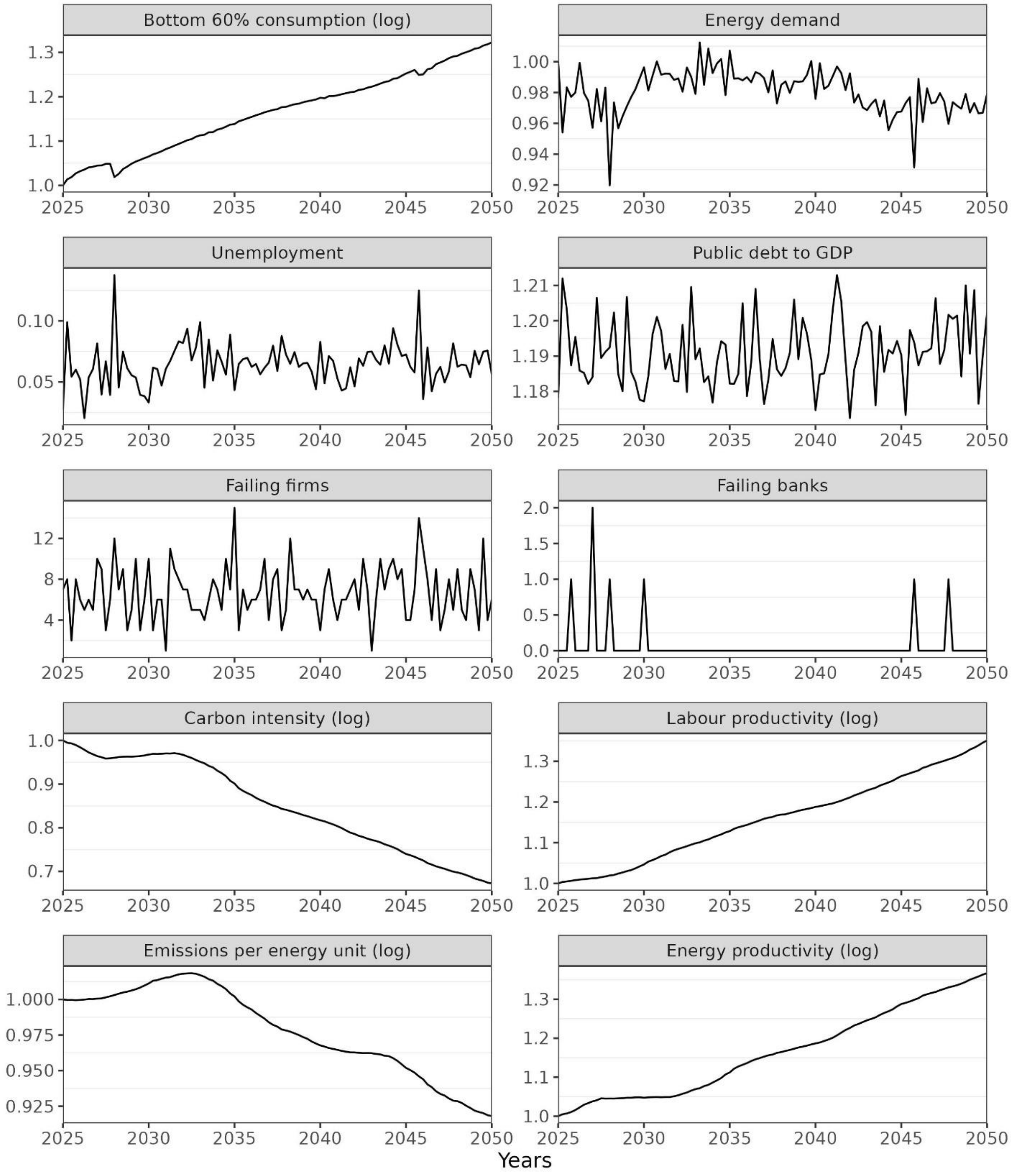

Figure S.1: time series of selected variables for one run of the model randomly selected. Bottom 60% consumption, Carbon intensity, Labour productivity, Emissions per energy unit and Energy productivity are in logarithmic scale. Values for Bottom 60% consumption, Energy demand, Carbon intensity, Labour productivity, Emissions per energy unit and Energy productivity are normalised to the value they have in the year 2025. Energy demand refers to the total final energy demand (from Firms, Households and the Government). Carbon intensity, Labour productivity, Emissions per energy unit and Energy productivity refer to the average value across C-firms.

Table S.4: volatilities of selected variables, our model simulations, calculated as the relative standard deviation of bandpass-filtered quarterly simulated time series. Values are average over 300 Monte Carlo runs and 100 timesteps, after a discarded burn-in period of 200 timesteps.

Volatility of	**Value**
GDP	0.0276
Consumption	0.0121
Investment	0.1436
Unemployment	0.0191
Inflation	0.0143

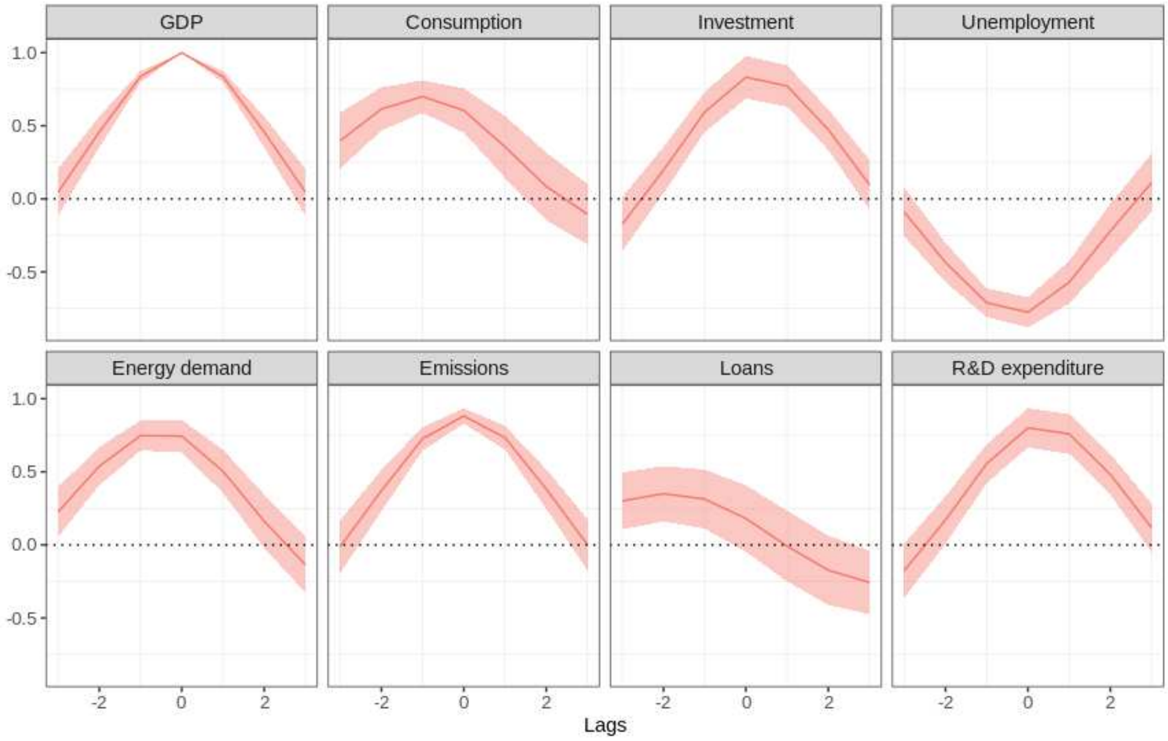

Figure S.2: cross-correlations between real GDP and macroeconomic variables. Red lines represent averages and shaded areas 95% confidence intervals over 300 Monte Carlo runs. Cross-correlations are calculated over bandpass-filtered simulated time series.

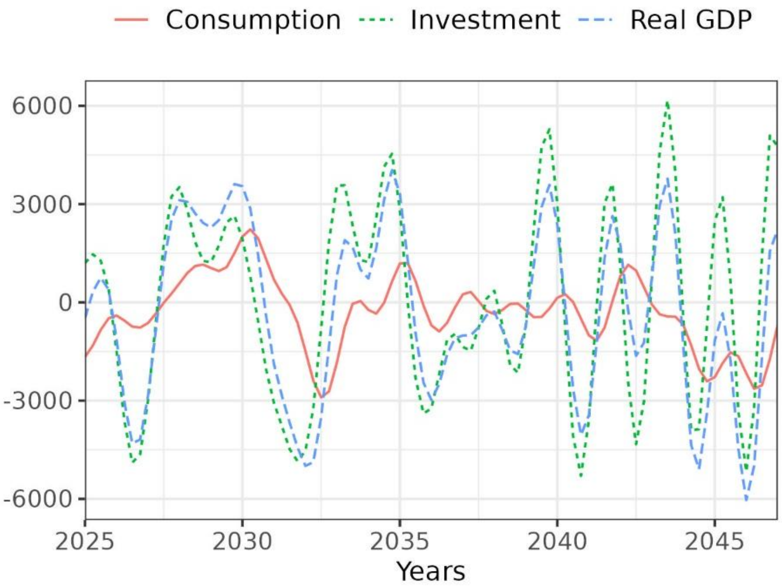

Figure S.3: bandpass-filtered time series of selected variables for a single run of the model randomly selected.

Table S.5: main stylised facts that our model replicates, adapted from Reissl et al. (2024).

Stylised fact	Reference(s)
Endogenous growth with persistent fluctuations	Burns and Mitchell (1946); Kuznets (1966); Zarnowit (1985); Stock and Watson (1999)
Fat-tailed GDP growth-rate distribution	Fagiolo et al. (2008); Castaldi and Dosi (2009); Lamperti and Mattei (2018)
Relative volatility of main macroeconomic aggregates	Stock and Watson (1999); Napoletano et al. (2006)
Cross-correlations of main macroeconomic aggregates	Stock and Watson (1999); Napoletano et al. (2006)
Pro-cyclical private debt	Lown and Morgan (2006)
Pro-cyclical R&D investment	Wälde and Woitek (2004)
Pro-cyclical energy demand	Moosa (2000)
Pro-cyclical emissions	Doda (2014)
Cross-correlation between private debt and loan losses	Foos et al. (2010); Mendoza and Terrones (2012)
Fat-tailed Firm growth-rate distribution	Bottazzi and Secchi (2006, 2003)
Lumpy investment rates at Firm level	Doms and Dunne (1998)
Persistent productivity heterogeneity across Firms	Bartelsman and Doms (2000); Dosi (2007)
Persistent energy productivity heterogeneity across Firms	DeCanio, S. and Watkins, W. (1998); Petrick (2013)
Persistent emissions per unit of energy heterogeneity across Firms	Petrick (2013)

Appendix B Individual policies

B.1 Policies description

Progressive income tax. We designed a policy that through a single parameter (θ_1) can change the progressivity of tax rates on Households' wages, while keeping the total amount of labour income taxes collected at the time of policy implementation unchanged. The implementation of this policy was inspired by (Caiani et al., 2019). The ratio between each Household class *cl* share of labour income (WSh_{cl}) and share of population ($LSSh_{cl}$) is equal to the ratio between the average per capita labour income of the household class and of all Households:

$$\frac{WSh_{cl}}{LSSh_{cl}} = \frac{W_{cl}/\sum_{cl} W_{cl}}{LS_{cl}/\sum_{cl} LS_{cl}} = \frac{W_{cl}/LS_{cl}}{\sum_{cl} W_{cl}\,/\sum_{cl} LS_{cl}}. \tag{S.7}$$

Considering that with a flat tax rate each Household class pays a share of taxes equal to its labour income share, we can use the ratio above to calculate a correction factor ($correction_{cl}$) determining the share of labour income tax paid by each Household class, based on how their per-capita income compared to the average per-capita income:

$$correction_{cl} = WSh_{cl} \cdot \left(\frac{WSh_{cl}}{LSSh_{cl}}\right)^{\theta_1}. \tag{S.8}$$

θ_1 is the policy parameter determining the progressivity of labour income taxation. The normalised correction factors determine the new shares of taxes on labour income paid by each Household class:

$$TaxSh^{*w}_{cl} = \frac{correction_{cl}}{\sum_{cl} correction_{cl}}, \tag{S.9}$$

The average tax rates on labour income of each class after policy implementation (τ^{*w}_{cl}) can be obtained from the identity $Tax^w_H \cdot TaxSh^{*w}_{cl} = W_{cl} \cdot \tau^{*w}_{cl}$, where $Tax^w_H = \sum_{cl} Tax^w_{cl}$ is the total taxes collected on Households' labour income, which we impose to remain equal before and after policy implementation:

$$\tau^{*w}_{cl} = \frac{Tax^w_H \cdot TaxSh^{*w}_{cl}}{W_{cl}} = \frac{\overline{\tau^w_H} \cdot TaxSh^{*w}_{cl}}{WSh_{cl}}. \tag{S.10}$$

$Tax^w_{H,t} = \sum_{cl} Tax^w_{cl,t}$ are the total taxes collected on Households' labour income and $\overline{\tau^w_H}$ is the average tax rate on Households' labour income (total taxes paid on labour income divided by total labour income), which can be calculated as the average tax rates weighted by each Household class's labour income share:

$$\overline{\tau^w_H} = \sum_{cl} \tau^w_{cl} \cdot WSh_{cl}. \tag{S.11}$$

$\theta_1 = 0$ results in a flat tax rate and $\theta_1 > 0$ ($\theta_1 < 0$) in a progressive (regressive) tax scheme. Our baseline scenario corresponds to $\theta_1 \approx 0.2$, with average labour income tax rates for Bottom 60%, Middle 30% and Top 10% Households respectively of 25%, 30% and 35%. Figure S.4 reports the resulting tax rates on Household classes at different values of θ_1.

