

Research Paper

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

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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.

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

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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., 2025a; 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. 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 heterogeneous 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., 2021, 2020, 2019a, 2018; Reissl et al., 2025) 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., 2025b). 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., 2021, 2020, 2018a), as well as the macroeconomic effects of inequality and redistribution (Ciarli et al., 2019; Dosi et al., 2018b; Fierro et al., 2022; 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.¹ Section 5 concludes.

¹ The Appendices report more detailed descriptions of our policies and scenarios, together with additional results and sensitivity analyses.

2. The model

The core of the DSK model² (Lamperti et al., 2021, 2020, 2019a, 2018; Reissl et al., 2025) consists of two agent-based industrial sectors composed of firms producing either consumption goods or capital goods. Capital good 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. Capital good firms invest in R&D activities, which drive the emergence of new and improved capital machines and production techniques. This innovation process is the engine of growth of the model. Capital good firms sell capital machines to consumption good firms, which can switch supplier based on the technology they sell to reduce production costs. Consumption good firms use capital machines to produce a homogenous consumption good. Both capital and consumption good 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 energy from the energy sector and goods from consumption good firms. Consumption good firms invest in new capital to expand their productive capacity based on the expected demand from households. Capital good firms finance their production and R&D through retained earnings. Consumption good firms' finance their production and investment also by applying for loans from a banking sector composed of multiple banks. In addition to lending to consumption good 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 capital and consumption good 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. Fossil fuels are supplied from an external sector, which is the only exception to the model which otherwise represents a large closed economy. A climate module accounts for emissions from the energy sector and the production of capital and consumption good firms.

Fig. 1 represents the DSK model with the extensions introduced in this paper³: 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. After presenting the sequence of events, the following sections describe these parts of the model, and some additional aspects of the energy sector, technological change and firms' and banks' failure that are relevant for understanding the policies we implement and our results. Tables S.1 and S.2 in Appendix A.1 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. (2025).

2.1. Model description

2.1.1. 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. Consumption good firms receive capital machines purchased in the previous period.
3. Capital and consumption good 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. Capital good firms advertise their vintages and consumption good firms may update their supplier.
6. Consumption good firms determine their desired production based on expected demand.
7. Consumption good firms decide which worn-out machines to scrap and which not worn-out machines to replace.
8. Consumption good firms determine desired expansion investment based on desired production and scrapped machines.
9. Consumption good firms calculate their effective production costs based on desired production and capital machines used.
10. Consumption good 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 consumption good firms; credit-rationed consumption good firms scale back production and investment; consumption good firms that cannot roll over loans become inactive and are prepared to exit.
12. Capital and consumption good firms calculate the labour required for production.
13. Total labour demand is determined as the sum of demand for production by capital and consumption good firms and of demand for R&D from capital good firms and the energy sector from the previous period. If labour supply is insufficient to cover demand, capital and consumption good firms scale back production.
14. Production takes place. Realised production determines energy demand and emissions from industry.

² 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.

³ The code of the model's version developed and used in this paper, together with instructions on how to reproduce the scenarios presented, is available at https://github.com/CoMoS-SA/Ravaoli_2025.