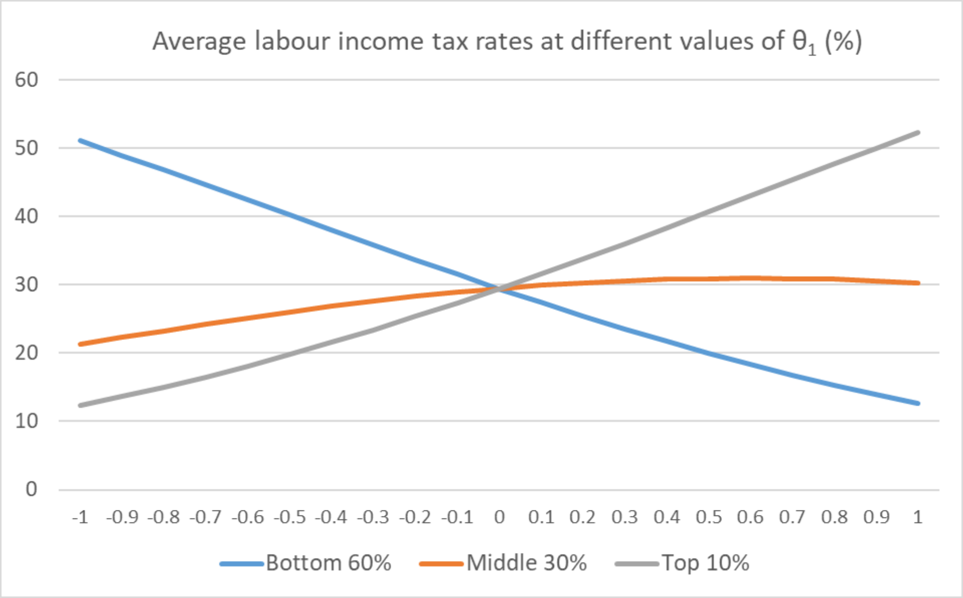

Figure S.4: average income tax rates on household classes resulting from implementing a change in labour income tax scheme with different values of the policy parameter determining its progressivity. The x-axis reports the values of the parameter, which corresponds to θ_1 in Eq. (S.8).

Shift taxes to capital. This policy increases the tax rates on Households' wages and decreases the one on dividends, to shift a fraction (θ_2, the policy parameter) of taxes collected by the Government on Households' income from their labour to capital income. At the time of policy implementation, the sum of taxes on capital and labour income and the progressivity of the labour income tax scheme remain unchanged.

If $Tax_H = Tax^w_H + Tax^{div}_w$ are the total taxes collected on Households' income, their shares from labour and from capital income after policy implementation are given respectively by:

$$\left(\frac{Tax^{w^*}_H}{Tax_H}\right) = \left(\frac{Tax^w_H}{Tax_H}\right) - \theta_2, \tag{S.12}$$

$$\left(\frac{Tax^{div^*}_H}{Tax_H}\right) = \left(\frac{Tax^{div}_H}{Tax_H}\right) + \theta_2. \tag{S.13}$$

From these two equations we can obtain the taxes to be collected from wages ($Tax^{w^*}_H$) and from dividends ($Tax^{div^*}_H$). The new tax rate on dividends is then:

$$\tau^{div^*} = \frac{Tax_H^{div^*}}{Div_{cl}}. \tag{S.14}$$

We can calculate the new amount of labour income taxes to collect from each Household class ($Tax_{cl}^{w^*}$) from the share of labour income taxes collected from each Household class ($TaxSh_{cl}^{w}$), that we keep unaltered to maintain the same progressivity of taxes on labour income:

$$Tax_{cl}^{w^*} = TaxSh_{cl}^{w} \cdot Tax_H^{w^*}. \tag{S.15}$$

The new tax rate on wages for each Household class is then:

$$\tau_{cl}^{w^*} = \frac{Tax_{cl}^{w^*}}{W_{cl}}. \tag{S.16}$$

Figure S.5 reports the resulting tax rates at different values of θ_2.

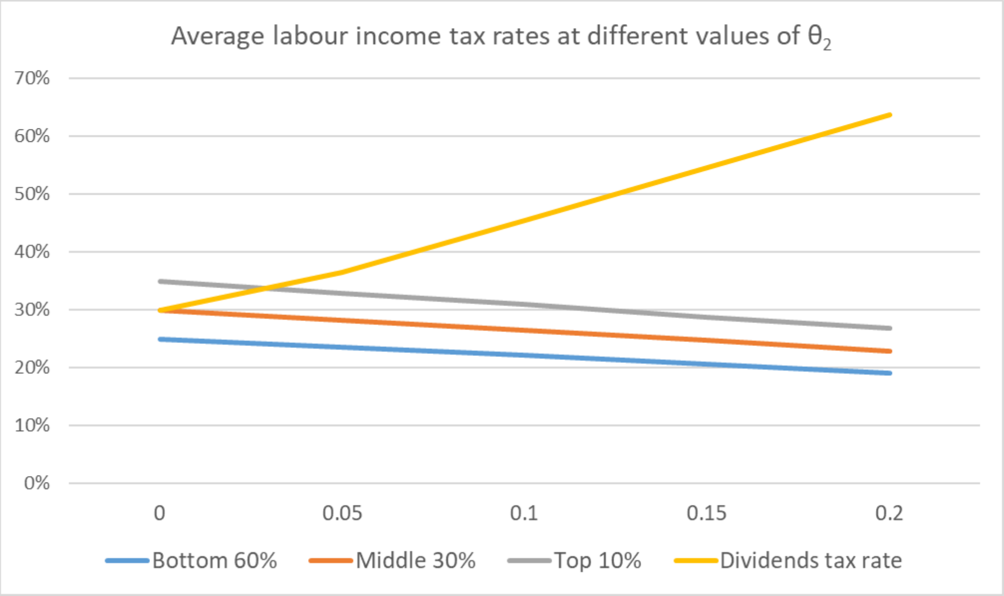

Figure S.5: average Households' labour income and dividends tax rate resulting from shifting taxes from labour to capital income. The x-axis reports the values of the policy parameter determining the extent of the shift, corresponding to θ_2 in Eq. (S.12) and (S.13).

Higher tax Top 10%. Following the implementation of this policy, the new tax rate on labour income of Top 10% Households becomes:

$$\tau^{*w}_{TI} = \tau^{w}_{TI} + \Delta\tau_{TI}, \tag{S.17}$$

where $\Delta\tau_{TI}$ is the policy parameter, expressed as a fraction of labour income.

Lower tax Bottom 60% Following the implementation of this policy, the tax rate on labour income of Bottom 60% Households becomes:

$$\tau^{*w}_{BI} = \tau^{w}_{BI} - \Delta\tau_{BI}, \tag{S.18}$$

where $\Delta\tau_{BI}$ is the policy parameter, expressed as a fraction of labour income.

Green capital subsidies (dirty capital taxation). The Government subsidises (taxes) C-firms to purchase capital machines with low (high) carbon intensity. We assume that in each period the Government collects information on the price and carbon intensity of the vintage produced by each K-firm, to set the value of subsidies (taxes) for the following quarter. The maximum subsidy ($es_{max,t}$) or tax ($et_{max,t}$) per machine are set as:

$$es_{max,t} = \epsilon_s \cdot \overline{p_{k,t-1}}, \tag{S.19}$$

$$et_{max,t} = \epsilon_t \cdot \overline{p_{k,t-1}}, \tag{S.20}$$

where ϵ_s (ϵ_t) is the policy parameter and $\overline{p_{k,t-1}}$ is the average price per machine across K-firms in the previous period. The actual subsidy (tax) per machine for each K-firm depends on the carbon intensity of the vintage it produces CI_κ compared to the average carbon intensity of vintages produced across K-firms ($\overline{CI_{\kappa,t}}$). In particular, the Government does not subsidise (tax) machines whose carbon intensity is higher (lower) than average, while it offers a subsidy (imposes a tax) that decreases linearly from $es_{max,t}$ ($et_{max,t}$) for the machine with the lowest (highest) carbon intensity $CI_{\kappa,t}^{min}$ ($CI_{\kappa,t}^{max}$) to 0 for machines that have carbon intensity equal to the average. The subsidy offered ($es_{\kappa,t}$) or the tax imposed ($et_{\kappa,t}$) per machine are set as:

$$es_{\kappa,t} = \begin{cases} 0, & CI_\kappa \geq \overline{CI_{\kappa,t}} \\ es_{max,t} \cdot \dfrac{\overline{CI_{\kappa,t}} - CI_\kappa}{\overline{CI_{\kappa,t}} - CI_{\kappa,t}^{min}}, & CI_\kappa < \overline{CI_{\kappa,t}} \end{cases}, \tag{S.21}$$

$$et_{\kappa,t} = \begin{cases} 0, & CI_\kappa \leq \overline{CI_{\kappa,t}} \\ et_{max,t} \cdot \dfrac{CI_\kappa - \overline{CI_{\kappa,t}}}{CI_{\kappa,t}^{max} - \overline{CI_{\kappa,t}}}, & CI_\kappa > \overline{CI_{\kappa,t}} \end{cases}. \tag{S.22}$$

The subsidies paid to (taxes paid by) each C-firm are calculated by multiplying the number of machines it purchases from its K-firm supplier (both for expansion and for replacement investment) for the subsidy (taxes) per machine offered for (imposed on) its capital vintages. Subsidies (taxes) are paid to (by) C-firms after they already pay for the machines, and therefore do not modify the credit C-firms require for investment. However, they influence the likelihood of C-firms failing and exiting, contributing to their deposits and thus net worth at the end of the period. In addition, C-firms might also directly fail for not being able to pay eventual taxes on dirty capital.

Firms know in advance the value of subsidy or taxes per machine, which therefore bias both C-firms' choice of K-firm supplier and K-firms' choice of technology to produce, by changing the actual price of machines. The measure of vintage attractiveness used to compare current, innovated and imitated vintages presented in Eq. (S.4) therefore becomes:

$$A_{\kappa,t} = p_{k,t} + uc_{\kappa,t} \cdot b - es_{\kappa,t} + et_{\kappa,t}. \tag{S.23}$$

To summarise, the main effect of subsidies on greener capital (taxes on dirtier capital) is that vintages with lower (higher) carbon intensity will be subsidised (taxed) more, and therefore it will be more (less) likely that C-firms decide to purchase it and that K-firms decide to produce it.

Carbon tax. The Government collects taxes on carbon emissions from the Energy Sector, C- and K-firms, setting a uniform tax rate τ_t^{Em} for all sectors. The total taxes collected are:

$$T_t^{Em} = \tau_t^{Em} \cdot Em_{E,t} + \tau_t^{Em} \cdot \sum_c Em_{c,t} + \tau_t^{Em} \cdot \sum_k Em_{k,t}. \tag{S.24}$$

τ_t^{Em} is indexed on inflation and increasing exponentially with time:

$$\tau_t^{Em} = \tau_0^{Em} \cdot \frac{CPI_t}{CPI_{t^*}} \cdot (t - t^*)^{g_\tau}, \tag{S.25}$$

Where t^* is the time of policy implementation, g_τ is a fixed growth rate of the carbon tax that we set to 1.007, CPI_t is the consumer price index and τ_0^{Em} is the policy parameter, which represents the initial value of the tax at time t^*. The main effect of the carbon tax is to increase prices of capital machines, consumption goods and energy, proportionally to their carbon intensity for C- and K-firms and to its emission per unit of energy supplied for the Energy Sector. All sectors consider in fact the carbon tax in the calculation of their unit cost of production. This also affects the process of technological change influencing the attractiveness of different vintages, since Eq. (S.5) for the unit price of K-firms and Eq. (S.6) for the unit cost of production using a capital vintage become:

$$p_{k,t} = (1+\mu^K)\cdot uc_{k,t} = (1+\mu^K)\left(\frac{w_{H,t}}{Pr_{k,t}\cdot a} + \frac{p_{e,t-1}}{EE_{k,t}} + \tau_t^{Em}\frac{EF_{k,t}}{EE_{k,t}}\right), \qquad (S.26)$$

$$uc_{\kappa,t} = \frac{w_{H,t}}{Pr_{\kappa,t}} + \frac{p_{e,t-1}}{EE_{\kappa,t}} + \tau_t^{Em}\frac{EF_{\kappa,t}}{EE_{\kappa,t}} = \frac{w_{H,t}}{Pr_{\kappa,t}} + \frac{p_{e,t-1}}{EF_{\kappa,t}}CI_{\kappa,t} + \tau_t^{Em}CI_{\kappa,t}. \qquad (S.27)$$

B.2 Additional results

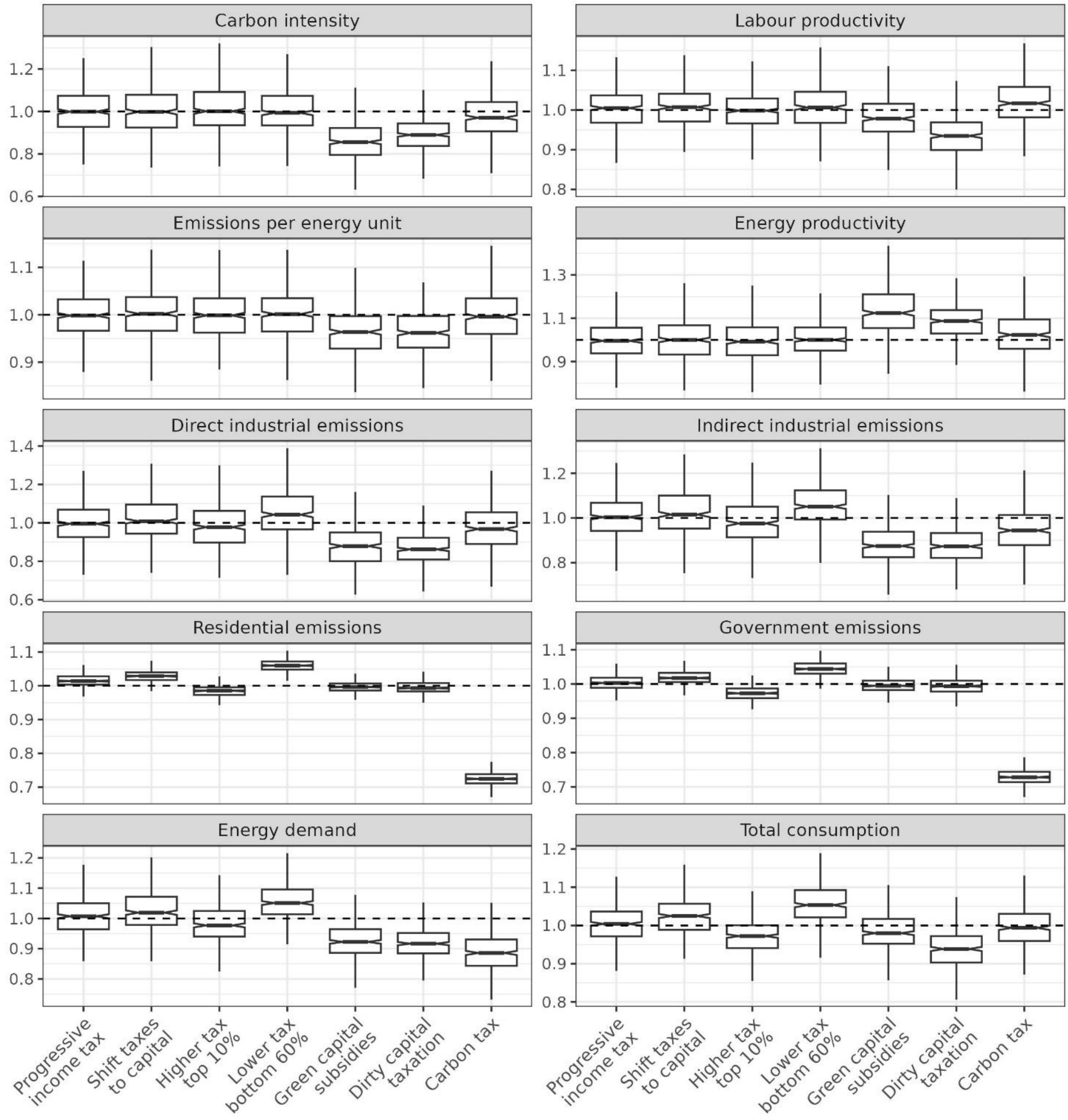

Figure S.6: effect on additional indicators (on top of each boxplot) of introducing fiscal policies individually. Boxplots are obtained over 300 Monte Carlo runs. We report different y-axis and exclude outliers for clearer visualization. Indicators are normalised to the value they assume in the baseline scenario, reported as black dashed lines. Carbon intensity, labour productivity, emissions per energy unit and energy productivity refer to the average value across C-firms. Direct industrial emissions, indirect industrial emissions, residential emissions and government emissions are measured as yearly values. Energy demand refers to the total final energy demand (from Firms, Households and the Government). Total consumption refers to the total real expenditure in consumption goods from Households and Government. All indicators are calculated at the final step of the simulation. The caption of Figure 3 describes the indicators and policies.

B.3 Sensitivity analysis

Each of the Figure S.7 to Figure S.13 report the results of the sensitivity analysis for one of the policies described in Section 3.1 and Appendix B.1, specified in the captions. The indicators are described at the beginning of Section 3.

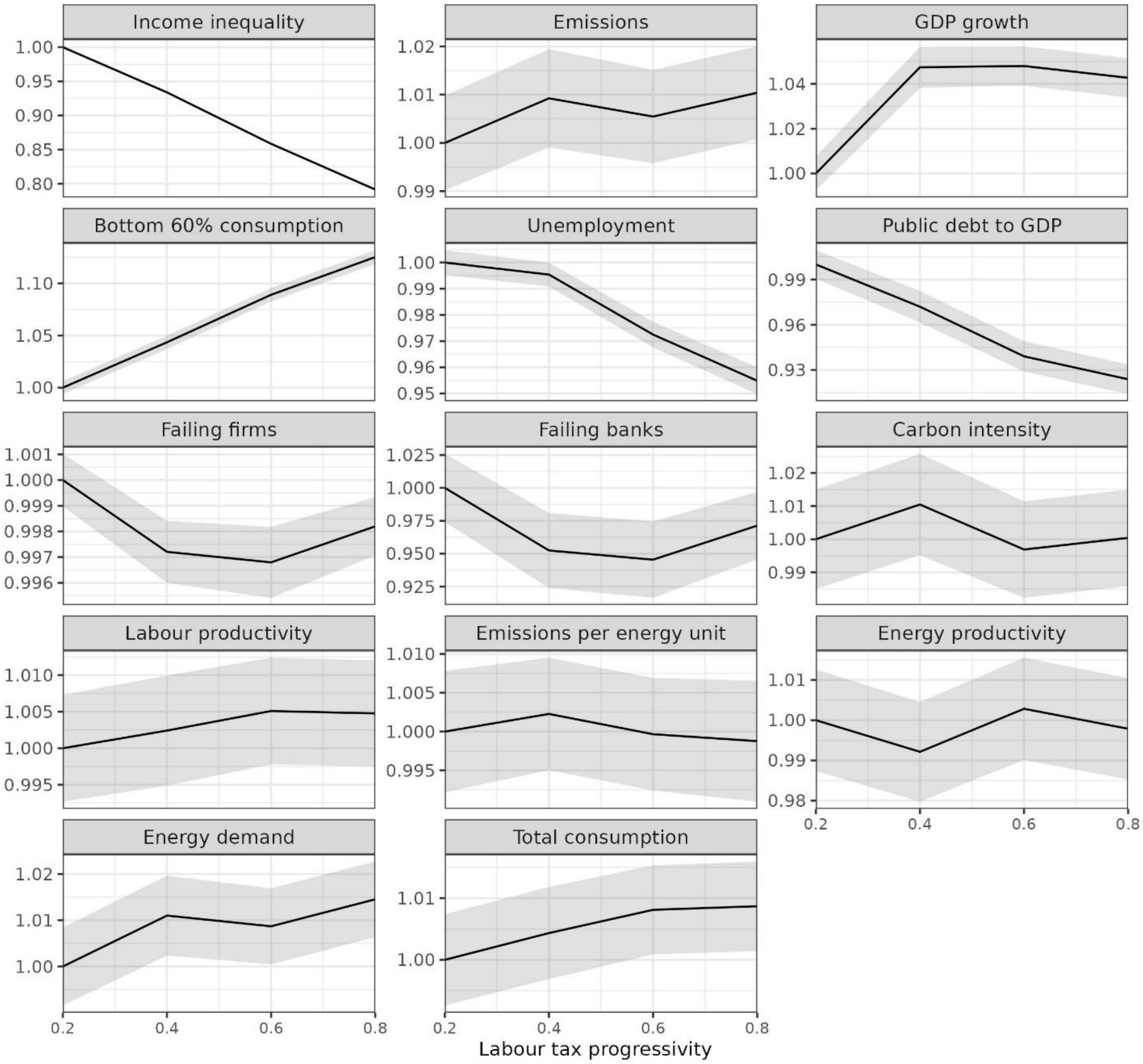

Figure S.7: sensitivity analysis for the "Progressive income tax" policy. Each graph reports the effect on a single indicator of increasing the policy parameter on the x-axis. The policy parameter corresponds to θ_1 in Eq. (S.8) and *determines the resulting tax rates on each household income group and thus the progressivity of the new labour income tax scheme. The values of the parameter tested are the ones on the x-axis, and the first on the left corresponds to the baseline scenario in which the policy is not active. All values of indicators on the y-axis are normalised to the value for the baseline scenario. The black line represents the average value and the grey areas 95% confidence intervals over 300 Monte Carlo runs.*