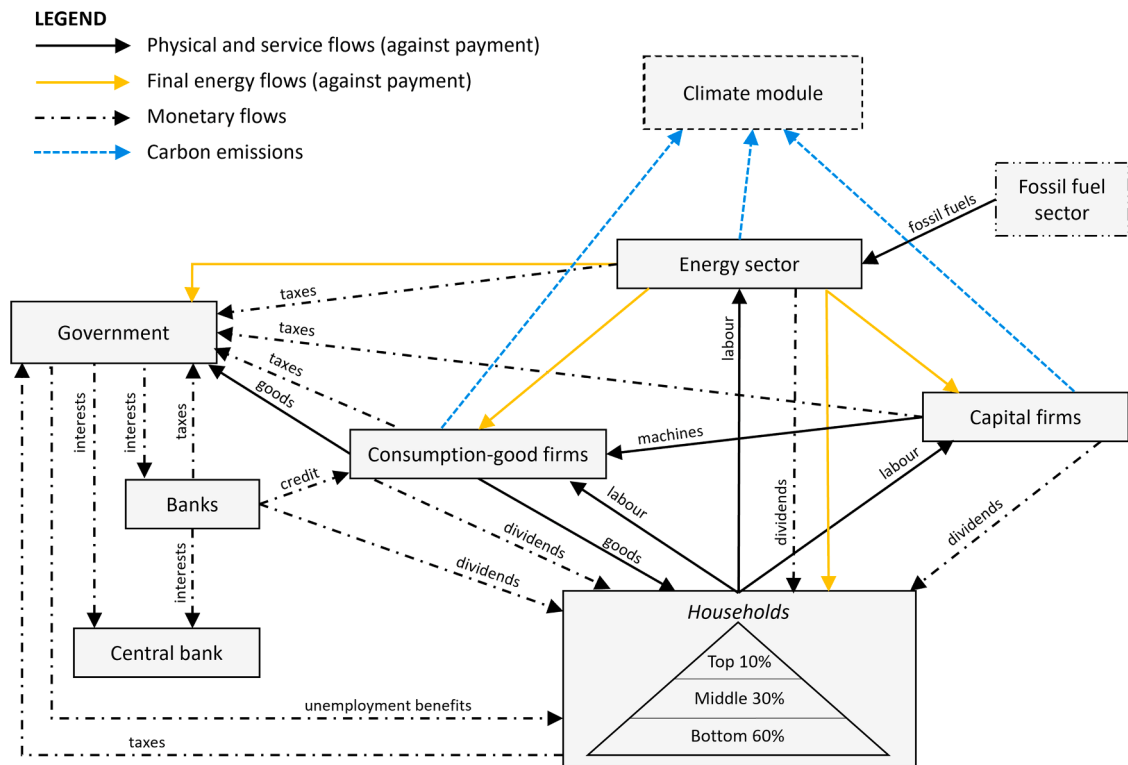


Fig. 1. Schematic representation of the model, with all agents and main flows. Flows are represented as arrows going from the providing to the receiving agent(s). Solid lines represent flows of goods or services, among which yellow ones represent flows of energy, to which correspond monetary flows in 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 Tables S.1 and S.2 in Appendix A.1.

- Households and the government determine their demand and expenditure for energy.
- 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.
- Consumption good firms pay for investment.
- Capital and consumption good firms and the energy sector pay wages and the government pays unemployment benefits to unemployed households (if any).
- Consumption good firms scrap machines.
- Consumption good firms' ex-ante market shares are determined; consumption good firms with low market shares become inactive and are prepared to exit.
- Capital good firms determine their profits and pay for energy, taxes and dividends. Capital good firms that cannot pay for energy become inactive and are prepared to exit.
- Households pay taxes. Households and the government determine their desired expenditure for goods' consumption, which is allocated to consumption good firms based on their market shares.
- Capital and consumption good firms determine their profits.
- Consumption good firms pay energy, principal and interest on loans and taxes. Consumption good firms that cannot pay or that have negative net worth become inactive and are prepared to exit.
- The energy sector determines its profits and pays fossil fuels and taxes; the fossil fuel sector pays dividends to households.
- The nominal wage of all household classes is updated.
- New firms replace exiting capital and consumption good firms.
- Banks determine their profits and pay taxes and dividends; the government bails-out banks with negative net worth.
- The government determines its budget and covers its deficit by selling bonds to banks and the central bank.
- The central bank sets the policy rate for the following period.
- Banks calculate net inflows and outflows of reserves and, if necessary, take advances from the central bank.
- Endogenous technical change takes place in capital good firms.
- The climate module accounts for all emissions in the current period.
- The fossil fuel sector updates its price and the energy sector updates its mark-up.

2.1.2. 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.⁴ 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 ($Tax_{cl,t}^w$), dividends ($Tax_{cl,t}^{div}$) and deposits ($Tax_{cl,t}^{dep}$). Each household class cl disposable income is:

$$YD_{cl,t} = W_{cl,t} + Div_{cl,t-1} + UB_{cl,t} + iD_{cl,t} - Tax_{cl,t}^w - Tax_{cl,t}^{div} - Tax_{cl,t}^{dep} \quad (1)$$

At the end of each period, the uniform nominal wage rate of bottom 60 % households $w_{Bl,t}$ is updated as:

$$w_{Bl,t} = w_{Bl,t-1} \cdot (1 + \min(\bar{\omega}, \max(-\bar{\omega}, \pi^* + \psi_1 \hat{\pi}_t + \psi_2 \widehat{Pr}_t - \psi_3 \hat{u}_t))) \quad (2)$$

where:

1. $\bar{\omega}$ is an exogenous parameter that limits the change in wage rate in each period.
2. π^* is the fixed inflation target of the central bank.
3. $\hat{\pi}_t$ is the deviation of the inflation rate from the inflation target.
4. $\widehat{Pr}_t$ is a weighted average of current and past changes in average productivity across capital and consumption firms.
5. $\hat{u}_t$ is the change in unemployment rate respect to $t-1$.
6. 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 $w_{MI,t} = w_{Bl,t} \cdot wr_{MI,Bl}$ and $w_{TI,t} = w_{Bl,t} \cdot wr_{TI,Bl}$, where $wr_{MI,Bl}$ and $wr_{TI,Bl}$ 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 capital and consumption good firm demands for production depends on its desired output and the labour productivity of its capital vintages. Each capital good 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 ($U_t = \sum_{cl}(1 - L_{cl,t})/\sum_{cl}LS_{cl,t}$). This also implies that for each bottom 60 % household employed firms pay a total wage $w_{H,t} = w_{Bl,t} + w_{MI,t} LS_{MI,t}/LS_{Bl,t} + w_{TI,t} LS_{TI,t}/LS_{Bl,t}$ 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.

Households receive dividends from capital and consumption 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. Capital and consumption good 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 $Tax_{cl,t}^w = \tau_{cl}^w \cdot W_{cl,t}$, $Tax_{cl,t}^{div} = \tau_{cl}^{div} \cdot Div_{cl,t-1}$ and $Tax_{cl,t}^{dep} = \tau_{cl}^{dep} \cdot D_{cl,t}$, where τ_{cl}^w is the exogenous tax rate on wages that can differ between household classes, τ_{cl}^{div} and τ_{cl}^{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.