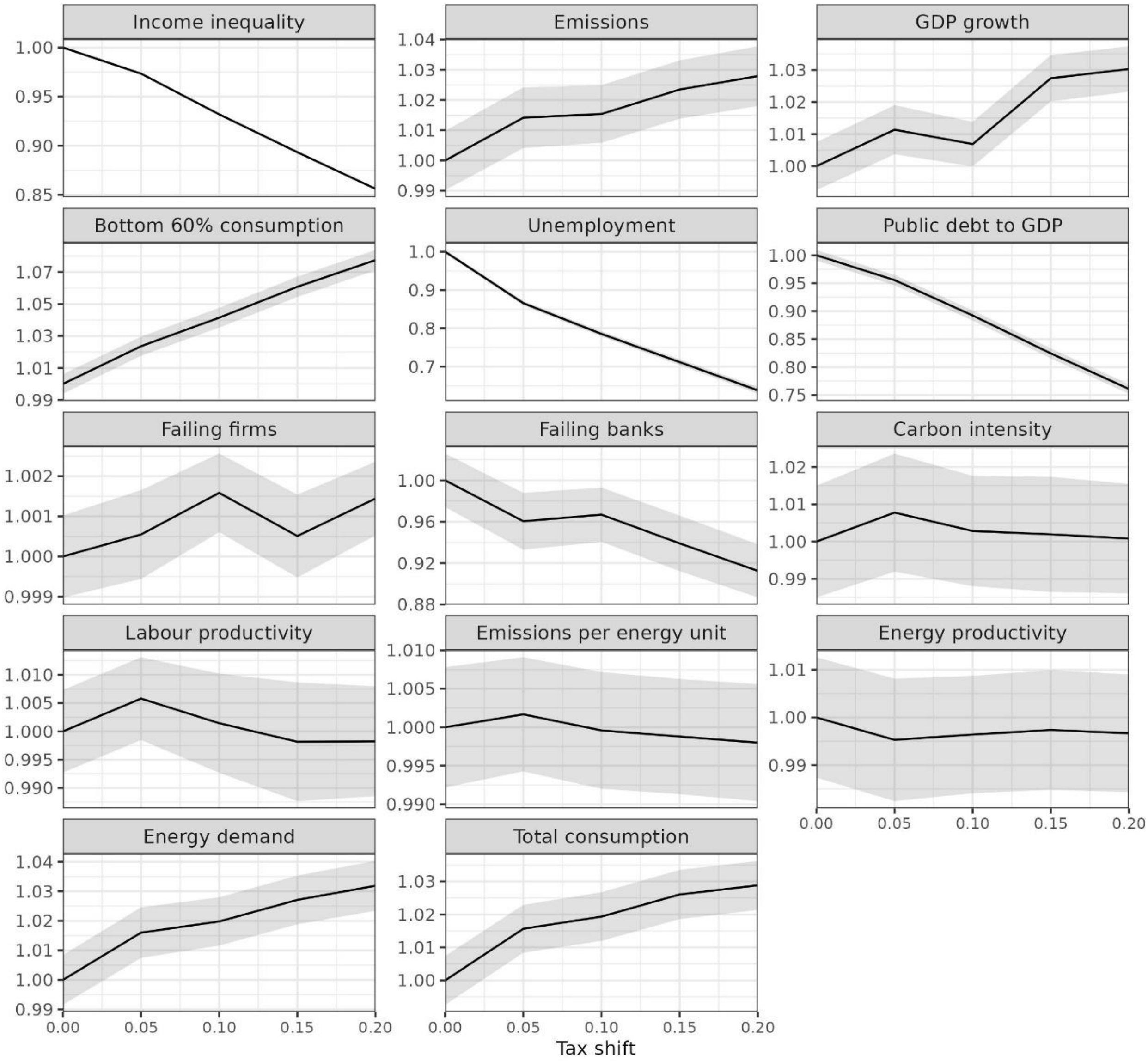

Figure S.8: sensitivity analysis for the "Shift taxes to capital" policy. Each graph reports the effect on a single indicator of increasing the policy parameter on the x-axis. The policy parameter corresponds to θ_2 in Eq. (S.12) and (S.13) and represents the fraction of income taxes collected that is shifted from labour to capital income. The values of the parameter tested are the ones on the x-axis, and the first on the left corresponds to the baseline scenario in which the policy is not active. All values of indicators on the y-axis are normalised to the value for the baseline scenario. The black line represents the average value and the grey areas 95% confidence intervals over 300 Monte Carlo runs.

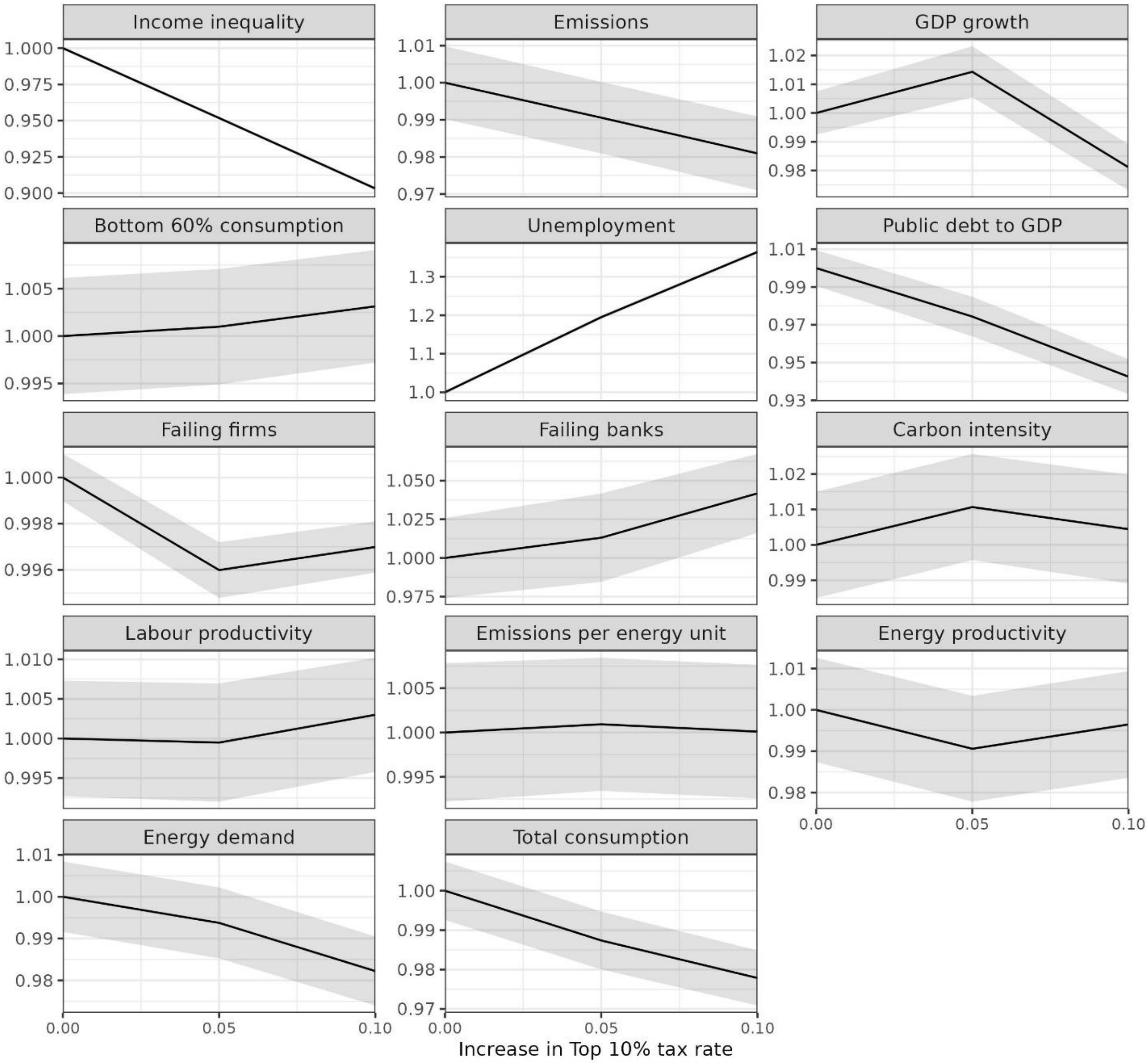

Figure S.9: sensitivity analysis for the "Higher tax Top 10%" policy. Each graph reports the effect on a single indicator of increasing the policy parameter on the x-axis. The policy parameter corresponds to $\Delta\tau_{TI}$ in Eq. (S.17) and is the increase of the tax rate on labour income of Top 10% Households. The values of the parameter tested are the ones on the x-axis, and the first on the left corresponds to the baseline scenario in which the policy is not active. All values of indicators on the y-axis are normalised to the value for the baseline scenario. The black line represents the average value and the grey areas 95% confidence intervals over 300 Monte Carlo runs.

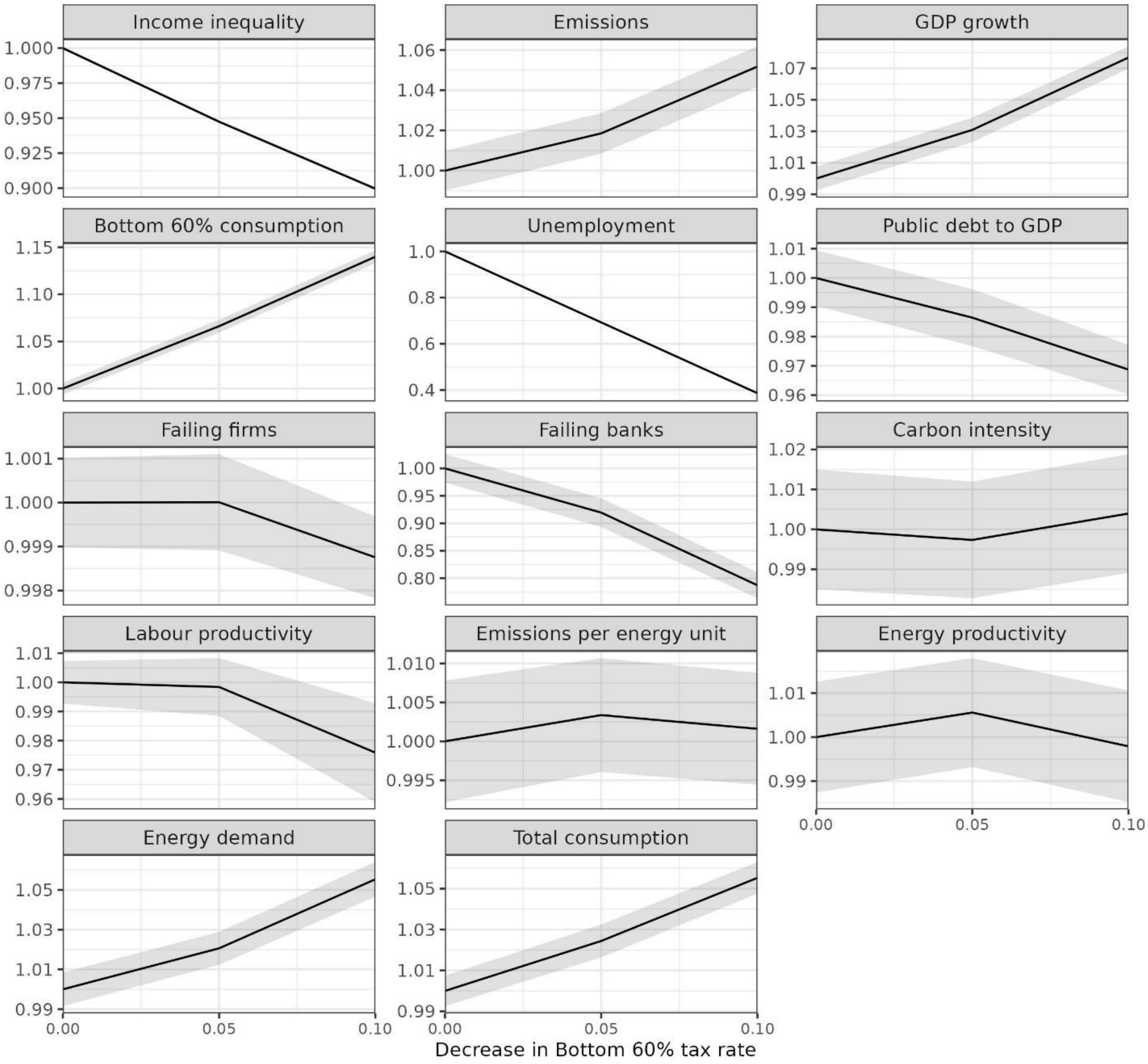

Figure S.10: sensitivity analysis for the "Lower tax Bottom 60%" policy. Each graph reports the effect on a single indicator of increasing the policy parameter on the x-axis. The policy parameter corresponds to $\Delta\tau_{BI}$ in Eq. (S.18) and is the decrease of the tax rate on labour income of Bottom 60% Households. The values of the parameter tested are the ones on the x-axis, and the first on the left corresponds to the baseline scenario in which the policy is not active. All values of indicators on the y-axis are normalised to the value for the baseline scenario. The black line represents the average value and the grey areas 95% confidence intervals over 300 Monte Carlo runs.

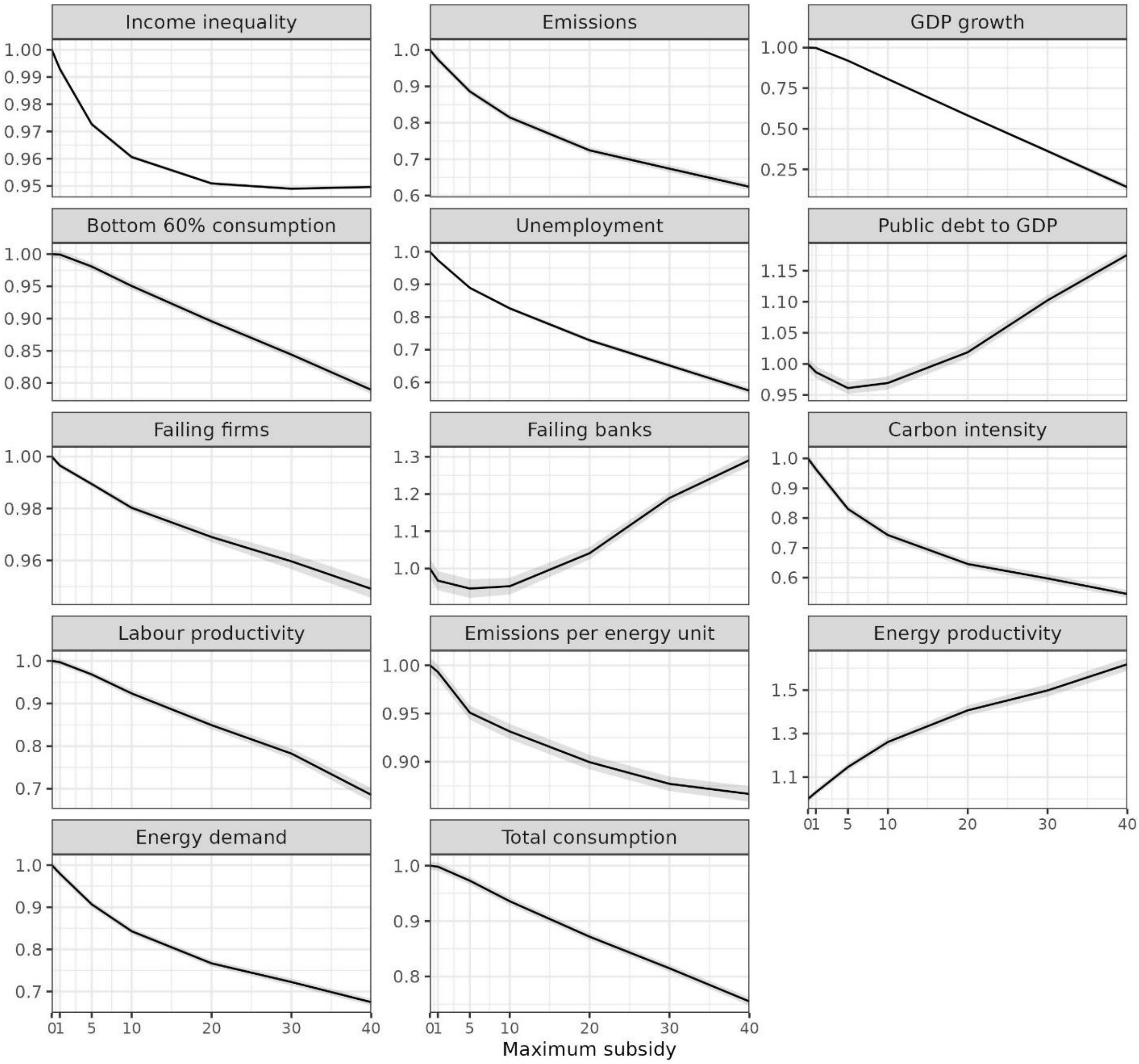

Figure S.11: sensitivity analysis for the "Green capital subsidies" policy. Each graph reports the effect on a single indicator of increasing the policy parameter on the x-axis. The policy parameter corresponds to ϵ_s *in Eq. (S.19) and is the maximum subsidy offered per capital machine, expressed as percentage of the average price of machines across K-firms. The values of the parameter tested are the ones on the x-axis, and the first on the left corresponds to the baseline scenario in which the policy is not active. All values of indicators on the y-axis are normalised to the value for the baseline scenario. The black line represents the average value and the grey areas 95% confidence intervals over 300 Monte Carlo runs.*

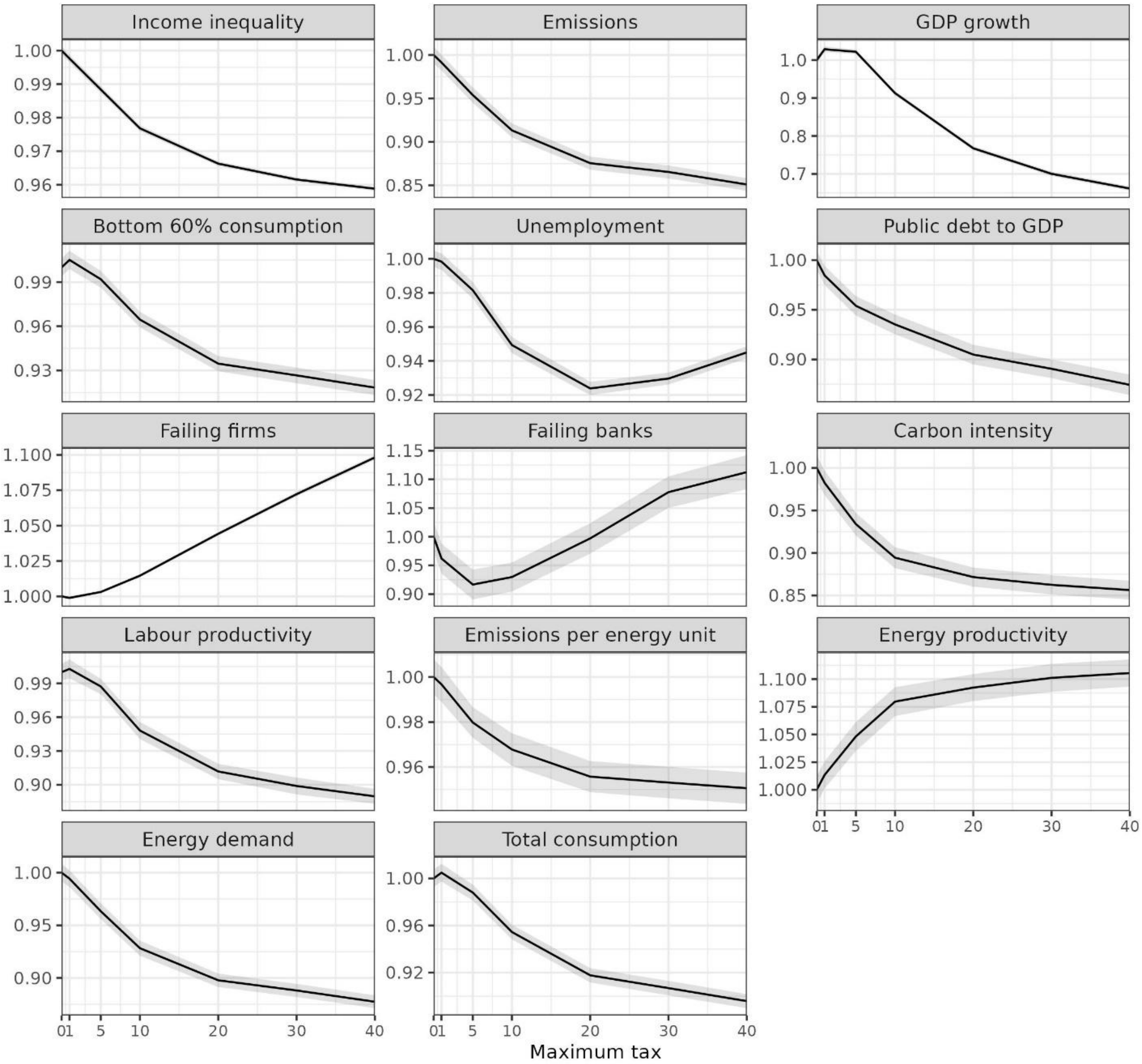

Figure S.12: sensitivity analysis for the "Dirty capital taxation" policy. Each graph reports the effect on a single indicator of increasing the policy parameter on the x-axis. The policy parameter corresponds to ϵ_t in Eq. (S.20) and is the maximum tax imposed per capital machine, expressed as percentage of the average price of machines across K-firms. The values of the parameter tested are the ones on the x-axis, and the first on the left corresponds to the baseline scenario in which the policy is not active. All values of indicators on the y-axis are normalised to the value for the baseline scenario. The black line represents the average value and the grey areas 95% confidence intervals over 300 Monte Carlo runs.

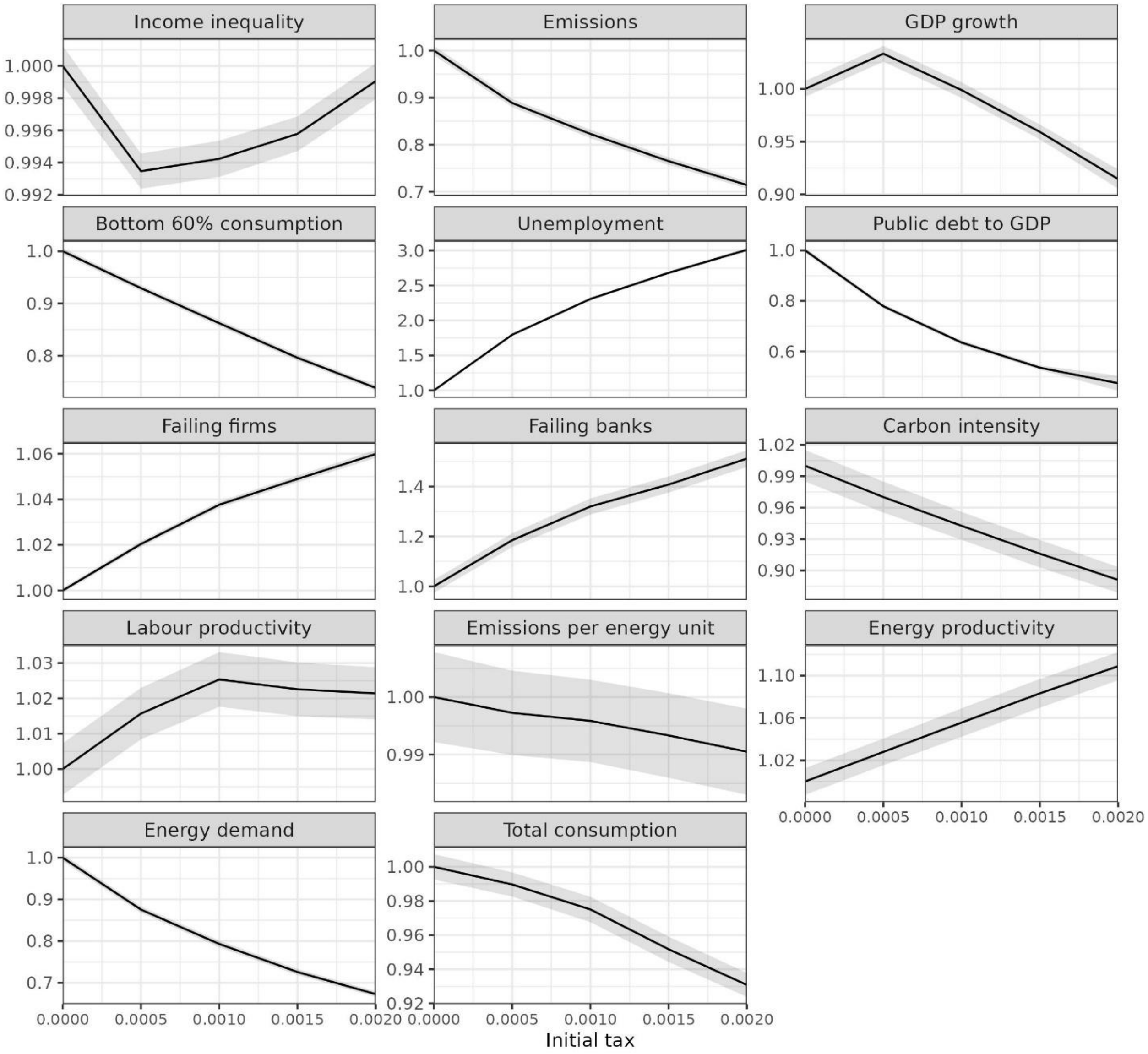

Figure S.13: sensitivity analysis for the "Carbon tax" policy. Each graph reports the effect on a single indicator of increasing the policy parameter on the x-axis. The policy parameter corresponds to τ_0^{Em} in Eq. (S.25) and is the initial tax rate imposed when the policy is introduced. The values of the parameter tested are the ones on the x-axis, and the first on the left corresponds to the baseline scenario in which the policy is not active. All values of indicators on the y-axis are normalised to the value for the baseline scenario. The black line represents the average value and the grey areas 95% confidence intervals over 300 Monte Carlo runs.

Appendix C Policies combination

Table S.6: values of each fiscal policy's parameter set to construct the policy mixes (in the third column). Horizontal dashed lines group policies and policy parameter values that are implemented alternatively. The fourth and fifth columns report the reductions of inequality (for progressive policies) and emissions (for environmental policies) obtained by implementing in isolation the corresponding policy with the value of its parameter on the same row. The last column reports the value of the policy parameter for each policy implemented (and a "/" if the policy is not implemented) in the Selected Policy Mix, the one reducing inequality and emissions the most among the policy mixes reducing both by at least 5% and not increasing unemployment, public debt to GDP and economic instability. For a description of the policies refer to the caption of Figure 6.