⁴ 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.

Households demand consumption goods from consumption good 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:

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

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 ($C_{cl,t-1}^{tot}$), as $C_{tg,cl,t}^E = EnExpSh_{cl} \cdot C_{cl,t-1}^{tot}$. 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 capital and consumption firms. Thus, the target energy demand of each household class is $E_{tg,cl,t} = C_{tg,cl,t}^E / (p_{e,t-1} \cdot \phi_E)$, where $p_{e,t-1}$ is the energy price set by the energy sector in the previous timestep for industry (see Section 2.1.4). The actual energy demanded and actual expenditure in energy are then respectively calculated as

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

$$C_{cl,t}^E = E_{cl,t} \cdot p_{e,t-1} \cdot \phi_E, \quad (5)$$

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: $C_{tg,cl,t}^C = C_{cl,t-1}^{tot} - C_{cl,t-1}^E$. The desired expenditure in consumption goods in real terms is also subject to persistency:

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

where $C_{cl,t-1}^C$ is the actual expenditure for consumption goods of households in the previous timestep. Household classes' desired total nominal expenditure is finally calculated as $C_{d,cl,t}^{tot} = C_{cl,t}^E + C_{d,cl,t}^C$. 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.⁵ Finally, the actual expenditure for consumption goods of households $C_{cl,t}^C$ is determined by households' interaction with consumption good firms, after having determined government desired expenditure as well (see Section 2.1.3). 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.

2.1.3. 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 capital and consumption 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:

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

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 consumption good firms and energy from the energy sector. Desired government spending is a fixed fraction of GDP in the previous period GDP_{t-1} :

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

⁵ 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.

where 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 $C_{G,t}^E = \overline{EnExpSh}_{cl} \cdot C_{G,t-1}^{tot}$, where $\overline{EnExpSh}_{cl}$ is the average energy expenditure share of household classes and $C_{G,t-1}^{tot}$ is the actual total public spending in the previous period. Thus, the energy demand from the government equals to $E_{G,t} = C_{G,t}^E / (p_{e,t-1} \cdot \phi_E)$. Desired public spending for consumption goods is equal to $C_{d,G,t}^C = C_{d,G,t}^{tot} - C_{G,t}^E$. The total desired expenditure in consumption goods (from both households and the government) is then $C_{d,tot,t}^C = C_{d,G,t}^C + \sum_{cl} C_{d,cl,t}^C$. If the total supply of consumption goods by consumption good firms is higher than $C_{d,tot,t}^C$, the actual expenditure in consumption goods of the government $C_{G,t}^C$ and each household class $C_{cl,t}^C$ 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 $C_{G,t} = C_{G,t}^C + C_{G,t}^E$.

2.1.4. Energy sector

The energy sector sells energy to capital and consumption 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 cannot 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 the previous Sections 2.1.2 and 2.1.3.

2.1.5. Carbon emissions

The climate module sums the carbon emissions from the different sectors and reports the total yearly value.⁶ 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 capital and consumption 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 ($\mathbb{E}_{I,t}^{dir}$) and to the latter as indirect industrial emissions ($\mathbb{E}_{I,t}^{indir}$). 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 ($\mathbb{E}_{H,t}$ and $\mathbb{E}_{G,t}$) are only caused by their use of electricity, neglecting energy-related direct emissions from households.⁷ We can decompose total emissions $\mathbb{E}_t$ as:

$$\mathbb{E}_t = \mathbb{E}_{I,t}^{dir} + \mathbb{E}_{E,t} = \mathbb{E}_{I,t}^{dir} + \mathbb{E}_{I,t}^{indir} + \mathbb{E}_{H,t} + \mathbb{E}_{G,t}, \quad (9)$$

where $\mathbb{E}_{E,t}$ are the total emissions from the energy sector, and:

$$\mathbb{E}_{I,t}^{dir} = \sum_c Q_{c,t} \frac{EF_{c,t}^e}{EE_{c,t}^e} + \sum_k Q_{k,t} \frac{EF_{k,t}^e}{EE_{k,t}^e} = \sum_c Q_{c,t} C_{c,t}^e + \sum_k Q_{k,t} \frac{EF_{k,t}^e}{EE_{k,t}^e}, \quad (10)$$

⁶ 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.

⁷ 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.

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

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

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

$Q_{c,t}$ and $Q_{k,t}$ are the output of the consumption good firm c and capital good 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 consumption good firm c . We also express the equations in terms of the effective carbon intensity of the consumption good firm $CI_{c,t}^e$, a function of the carbon intensity of consumption good firms' capital vintages which will be the object of some of the policies and scenarios assessed.⁸ 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 capital good 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 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). $\left(\frac{\mathbb{G}}{E} \right)_{E,t}$ 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.