Policy	**Policy parameter**	**Values when policy is Active**	**Reduction (%) compared to baseline of:**		**Value of policy parameter in the Selected Policy Mix**
			Inequality	**Emissions**	
Progressive income tax	θ_1	0.34	5		0.48
		0.48	10		
Shift taxes to capital	θ_2	0.07	5		0.14
		0.14	10		
Higher tax Top 10%	$\Delta\tau^{MA}$	0.5	5		/
Lower tax Bottom 60%	$\Delta\tau^{WR}$	0.5	5		0.5
Green capital subsidies	ϵ_S	0.025		5	0.75
		0.040		10	
		0.075		15	
Dirty capital taxation	ϵ_T	0.06		5	/
		0.13		10	
		0.4		15	
Carbon tax	τ_0^{Em}	0.00025		5	0.045
		0.00045		10	
		0.00075		15	

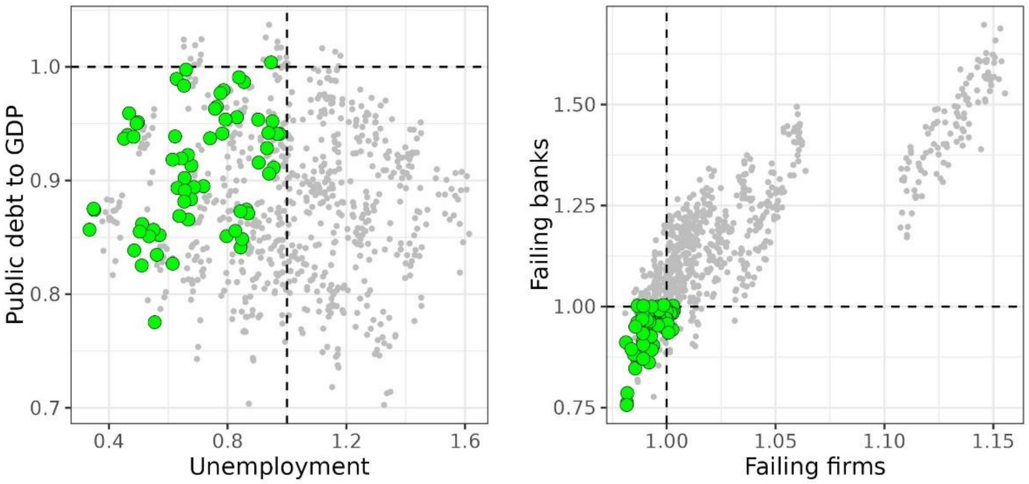

Figure S.14: effect of implementing policy combinations on economic indicators selected as constraints. Each dot represents the effects of one policy mix. Green-filled dots represent policy mixes that reduce inequality and emissions by more than 5% and do not increase unemployment, public debt to GDP and economic instability compared to the baseline scenario with no policy introduced. Grey smaller dots represent all other policy mixes that either do not reduce inequality nor emissions by 5%, or that increase unemployment, public debt to GDP or economic instability. All values are averaged over 50 Monte Carlo runs and normalised to the baseline scenario values - reported as black dashed lines. Failing Firms and Banks are measured as the average number failing in each timestep. All indicators are averaged over the 100 timesteps after policies introduction.

Appendix D Additional scenarios

D.1 More productive green technologies

In this scenario, for each K-firm that successfully innovates, we still calculate $Pr_{K_{in}}$ with Eq. (S.1), drawing $\mathfrak{I}_{1,k,t}$ from its beta distribution. However, instead of having independent draws, we calculate $\mathfrak{I}_{2,k,t}$ and $\mathfrak{I}_{3,k,t}$ by re-scaling $\mathfrak{I}_{1,k,t}$ within the corresponding intervals as:

$$\mathfrak{I}_{2,k,t} = \begin{cases} \mathfrak{I}_{1,k,t} \dfrac{b_9^K}{b_3^K}, & \mathfrak{I}_{1,k,t} < 0 \\ \mathfrak{I}_{1,k,t} \dfrac{b_{10}^K}{b_4^K}, & \mathfrak{I}_{1,k,t} \geq 0 \end{cases} \tag{S.28}$$

$$\mathfrak{I}_{3,k,t} = \begin{cases} \mathfrak{I}_{1,k,t} \dfrac{b_{13}^K}{b_3^K}, & \mathfrak{I}_{1,k,t} < 0 \\ \mathfrak{I}_{1,k,t} \dfrac{b_{14}^K}{b_4^K}, & \mathfrak{I}_{1,k,t} \geq 0 \end{cases} \tag{S.29}$$

In order to directly compare the effects of our policy mixes in this scenarios and in the baseline, we introduce three parameters multiplying $\mathfrak{I}_{1,k,t}$, $\mathfrak{I}_{2,k,t}$ and $\mathfrak{I}_{3,k,t}$ and calibrate them so that, in absence of policies, this scenarios replicates the baseline trends of labour productivity, energy productivity and energy-related emission intensity. $\mathfrak{I}_{2,k,t}$ and $\mathfrak{I}_{3,k,t}$ are then used to determine the energy productivity and emissions per energy unit of the innovated vintage in Eq. (S.2) and (S.3). In this way, we ensure that when $\mathfrak{I}_{1,k,t} > 0$ (< 0) and labour productivity of the innovated vintage is higher (lower) than the current one, energy productivity is higher (lower) and emissions per energy unit is lower (higher), so that carbon intensity is lower (higher).

D.2 Additional results

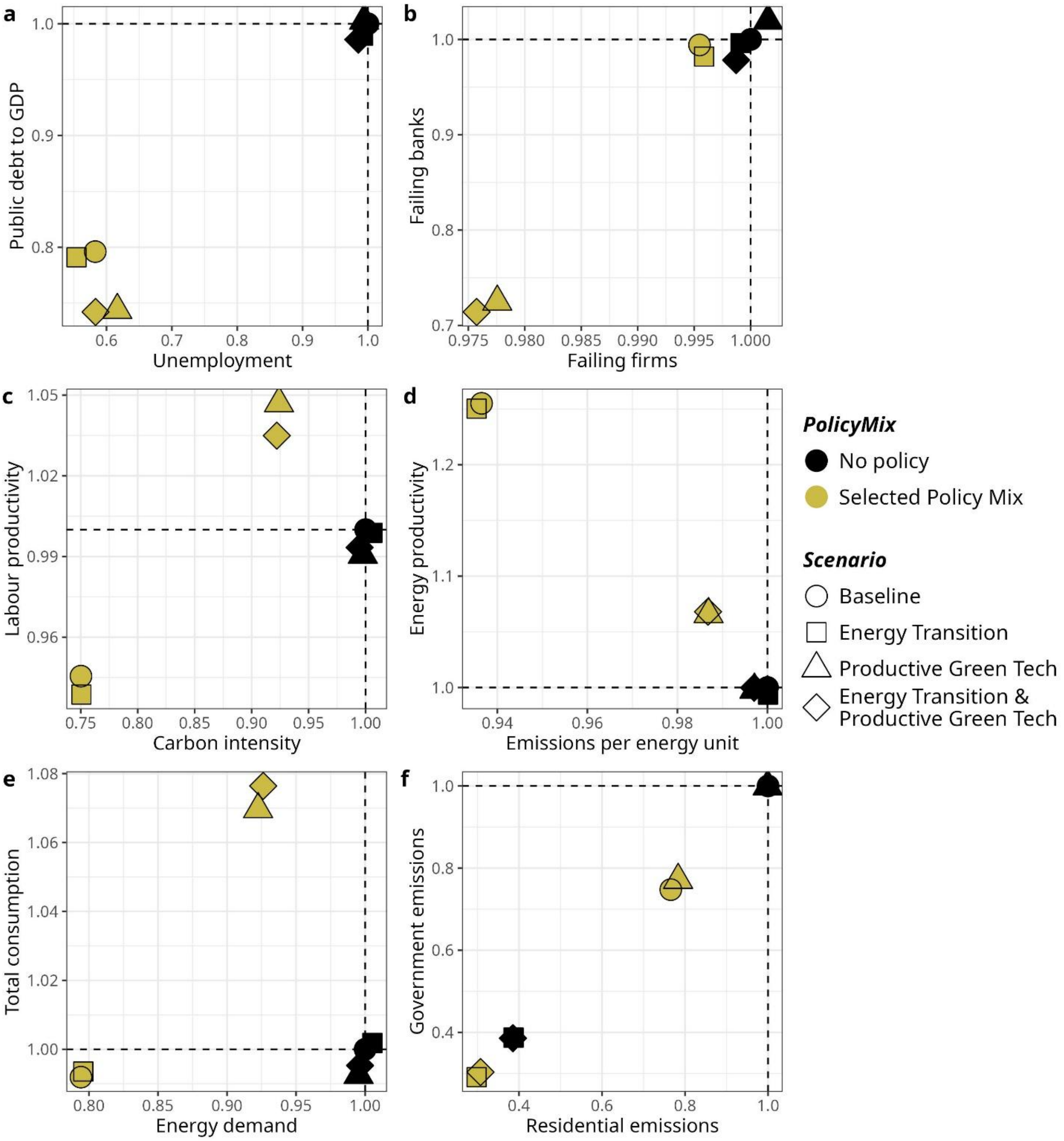

Figure S.15: effect on selected indicators of introducing the Selected Policy Mix under different scenarios. Each dot represents the average value of the indicators on the y-axis and x-axis under no policy or the Selected Policy Mix (identified by the dot's colour) and a scenario (identified by the dot's shape), averaged over 300 Monte Carlo runs run for 100 quarterly timesteps. "Energy Transition" refers to the scenario in which share of energy supplied from green plants increases linearly to a value of 70% at the end of the simulation. "Productive Green Tech" refers to the scenario where we assume that green innovation leads to higher labour productivity. Indicators are normalised to the value they assume in the baseline scenario with no policy mix implemented, which are reported as black dashed lines. The captions of Figure 3 and Figure S.6 describes the indicators and policies.

References

Aldieri, L., Kotsemir, M., Paolo Vinci, C., 2021. Environmental innovations and productivity: Empirical evidence from Russian regions. Resources Policy 74, 101444. https://doi.org/10.1016/j.resourpol.2019.101444

Balint, T., Lamperti, F., Mandel, A., Napoletano, M., Roventini, A., Sapio, A., 2017. Complexity and the Economics of Climate Change: A Survey and a Look Forward. Ecological Economics 138, 252–265. https://doi.org/10.1016/j.ecolecon.2017.03.032

Baltruszewicz, M., Steinberger, J.K., Paavola, J., Ivanova, D., Brand-Correa, L.I., Owen, A., 2023. Social outcomes of energy use in the United Kingdom: Household energy footprints and their links to well-being. Ecological Economics 205, 107686. https://doi.org/10.1016/j.ecolecon.2022.107686

Bartelsman, E.J., Doms, M., 2000. Understanding Productivity: Lessons from Longitudinal Microdata. Journal of Economic Literature 38, 569–594. https://doi.org/10.1257/jel.38.3.569

Bazzana, D., Rizzati, M., Ciola, E., Turco, E.M., Vergalli, S., 2024. Warming the MATRIX: a Climate Assessment under Uncertainty and Heterogeneity. SSRN Journal 107585. https://doi.org/10.1016/j.eneco.2024.107585

Berthe, A., Elie, L., 2015. Mechanisms explaining the impact of economic inequality on environmental deterioration. Ecological Economics 116, 191–200. https://doi.org/10.1016/j.ecolecon.2015.04.026

Bettarelli, L., Furceri, D., Pizzuto, P., Shakoor, N., 2024. Climate change policies and income inequality. Energy Policy 191, 114176. https://doi.org/10.1016/j.enpol.2024.114176

Bistline, J., Onda, C., Browning, M., Emmerling, J., Iyer, G., Mahajan, M., McFarland, J., McJeon, H., Orvis, R., Fonseca, F.R., Roney, C., Sandoval, N., Sarmiento, L., Weyant, J., Woollacott, J., Yuan, M., 2024. Equity implications of net-zero emissions: A multi-model analysis of energy expenditures across income classes under economy-wide deep decarbonization policies. Energy and Climate Change 5, 100118. https://doi.org/10.1016/j.egycc.2023.100118

Bottazzi, G., Secchi, A., 2006. Explaining the distribution of firm growth rates. The RAND J of Economics 37, 235–256. https://doi.org/10.1111/j.1756-2171.2006.tb00014.x

Bottazzi, G., Secchi, A., 2003. Common Properties and Sectoral Specificities in the Dynamics of U.S. Manufacturing Companies. Review of Industrial Organization 23, 217–232. https://doi.org/10.1023/B:REIO.0000031366.28559.c1

Büchs, M., Schnepf, S.V., 2013. Who emits most? Associations between socio-economic factors and UK households’ home energy, transport, indirect and total CO2 emissions. Ecological Economics 90, 114–123. https://doi.org/10.1016/j.ecolecon.2013.03.007

Budolfson, M., Dennig, F., Errickson, F., Feindt, S., Ferranna, M., Fleurbaey, M., Klenert, D., Kornek, U., Kuruc, K., Méjean, A., Peng, W., Scovronick, N., Spears, D., Wagner, F., Zuber, S., 2021. Climate action with revenue recycling has benefits for poverty, inequality and well-being. Nat. Clim. Chang. 11, 1111–1116. https://doi.org/10.1038/s41558-021-01217-0

Budolfson, M., Dennig, F., Fleurbaey, M., Siebert, A., Socolow, R.H., 2017. The comparative importance for optimal climate policy of discounting, inequalities and catastrophes. Clim Change 145, 481–494. https://doi.org/10.1007/s10584-017-2094-x

Burns, A., Mitchell, W., 1946. Measuring business cycles. National Bureau of Economic Research, New York, NY.

Caiani, A., Russo, A., Gallegati, M., 2019. Does inequality hamper innovation and growth? An AB-SFC analysis. J Evol Econ 29, 177–228. https://doi.org/10.1007/s00191-018-0554-8

Campigotto, N., Catola, M., Cieplinksi, A., D’Alessandro, S., Distefano, T., Guarnieri, P., Heydenreich, T., 2024. Scenario discovery for a just low-carbon transition. E-papers of the Department of Economics e Management – University di Pisa.

Castaldi, C., Dosi, G., 2009. The patterns of output growth of firms and countries: Scale invariances and scale specificities. Empir Econ 37, 475–495. https://doi.org/10.1007/s00181-008-0242-x

Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F., Konc, T., Savin, I., Bergh, J.C.J.M., 2020. A review of agent-based modeling of climate-energy policy. WIREs Clim Change 11, e647. https://doi.org/10.1002/wcc.647

Chancel, L., 2022. Global carbon inequality over 1990–2019. Nat Sustain 5, 931–938. https://doi.org/10.1038/s41893-022-00955-z

Ciarli, T., Lorentz, A., Valente, M., Savona, M., 2019. Structural changes and growth regimes. J Evol Econ 29, 119–176. https://doi.org/10.1007/s00191-018-0574-4

Ciola, E., Turco, E., Gurgone, A., Bazzana, D., Vergalli, S., Menoncin, F., 2023. Enter the MATRIX model:a Multi-Agent model for Transition Risks with application to energy shocks. Journal of Economic Dynamics and Control 146, 104589. https://doi.org/10.1016/j.jedc.2022.104589

Ciola, E., Turco, E.M., Rizzati, M., Bazzana, D., Vergalli, S., 2024. Taking the Green Pill: Macro-Financial Transition Risks and Policy Challenges in the MATRIX Model 27.2024. SSRN Journal. https://doi.org/10.2139/ssrn.5035934

Costantini, V., Martini, C., Mina, B., Zoli, M., 2025. The welfare impact of climate action: A distributional analysis for Italy. Energy Economics 143, 108181. https://doi.org/10.1016/j.eneco.2025.108181

Csereklyei, Z., 2020. Price and income elasticities of residential and industrial electricity demand in the European Union. Energy Policy 137, 111079. https://doi.org/10.1016/j.enpol.2019.111079

Czupryna, M., Franzke, C., Hokamp, S., Scheffran, J., 2020. An Agent-Based Approach to Integrated Assessment Modelling of Climate Change. JASSS 23, 7. https://doi.org/10.18564/jasss.4325

Dafermos, Y., McConnel, A., Pollination Group, Nikolaidi, M., Storm, S., Yanovski, B., 2024. Macroeconomic modelling in the Anthropocene: why the E-DSGE framework is not fit for purpose and what to do about it. Institute for New Economic Thinking Working Paper Series. https://doi.org/10.36687/inetwp229

Dafermos, Y., Nikolaidi, M., 2019. Fiscal Policy and Ecological Sustainability: A Post-Keynesian Perspective, in: Arestis, P., Sawyer, M. (Eds.), Frontiers of Heterodox Macroeconomics. Springer International Publishing, Cham, pp. 277–322. https://doi.org/10.1007/978-3-030-23929-9_7

Dawid, H., Delli Gatti, D., 2018. Agent-Based Macroeconomics, in: Hommes, C., LeBaron, B. (Eds.), Handbook of Computational Economics, Handbook of Computational Economics. Elsevier, pp. 63–156. https://doi.org/10.1016/bs.hescom.2018.02.006

Dawid, H., Harting, P., Neugart, M., 2018. Cohesion policy and inequality dynamics: Insights from a heterogeneous agents macroeconomic model. Journal of Economic Behavior & Organization 150, 220–255. https://doi.org/10.1016/j.jebo.2018.03.015

Dawid, H., Hepp, J., 2022. Distributional effects of technological regime changes: hysteresis, concentration and inequality dynamics. Rev Evol Polit Econ 3, 137–167. https://doi.org/10.1007/s43253-021-00052-5

Dawid, H., Neugart, M., 2023. Effects of technological change and automation on industry structure and (wage-)inequality: insights from a dynamic task-based model. J Evol Econ 33, 35–63. https://doi.org/10.1007/s00191-022-00803-5

DeCanio, S., Watkins, W., 1998. Investment in energy efficiency: Do the characteristics of firms matter? The Review of Economics and Statistics 80, 95–107. https://doi.org/10.1162/003465398557366

Doda, B., 2014. Evidence on business cycles and emissions. Journal of Macroeconomics 40, 214–227. https://doi.org/10.1016/j.jmacro.2014.01.003

Doms, M., Dunne, T., 1998. Capital Adjustment Patterns in Manufacturing Plants. Review of Economic Dynamics 1, 409–429. https://doi.org/10.1006/redy.1998.0011

Dorn, F., Maxand, S., Kneib, T., 2024. The nonlinear dependence of income inequality and carbon emissions: Potentials for a sustainable future. Ecological Economics 216, 108016. https://doi.org/10.1016/j.ecolecon.2023.108016

Dosi, G., 2007. Statistical regularities in the evolution of industries: a guide through some evidence and challenges for the theory, in: Malerba, F., Brusoni, S. (Eds.), Perspectives on Innovation. Cambridge University Press, pp. 153–186. https://doi.org/10.1017/CBO9780511618390.009

Dosi, G., Fagiolo, G., Napoletano, M., Roventini, A., 2013. Income distribution, credit and fiscal policies in an agent-based Keynesian model. Journal of Economic Dynamics and Control 37, 1598–1625. https://doi.org/10.1016/j.jedc.2012.11.008

Dosi, G., Fagiolo, G., Napoletano, M., Roventini, A., Treibich, T., 2015. Fiscal and monetary policies in complex evolving economies. Journal of Economic Dynamics and Control 52, 166–189. https://doi.org/10.1016/j.jedc.2014.11.014

Dosi, G., Fagiolo, G., Roventini, A., 2010. Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles. Journal of Economic Dynamics and Control 34, 1748–1767. https://doi.org/10.1016/j.jedc.2010.06.018

Dosi, G., Freeman, R.B., Pereira, M.C., Roventini, A., Virgillito, M.E., 2021. The impact of deunionization on the growth and dispersion of productivity and pay. Industrial and Corporate Change 30, 377–408. https://doi.org/10.1093/icc/dtaa025

Dosi, G., Pereira, M.C., Roventini, A., Virgillito, M.E., 2022. Technological paradigms, labour creation and destruction in a multi-sector agent-based model. Research Policy 51, 104565. https://doi.org/10.1016/j.respol.2022.104565

Dosi, G., Pereira, M.C., Roventini, A., Virgillito, M.E., 2018a. The effects of labour market reforms upon unemployment and income inequalities: an agent-based model. Socio-Economic Review 16, 687–720. https://doi.org/10.1093/ser/mwx054

Dosi, G., Pereira, M.C., Roventini, A., Virgillito, M.E., 2018b. Causes and consequences of hysteresis: aggregate demand, productivity, and employment. Industrial and Corporate Change 27, 1015–1044. https://doi.org/10.1093/icc/dty010

Dosi, G., Roventini, A., 2019. More is different ... and complex! the case for agent-based macroeconomics. J Evol Econ 29, 1–37. https://doi.org/10.1007/s00191-019-00609-y

Dynan, K.E., Skinner, J., Zeldes, S., 2004. Do the Rich Save More? Journal of Political Economy 112, 397–444.

Emmerling, J., Andreoni, P., Charalampidis, I., Dasgupta, S., Dennig, F., Feindt, S., Fragkiadakis, D., Fragkos, P., Fujimori, S., Gilli, M., Grottera, C., Guivarch, C., Kornek, U., Kriegler, E., Malerba, D., Marangoni, G., Méjean, A., Nijsse, F., Piontek, F., Simsek, Y., Soergel, B., Taconet, N., Vandyck, T., Young-Brun, M., Zhao, S., Zheng, Y., Tavoni, M., 2024. A multi-model assessment of inequality and climate change. Nat. Clim. Chang. https://doi.org/10.1038/s41558-024-02151-7

Emmerling, J., Tavoni, M., 2021. Representing inequalities in integrated assessment modeling of climate change. One Earth 4, 177–180. https://doi.org/10.1016/j.oneear.2021.01.013

Eurostat, 2024a. Income, consumption and wealth - experimental statistics [icw_sr_10]. https://doi.org/10.2908/ICW_SR_10

Eurostat, 2024b. Disaggregated final energy consumption in households - quantities [nrg_d_hhq]. https://doi.org/doi.org/10.2908/NRG_D_HHQ

Fagiolo, G., 2016. Macroeconomic Policy in DSGE and Agent-Based Models Redux: New Developments and Challenges Ahead. SSRN Journal. https://doi.org/10.2139/ssrn.2763735

Fagiolo, G., Guerini, M., Lamperti, F., Moneta, A., Roventini, A., 2019. Validation of Agent-Based Models in Economics and Finance, in: Beisbart, C., Saam, N.J. (Eds.), Computer Simulation Validation, Simulation Foundations, Methods and Applications. Springer International Publishing, Cham, pp. 763–787. https://doi.org/10.1007/978-3-319-70766-2_31

Fagiolo, G., Napoletano, M., Roventini, A., 2008. Are output growth-rate distributions fat-tailed? some evidence from OECD countries. J of Applied Econometrics 23, 639–669. https://doi.org/10.1002/jae.1003

Farmer, J.D., Hepburn, C., Mealy, P., Teytelboym, A., 2015. A Third Wave in the Economics of Climate Change. Environ Resource Econ 62, 329–357. https://doi.org/10.1007/s10640-015-9965-2

Fierro, L.E., Caiani, A., Russo, A., 2022. Automation, Job Polarisation, and Structural Change. Journal of Economic Behavior & Organization 200, 499–535. https://doi.org/10.1016/j.jebo.2022.05.025

Fierro, L.E., Giri, F., Russo, A., 2023. Inequality-constrained monetary policy in a financialized economy. Journal of Economic Behavior & Organization 216, 366–385. https://doi.org/10.1016/j.jebo.2023.10.031

Fodstad, M., Crespo del Granado, P., Hellemo, L., Knudsen, B.R., Pisciella, P., Silvast, A., Bordin, C., Schmidt, S., Straus, J., 2022. Next frontiers in energy system modelling: A review on challenges and the state of the art. Renewable and Sustainable Energy Reviews 160, 112246. https://doi.org/10.1016/j.rser.2022.112246

Foos, D., Norden, L., Weber, M., 2010. Loan growth and riskiness of banks. Journal of Banking & Finance 34, 2929–2940. https://doi.org/10.1016/j.jbankfin.2010.06.007

Garbinti, B., Goupille-Lebret, J., Piketty, T., 2018. Income inequality in France, 1900–2014: Evidence from Distributional National Accounts (DINA). Journal of Public Economics 162, 63–77. https://doi.org/10.1016/j.jpubeco.2018.01.012

Gössling, S., Humpe, A., 2023. Millionaire spending incompatible with 1.5 °C ambitions. Cleaner Production Letters 4, 100027. https://doi.org/10.1016/j.clpl.2022.100027

Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P., Fishman, T., Hausknost, D., Krausmann, F., Leon-Gruchalski, B., Mayer, A., Pichler, M., Schaffartzik, A., Sousa, T., Streeck, J., Creutzig, F., 2020. A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. Environ. Res. Lett. 15, 065003. https://doi.org/10.1088/1748-9326/ab842a

Hardt, L., O'Neill, D.W., 2017. Ecological Macroeconomic Models: Assessing Current Developments. Ecological Economics 134, 198–211. https://doi.org/10.1016/j.ecolecon.2016.12.027

Havranek, T., Rusnak, M., Sokolova, A., 2017. Habit formation in consumption: A meta-analysis. European Economic Review 95, 142–167. https://doi.org/10.1016/j.euroecorev.2017.03.009

Hickel, J., Kallis, G., 2020. Is Green Growth Possible? New Political Economy 25, 469–486. https://doi.org/10.1080/13563467.2019.1598964

Hofbauer, L., McDowall, W., Pye, S., 2022. Challenges and opportunities for energy system modelling to foster multi-level governance of energy transitions. Renewable and Sustainable Energy Reviews 161, 112330. https://doi.org/10.1016/j.rser.2022.112330

Hötte, K., 2020. How to accelerate green technology diffusion? Directed technological change in the presence of coevolving absorptive capacity. Energy Economics 85, 104565. https://doi.org/10.1016/j.eneco.2019.104565

IRENA, 2020. Global Renewables Outlook: Energy transformation 2050 (Edition: 2020). International Renewable Energy Agency, Abu Dhabi.