2.1.6. Technological change

The process of technological change is driven by capital good firms, which aim to improve their production technique to offer capital machines with lower production costs to consumption good firms. Each capital good 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 consumption good 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 capital good firms produce machines of that vintage ($Pr_{\kappa,t}$, $EE_{\kappa,t}$ and $EF_{\kappa,t}$).

Capital good 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, capital good firms can start producing the technology of a competitor selected based on a measure of their technological proximity.⁹ A successful innovation results in a new capital vintage κ_{in} , whose characteristics are determined through a stochastic process as:

$$Pr_{\kappa_{in}} = (1 + \mathfrak{V}_{1,k,t}) Pr_\kappa, \quad (14)$$

$$EE_{\kappa_{in}} = (1 + \mathfrak{V}_{2,k,t}) EE_\kappa, \quad (15)$$

$$EF_{\kappa_{in}} = (1 + \mathfrak{V}_{3,k,t}) EF_\kappa, \quad (16)$$

where $\mathfrak{V}_{1,k,t}$ 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_3^K, b_4^K) . Similarly, $\mathfrak{V}_{2,k,t}$ ($\mathfrak{V}_{3,k,t}$) 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.

⁸ Consumption good 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, consumption good 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 $EE_{c,t}^e = \sum_{\kappa \in \Phi_{\kappa,c,t}} EE_{\kappa,t} \frac{K_{\kappa,c,t}}{K_{c,t}}$, 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 , $K_{\kappa,c,t}$ is the productive capacity of machines of technology κ that the consumption good firm has available in the current period, and $K_{c,t}$ is the current total productive capacity of the firm. The formula is the same for $EF_{c,t}^e$ and $CI_{c,t}^e$.

⁹ For a detailed description of capital good firms' spending on innovation and imitation, how this influences their likelihood of being successful and the imitation process please refer to [Reissl et al. \(2025\)](#). 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.

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

$$A_{\kappa,t} = p_{\kappa,t} + uc_{\kappa,t} \cdot b, \quad (17)$$

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

$$p_{\kappa,t} = (1 + \mu^K) \cdot uc_{\kappa,t} = (1 + \mu^K) \left(\frac{w_{H,t}}{Pr_{\kappa,t}} + \frac{p_{e,t-1}}{EE_{\kappa,t}} \right), \quad (18)$$

$$uc_{\kappa,t} = \frac{w_{H,t}}{Pr_{\kappa,t}} + \frac{p_{e,t-1}}{EE_{\kappa,t}} = \frac{w_{H,t}}{Pr_{\kappa,t}} + \frac{p_{e,t-1}}{EF_{\kappa,t}} CI_{\kappa,t}, \quad (19)$$

where μ^K is the (homogenous) mark-up of capital good firms and $uc_{\kappa,t}$ is the unit cost of production using the associated technology. Capital good firms will produce the vintage having a lower value of $A_{\kappa,t}$, since consumption good firms use the same measure of attractiveness to compare capital good firms when deciding to switch the capital supplier. This implies that capital good firms might decide to adopt (and consumption good 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.

2.1.7. Consumption good firms and banks failure

A consumption good 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. Consumption good 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 consumption good firm exits, at the end of the timestep a new consumption good firm enters the model, receiving a transfer from households' deposits as described in [Section 2.1.2](#) and an initial stock of second-hand capital machines.

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 consumption good firms.

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.2 for a description of the re-calibration procedure and refer to [Reissl et al. \(2025\)](#) 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](#)).

[Fig. 2](#) shows the time series of selected variables generated by our model (see [Fig. S.1](#) in Appendix A.2 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.¹⁰ 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.2.

¹⁰ 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.

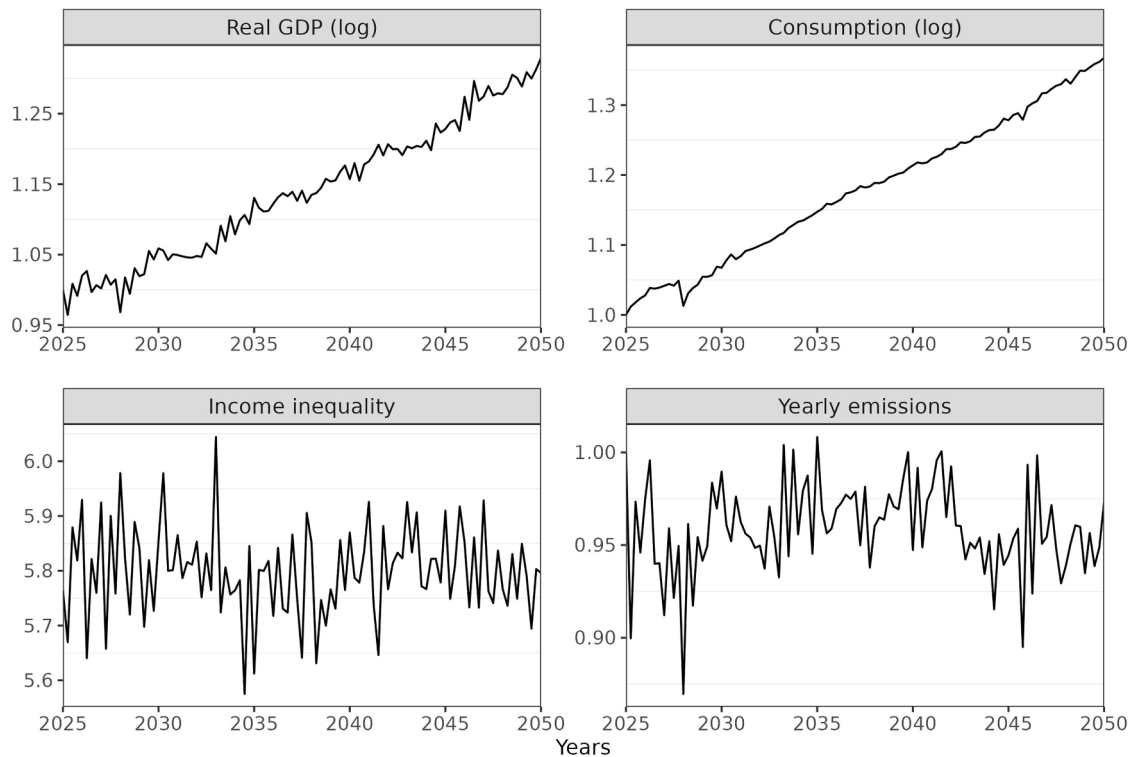


Fig. 2. Time series of selected variables for one run of the model, randomly selected. Real GDP and consumption are in logarithmic scales. Values for real GDP, consumption and yearly emissions are normalised to the value they have in the year 2025. Income inequality is measured as the net income ratio 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, in [Section 3.3](#) we analyse a policy mix in two additional scenarios aimed at relaxing key modelling assumptions, 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 consumption good 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.¹¹ 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 consumption good firms.¹²

3.1. Single policies

We select and design seven fiscal policies,¹³ 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:

1. 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.
2. 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 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:

1. 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.
2. 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:

1. Green capital subsidies: the government subsidises consumption good 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 capital good 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.
2. Dirty capital taxation: the government taxes consumption good 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 capital good 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.
3. Carbon tax: the government collects a tax on carbon emissions from the energy sector, capital and consumption 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 %,

¹¹ 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.

¹² We report these indicators only for consumption good 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).

¹³ 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.

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.¹⁴ The shape of the “efficiency 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 capital good firms are determined independently through a stochastic process (see Section 2.1.6): 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; Cappa et al., 2024; Mazzanti and Zoboli, 2009; Mercure et al., 2025; 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 capital good 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.¹⁵ Appendix D.1 details the exact implementation of this scenario. Appendix D.3 presents the effects of implementing the Selected Policy Mix in an additional scenario where we introduce bonuses paid to top 10 % households to partially endogenize labour income.

¹⁴ 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 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.

¹⁵ The three parameters multiplying $\mathfrak{S}_{1,k,t}$, $\mathfrak{S}_{2,k,t}$ and $\mathfrak{S}_{3,k,t}$ 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?”.

4. Results

4.1. Single policies

Fig. 3 reports the effects of introducing each policy individually as compared to the baseline scenario (see also Fig. S.6 in Appendix B.2 for additional indicators). Environmental fiscal policies incentivise firms to 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 consumption good firms will adopt them (see Eq. (S.17) in Appendix B.1). More specifically, these policies increase consumption good 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.¹⁶ 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 consumption good firms' profits increasing their failure rate. These effects are particularly relevant for taxes on dirtier capital, which also increase consumption good firms' failures by decreasing their deposits and net worth (whereas subsidies have an opposite compensating effect). However, with lower deposits consumption good 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., 2025b; Niedo 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.21) in Appendix B.1). This biases consumption good 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.¹⁷ 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, 2024).¹⁸ In contrast, reducing the tax rate on the wages of 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.

Income inequality is measured as the net income ratio of a household in the top 10 % to one in the bottom 60 %. Emissions are

¹⁶ 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.

¹⁷ 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 2.1.2), 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.

¹⁸ To sustain consumption and match unemployment levels, we could not further reduce households' propensities to consume (see Appendix A.2 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.