Ivanova, D., Wood, R., 2020. The unequal distribution of household carbon footprints in Europe and its link to sustainability. Glob. Sustain. 3, e18. https://doi.org/10.1017/sus.2020.12

Jackson, T., Victor, P.A., 2019. Unraveling the claims for (and against) green growth. Science 366, 950–951. https://doi.org/10.1126/science.aay0749

Känzig, D.R., 2023. The Unequal Economic Consequences of Carbon Pricing. NBER Working Paper No. 31221.

Keen, S., 2020. The appallingly bad neoclassical economics of climate change. Globalizations 1–29. https://doi.org/10.1080/14747731.2020.1807856

Kuznets, S., 1966. Modern economic growth - rate, structure, and spread. Yale University Press, New Haven, Connecticut and London.

Lackner, T., Fierro, L.E., Mellacher, P., 2025. Opinion dynamics meet agent-based climate economics: An integrated analysis of carbon taxation. Journal of Economic Behavior & Organization 229, 106816. https://doi.org/10.1016/j.jebo.2024.106816

Lamarche, P., Oehler, F., Rioboo, I., 2020. European household's income, consumption and wealth. SJI 36, 1175–1188. https://doi.org/10.3233/SJI-190528

Lamperti, F., Bosetti, V., Roventini, A., Tavoni, M., 2019a. The public costs of climate-induced financial instability. Nat. Clim. Chang. 9, 829–833. https://doi.org/10.1038/s41558-019-0607-5

Lamperti, F., Bosetti, V., Roventini, A., Tavoni, M., Treibich, T., 2021. Three green financial policies to address climate risks. Journal of Financial Stability 54, 100875. https://doi.org/10.1016/j.jfs.2021.100875

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., Sapio, A., 2020. Climate change and green transitions in an agent-based integrated assessment model. Technological Forecasting and Social Change 153, 119806. https://doi.org/10.1016/j.techfore.2019.119806

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., Sapio, A., 2018. Faraway, So Close: Coupled Climate and Economic Dynamics in an Agent-based Integrated Assessment Model. Ecological Economics 150, 315–339. https://doi.org/10.1016/j.ecolecon.2018.03.023

Lamperti, F., Mandel, A., Napoletano, M., Sapio, A., Roventini, A., Balint, T., Khorenzhenko, I., 2019b. Towards agent-based integrated assessment models: examples, challenges, and future developments. Reg Environ Change 19, 747–762. https://doi.org/10.1007/s10113-018-1287-9

Lamperti, F., Mattei, C.E., 2018. Going up and down: rethinking the empirics of growth in the developing and newly industrialized world. J Evol Econ 28, 749–784. https://doi.org/10.1007/s00191-018-0551-y

Lamperti, F., Palagi, E., Perniola, T., 2025. The emission-inequality nexus across stages of development. LEM Working Paper Series. https://doi.org/10.57838/sssa/tnad-hq04

Lamperti, F., Wieners, C., Dosi, G., Roventini, A., 2024. Macroeconomic policies for rapid decarbonization, steady economic transition and employment creation. In Review. https://doi.org/10.21203/rs.3.rs-4637209/v1

Liobikienė, G., 2020. The revised approaches to income inequality impact on production-based and consumption-based carbon dioxide emissions: literature review. Environ Sci Pollut Res 27, 8980–8990. https://doi.org/10.1007/s11356-020-08005-x

Lown, C.S., Morgan, D.P., 2006. The Credit Cycle and the Business Cycle: New Findings Using the Loan Officer Opinion Survey. Journal of Money, Credit, and Banking 38, 1575–1597. https://doi.org/10.1353/mcb.2006.0086

Maestre-Andrés, S., Drews, S., van den Bergh, J.C.J.M., 2019. Perceived fairness and public acceptability of carbon pricing: a review of the literature. Climate Policy 19, 1186–1204. https://doi.org/10.1080/14693062.2019.1639490

Malafry, L., Brinca, P., 2022. Climate policy in an unequal world: Assessing the cost of risk on vulnerable households. Ecological Economics 194, 107309. https://doi.org/10.1016/j.ecolecon.2021.107309

Mendoza, E., Terrones, M., 2012. An Anatomy of Credit Booms and their Demise (No. w18379). National Bureau of Economic Research, Cambridge, MA. https://doi.org/10.3386/w18379

Millward-Hopkins, J., Oswald, Y., 2021. ‘Fair’ inequality, consumption and climate mitigation. Environ. Res. Lett. 16, 034007. https://doi.org/10.1088/1748-9326/abe14f

Moosa, I.A., 2000. Cyclical asymmetry in energy consumption and intensity: the Japanese experience. OPEC Review 24, 53–59. https://doi.org/10.1111/1468-0076.00074

Mumtaz, H., Theophilopoulou, A., 2024. The distributional effects of climate change. An empirical analysis. European Economic Review 169, 104828. https://doi.org/10.1016/j.euroecorev.2024.104828

Napoletano, M., Roventini, A., Sapio, S., 2006. Are Business Cycles All Alike? A Bandpass Filter Analysis of the Italian and US Cycles. Rivista italiana degli economisti 87–118. https://doi.org/10.1427/23296

Nieddu, M., Raberto, M., Ponta, L., Teglio, A., Cincotti, S., 2024. Evaluating policy mix strategies for the energy transition using an agent-based macroeconomic model. Energy Policy 193, 114276. https://doi.org/10.1016/j.enpol.2024.114276

Nielsen, K.S., Nicholas, K.A., Creutzig, F., Dietz, T., Stern, P.C., 2021. The role of high-socioeconomic-status people in locking in or rapidly reducing energy-driven greenhouse gas emissions. Nat Energy 6, 1011–1016. https://doi.org/10.1038/s41560-021-00900-y

Oswald, Y., Owen, A., Steinberger, J.K., 2020. Large inequality in international and intranational energy footprints between income groups and across consumption categories. Nat Energy 5, 231–239. https://doi.org/10.1038/s41560-020-0579-8

Oswald, Y., Steinberger, J.K., Ivanova, D., Millward-Hopkins, J., 2021. Global redistribution of income and household energy footprints: a computational thought experiment. Glob. Sustain. 4, 1–13. https://doi.org/10.1017/sus.2021.1

Palagi, E., Coronese, M., Lamperti, F., Roventini, A., 2022. Climate change and the nonlinear impact of precipitation anomalies on income inequality. Proceedings of the National Academy of Sciences 119, e2203595119. https://doi.org/10.1073/pnas.2203595119

Palagi, E., Napoletano, M., Roventini, A., Gaffard, J.-L., 2023. An agent-based model of trickle-up growth and income inequality. Economic Modelling 129, 106535. https://doi.org/10.1016/j.econmod.2023.106535

Pellini, E., 2021. Estimating income and price elasticities of residential electricity demand with Autometrics. Energy Economics 101, 105411. https://doi.org/10.1016/j.eneco.2021.105411

Petrick, S., 2013. Carbon efficiency, technology, and the role of innovation patterns: Evidence from German plant-level microdata., Kiel Institute for the World Economy Working Paper 1833.

Piontek, F., Drouet, L., Emmerling, J., Kompas, T., Méjean, A., Otto, C., Rising, J., Soergel, B., Taconet, N., Tavoni, M., 2021. Integrated perspective on translating biophysical to economic impacts of climate change. Nat. Clim. Chang. 11, 563–572. https://doi.org/10.1038/s41558-021-01065-y

Ponta, L., Raberto, M., Teglio, A., Cincotti, S., 2018. An Agent-based Stock-flow Consistent Model of the Sustainable Transition in the Energy Sector. Ecological Economics 145, 274–300. https://doi.org/10.1016/j.ecolecon.2017.08.022

Rademaekers, K., Smith, M., Demurtas, A., Vega, P.C.T., Natalie Janzow, Laurent Zibell, Onne Hoogland, Karine Pollier, Morgan Crènes, Geoffrey Radigois, Fabien Gaillard-Blancard, Yacine El Idrissi, Imane Sakhaoui, Jamie Pirie, Shaun Micallef, Matthias Altman, 2020. Study on energy prices, costs and their impact on industry and households. European Commission, DG ENER.

Rao, N.D., Min, J., 2018. Less global inequality can improve climate outcomes. WIREs Clim Change 9, e513. https://doi.org/10.1002/wcc.513

Rao, N.D., van Ruijven, B.J., Riahi, K., Bosetti, V., 2017. Improving poverty and inequality modelling in climate research. Nature Clim Change 7, 857–862. https://doi.org/10.1038/s41558-017-0004-x

Reissl, S., Fierro, L.E., Lamperti, F., Roventini, A., 2024. The DSK-SFC stock-flow consistent agent-based integrated assessment model. LEM Working Paper Series.

Rengs, B., Scholz-Wäckerle, M., van den Bergh, J.C.J.M., 2020. Evolutionary macroeconomic assessment of employment and innovation impacts of climate policy packages. Journal of Economic Behavior & Organization 169, 332–368. https://doi.org/10.1016/j.jebo.2019.11.025

Rizzati, M., Ciola, E., Turco, E., Bazzana, D., Vergalli, S., 2024. Beyond Green Preferences: Alternative Pathways to Net-Zero Emissions in the MATRIX model (No. 3), FEEM Working Paper. Fondazione Eni Enrico Mattei (FEEM).

Safarzynska, K., van den Bergh, J.C.J.M., 2022. ABM-IAM: Optimal climate policy under bounded rationality and multiple inequalities. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/ac8b25

Sager, L., 2019. Income inequality and carbon consumption: Evidence from Environmental Engel curves. Energy Economics 84, 104507. https://doi.org/10.1016/j.eneco.2019.104507

Sensfuß, F., Ragwitz, M., Genoese, M., 2008. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy 36, 3086–3094. https://doi.org/10.1016/j.enpol.2008.03.035

Stechemesser, A., Koch, N., Mark, E., Dilger, E., Klösel, P., Menicacci, L., Nachtigall, D., Pretis, F., Ritter, N., Schwarz, M., Vossen, H., Wenzel, A., 2024. Climate policies that achieved major emission reductions: Global evidence from two decades. Science 385, 884–892. https://doi.org/10.1126/science.adl6547

Stern, N., Stiglitz, J., Taylor, C., 2022. The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change. Journal of Economic Methodology 29, 181–216. https://doi.org/10.1080/1350178X.2022.2040740

Stock, J.H., Watson, M.W., 1999. Business cycle fluctuations in us macroeconomic time series, in: Taylor, J., Woodford, M. (Eds.), Handbook of Macroeconomics. Elsevier, pp. 3–64. https://doi.org/10.1016/S1574-0048(99)01004-6

Tian, P., Zhong, H., Chen, X., Feng, K., Sun, L., Zhang, N., Shao, X., Liu, Y., Hubacek, K., 2024. Keeping the global consumption within the planetary boundaries. Nature 635, 625–630. https://doi.org/10.1038/s41586-024-08154-w

van den Bergh, J.C.J.M., Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F., Konc, T., Savin, I., 2021. Designing an effective climate-policy mix: accounting for instrument synergy. Climate Policy 21, 1–20. https://doi.org/10.1080/14693062.2021.1907276

Vogel, J., Hickel, J., 2023. Is green growth happening? An empirical analysis of achieved versus Paris-compliant CO2–GDP decoupling in high-income countries. The Lancet Planetary Health 7, e759–e769. https://doi.org/10.1016/S2542-5196(23)00174-2

Vona, F., 2023. Managing the distributional effects of climate policies: A narrow path to a just transition. Ecological Economics 205, 107689. https://doi.org/10.1016/j.ecolecon.2022.107689

Wälde, K., Woitek, U., 2004. R&D expenditure in G7 countries and the implications for endogenous fluctuations and growth. Economics Letters 82, 91–97. https://doi.org/10.1016/j.econlet.2003.07.014

Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K., 2020. Scientists’ warning on affluence. Nat Commun 11, 3107. https://doi.org/10.1038/s41467-020-16941-y

Woo, C., Chung, Y., Chun, D., Han, S., Lee, D., 2014. Impact of Green Innovation on Labor Productivity and its Determinants: an Analysis of the Korean Manufacturing Industry. Business Strategy and the Environment 23, 567–576. https://doi.org/10.1002/bse.1807

Zarnowit, V., 1985. Recent work on business cycles in historical perspective: A review of theories and evidence. Journal of Economic Literature 23, 523–580. http://www.jstor.org/stable/2725624