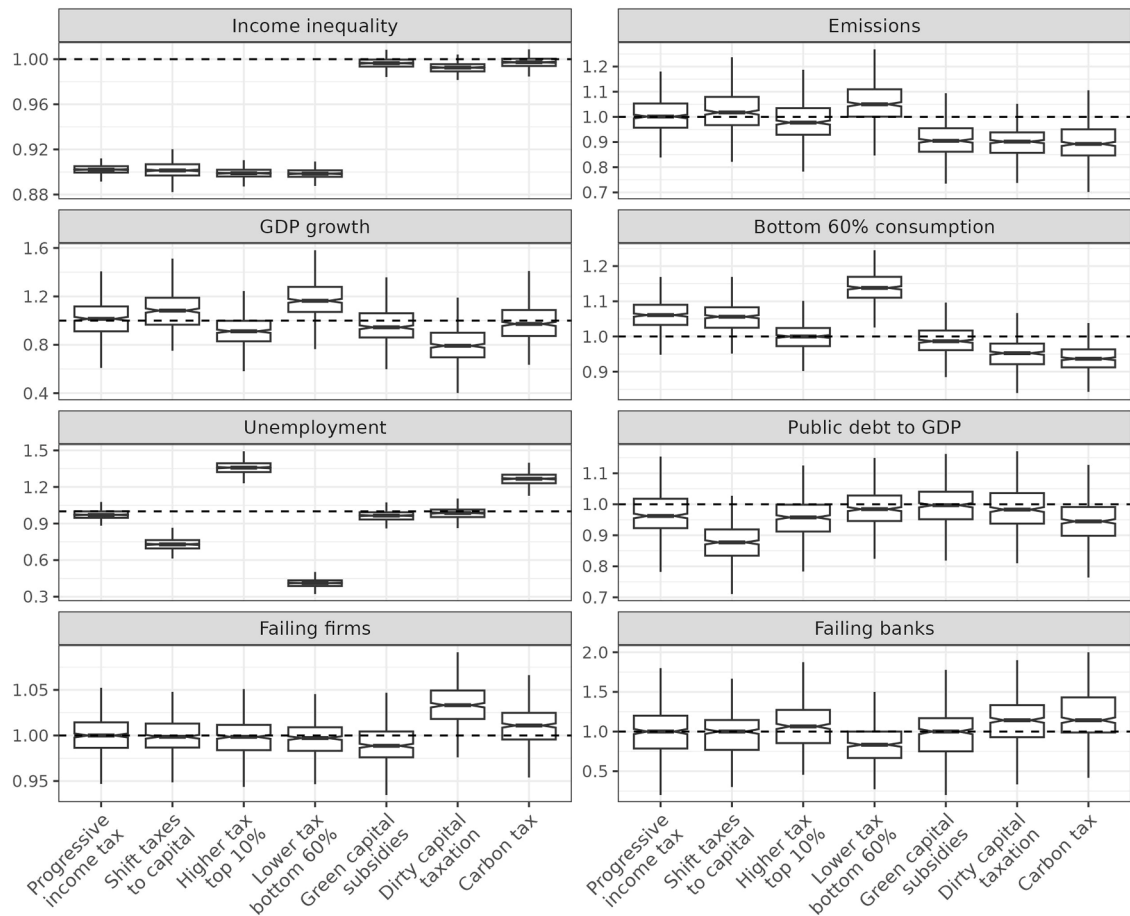


Fig. 3. Effect on selected indicators (on top of each boxplot) of introducing policies (reported in the x-axis) individually. Boxplots are obtained over 300 Monte Carlo runs. We report different y-axis and exclude outliers for clearer visualization. Indicators are normalised to the value they assume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

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 consumption good 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.

4.2. Policy mixes

Fig. 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 Fig. S.14 in Appendix C). Most successful policy mixes also increase the consumption of bottom 60 % households compared to the baseline (Fig. 4d and e), while a minority increases economic growth (Fig. 4b and c). The efficiency frontiers in Fig. 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, Fig. 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 Fig. 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.

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 Fig. 3 describes the indicators and policies.

	Emissions	Income inequality	Unemployment	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	↓	→	↑	↑	↓	→/↓	↓

Among the successful policy mixes on the efficiency frontier for reducing inequality and emissions (Fig. 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.¹⁹ 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., 2025b; 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. 2025). Nevertheless, almost half of successful policy mixes feature a carbon tax, highlighting its contribution if included in a more comprehensive policy mix.

4.3. Selected policy mix and additional scenarios

Fig. 5 reports the effects of the Selected Policy Mix across the two additional 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 Fig. 5a) and increases the consumption of bottom 60 % households by 5 % (Fig. 5c). It also lowers unemployment and public debt to GDP by over 20 %, without increasing economic instability (see Fig. S.15a and b in Appendix D.2). Fig. 5a further shows that the reduction of inequality achieved through the Selected Policy Mix remains similar in all scenarios. This holds also when labour income inequality is partially endogenized, as shown by the results of the scenario where we introduced bonus payments to top 10 % households, presented in Appendix

¹⁹ 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.

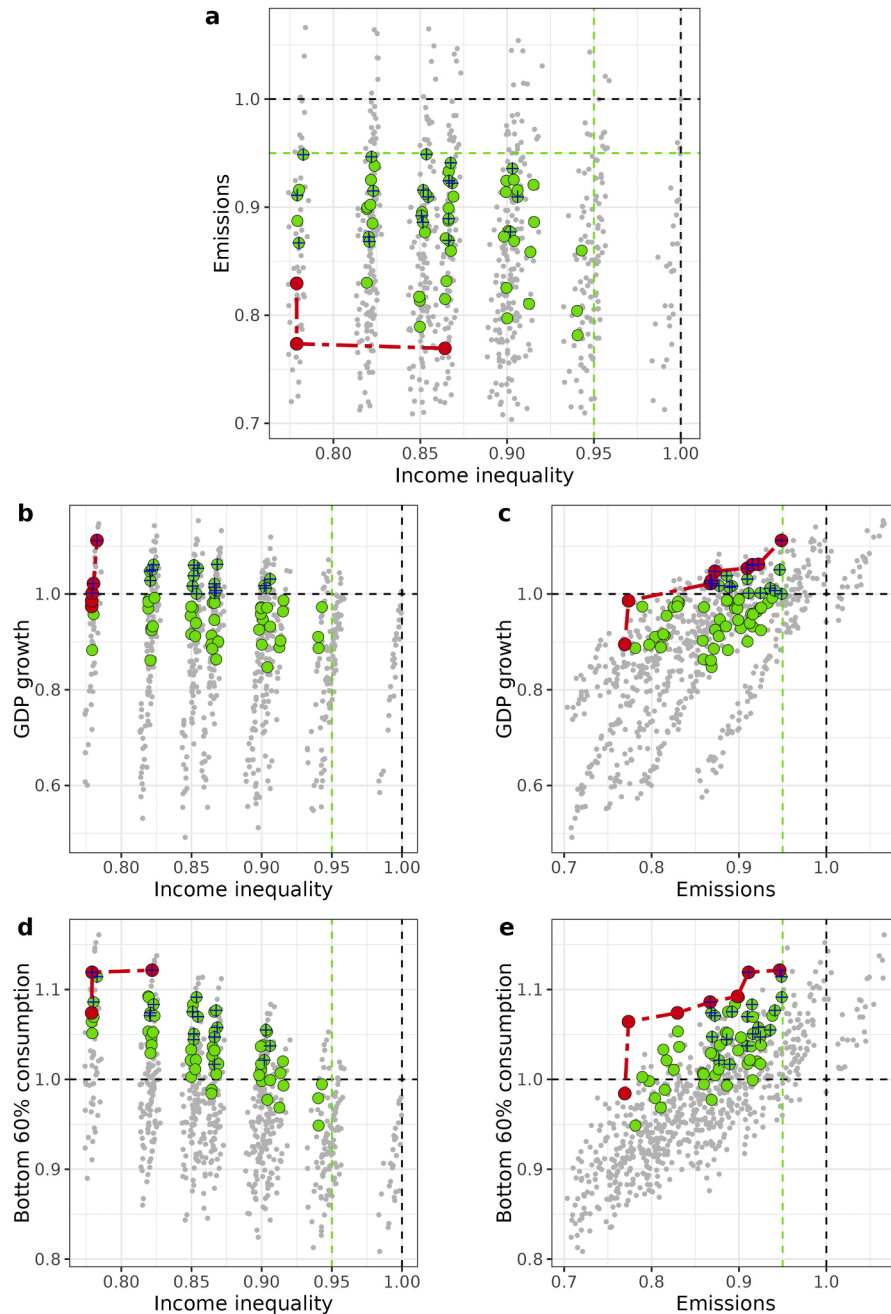


Fig. 4. Effect of policy mixes. Each dot in the scatter plots represents the outcome of one policy mix on the indicators reported in the axes (note the different scales). Green-filled dots represent successful policy mixes in reducing inequality and emissions by at least 5 % without increasing unemployment, 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).

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 Fig. 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	✓	✓	✗	✓	✓	✗	✓

D.3. Instead, the effectiveness of the Selected Policy Mix in reducing emissions weakens both under an energy transition and when green innovation increases labour productivity (Fig. 5a).

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 Fig. 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 (Fig. 5b and Fig. 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 Fig. 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 Fig. 5a), with industrial emissions declining only marginally (Fig. 5b). This occurs because consumption good 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 Fig. 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 Fig. 5c). Additionally, the carbon tax is still effective in reducing residential and government emissions (see Fig. 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 Fig. 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 Fig. 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.

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., 2025) 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

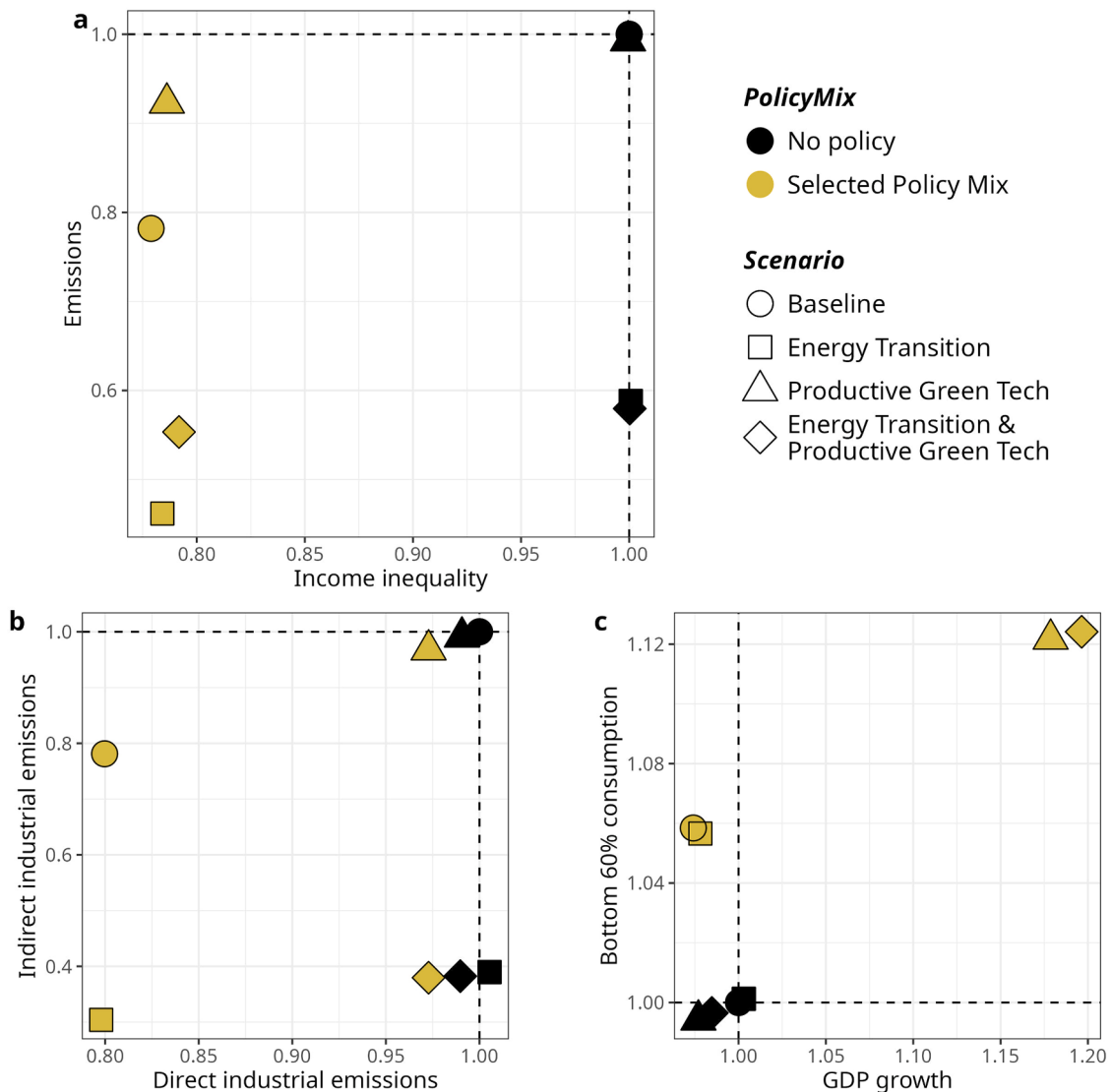


Fig. 5. Effect on selected indicators of introducing the Selected Policy Mix under different scenarios. Each dot represents the average value of the indicators on the y-axis and x-axis under no policy or the Selected Policy Mix (identified by the dot's colour) and a scenario (identified by the dot's 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 Fig. 4. Figure b) shows the effects on direct and indirect industrial emissions, measured as the yearly values at the end of the simulation.

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.

To test the robustness of our results to key modelling assumptions we designed two alternative scenarios on which our policy packages have been examined. One scenario features relatively more productive green technologies, to mimic some empirical evidence suggesting that green innovation leads to higher productivity (see e.g. Aldieri et al., 2021; Cappa et al., 2024; Mercure et al., 2025); the other includes an ongoing energy transition reflecting ambitious EU targets of green energy share. The effectiveness of various policies has been largely confirmed, though some minor quantitative differences emerged (see results in Section 4.3 and Appendix D.3).

This work could be extended in several complementary directions to enrich our analyses and explore new scenarios.

First, we could study the emergent dynamics of the model under scenarios where the energy transition is endogenous as in other version of the DSK model (Lamperti et al., 2025b, 2020; Reissl et al., 2025). Our exogenous energy transition scenario showed that its speed critically determines the effectiveness of policy mixes in further reducing emission. Scenarios with an endogenous transition would allow us to better investigate its interlinkages with residential energy demand and industrial dynamics. 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. (2025).

Second, we could expand the model to a multi-regional modelling framework. The successful decarbonisation of the energy sector depends on the relative prices of fossil fuels and renewable energy, both of which are shaped by global dynamics. Modelling international trade and competition would be essential to investigate the combined effects of exchange rates, trade policies and domestic instruments, such as the interaction between carbon pricing and a carbon border adjustment mechanism.

Finally, we will extend the model to account for a fine-grained disaggregation of the household sector. Even if the scenario presented in Appendix D.3 showed that our results remain robust even when labour income inequality is partially endogenized through the introduction of bonus payments to top 10 % households, modelling individual workers would enable the introduction of a proper labour market module, as implemented in other ABMs (Dawid and Hepp, 2022; Dosi et al., 2020, 2018a; Fierro et al., 2022). This extension would allow us to overcome the assumption of fixed wage ratios between household classes and fully endogenize personal income inequality. Together with the activation of endogenous climate damages already featured in the DSK model (Lamperti et al., 2018), this would deliver a more comprehensive assessment of the distributional impact of climate change and climate policies and how these would feedback into consumption and thus emissions. Further disaggregating low- and high-income households would also enable an improved assessment of 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.

Declaration of competing interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.jebo.2025.107188](https://doi.org/10.1016/j.jebo.2025.107188).

Data availability

We have shared the link to the code of the model in footnote 3 in the manuscript.

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