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Summary

Green preferences are often regarded as crucial factors in facilitating the energy transition. However, it is unclear if they can alone propel an economy towards achieving a net-zero emissions outcome. In this study, we expand the multi-agent integrated assessment model MATRIX by incorporating considerations on implicit emissions in the decision-making process of consumers and firms. To evaluate the efficacy of those green preferences, we construct a range of experiments encompassing varying degrees of pro-environmental attitudes. Those scenarios are then compared to more conventional incentive-based climate policies, such as a carbon tax and a Cap-and-Trade mechanism, with and without a subsidy for abatement technology, each implemented at different stringency. Our findings indicate that only exceptionally high and unrealistic values of green preferences for both firms and consumers can achieve a net-zero outcome in the absence of an active policy. Moreover, the most favorable scenario in terms of environmental, economic and distributional outcomes emerges from a carbon tax accompanied by a moderate subsidy. Without subsidy, policies entail mainly negative economic and distributional consequences as firms transfer the increased costs to consumers.

Keywords: Energy Sector, Agent-Based Models, Macroeconomic Dynamics, Climate Policy, Emission Abatement, Green preferences

JEL classification: C63, Q52, Q58

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Beyond Green Preferences: Alternative Pathways to Net-Zero Emissions in the MATRIX model

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Abstract

Green preferences are often regarded as crucial factors in facilitating the energy transition. However, it is unclear if they can alone propel an economy towards achieving a net-zero emissions outcome. In this study, we expand the multi-agent integrated assessment model MATRIX by incorporating considerations on implicit emissions in the decision-making process of consumers and firms. To evaluate the efficacy of those green preferences, we construct a range of experiments encompassing varying degrees of pro-environmental attitudes. Those scenarios are then compared to more conventional incentive-based climate policies, such as a carbon tax and a Cap-and-Trade mechanism, with and without a subsidy for abatement technology, each implemented at different stringency. Our findings indicate that only exceptionally high and unrealistic values of green preferences for both firms and consumers can achieve a net-zero outcome in the absence of an active policy. Moreover, the most favorable scenario in terms of environmental, economic and distributional outcomes emerges from a carbon tax accompanied by a moderate subsidy. Without subsidy, policies entail mainly negative economic and distributional consequences as firms transfer the increased costs to consumers.

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1 Introduction

The 2023 IPCC report reaffirmed the link between the observed increase in global temperature and Greenhouse Gas (GHG) emissions, highlighting how human-induced climate change is already causing extreme weather events and widespread economic damage (IPCC, 2023). Given the urgent need for an energy transition, the likelihood of achieving a net-zero scenario will thus depend on the ability of policymakers to steer the economy toward cost-effective and environmentally sustainable energy sources (e.g., through a carbon tax or investment subsidies). However, it is unclear how long the process will take and the related macro-financial risks (IMF, 2022).

At the same time, despite the growing awareness of environmental problems, the ratio of carbon emissions from direct and indirect household consumption to total global carbon emissions has increased because of economic development (Csutora et al., 2021; Wei et al., 2023). Therefore, climate change mitigation will likely require not only a change in production processes but also a shift in consumption patterns toward low-carbon goods. Consequently, researchers have turned their attention to consumers' behavior, as reducing carbon emissions from household consumption can play a critical role in achieving the goal of climate governance (Peattie, 2010).

The main idea of this strand of literature is that changing social norms and values can influence purchasing behavior and (indirectly) production technology (Bezin, 2019; Konc et al., 2021; Torren-Peraire et al., 2024; Castro-Santa et al., 2023). Indeed, the value for money of a green product is positively influenced by a pro-environmental attitude (Biswas and Roy, 2015), thus potentially generating additional revenues and profits for firms investing in less polluting techniques. Nevertheless, few works analyzed the effects (and feedback) at the aggregate level of such a change in consumers' behavior (Aghion et al., 2023; Konc et al., 2021; Busato et al., 2023).

Furthermore, it is crucial to compare this against the policy context in which consumers are situated, given the increasing implementation and advancement of these mechanisms worldwide (Rontard and Hernandez, 2022). This trend aligns with the adoption of more rigorous climate objectives by nations. As incentive-based climate policies are generally favored by policymakers and economists for their enhanced efficiency (de Vries and Hanley, 2016), it is imperative to thoroughly evaluate how environmentally conscious preferences differ from policies in transitioning towards a greener economy.

Several works already consider incentive-based policies within a multi-agent framework. These span from consumer and manufacturers subsidies (Sun et al., 2019), carbon taxes and green subsidies (Lamperti et al., 2020), green prudential instruments (D'Orazio and Popoyan, 2019), carbon pricing under multiple needs (Foramitti et al., 2024), Cap-and-Trade (CaT) or Emission Trading Schemes (ETS) (Zhu et al., 2016; Tang et al., 2017; Yu et al., 2020; Foramitti et al., 2021), and the linkages of multiple ETSs (Fang and Ma, 2020).

Our work contributes to this strand of the literature by providing new theoretical evidence on the macroeconomic effects of a switch in the preferences of economic agents toward less polluting goods and compares against climate policy scenarios. In particular, we extend the climate version of the Multi-Agent model for Transition Risks (MATRIX) (Ciola et al., 2023; Turco et al., 2023; Bazzana et al., 2023) by including a preference structure for consumers that weighs produced goods by their implicit emissions content. At the same time, we introduce an endogenous learning process for firms to model their emissions reduction choice. Indeed, we aim to assess if a pro-environmental attitude (i.e., one that considers product emission levels) can generate sufficient incentives to affect firms' investment decisions and the related macroeconomic effects. This is tested both alone and compared in terms of emission reduction, macroeconomic, and distributional impacts with different policy scenarios (with different stringency), which include a carbon tax and a Cap-and-Trade mechanism. We also include in the analysis a technological subsidy in all scenarios to support the investment in abatement by firms. Finally, as a robustness exercise, we consider different political preferences of the government, detailing two extreme representative cases, one aiming at redistributive transfer maximization and the other about tax reductions.

We find that consumers' green preferences, even at a very high level, are not sufficient to significantly reduce emissions. If also firms internalize this aspect, the reduction is enhanced, even reaching a Net-Zero Emissions (NZE) scenario. The policies (carbon tax and Cap-and-Trade) can reach net zero quicker but with increased negative economic outcomes, mostly due to firms transferring the surge in abatement costs to final consumers. Between policies, carbon tax is posing less distortions than the permits market. Introducing an abatement technology subsidy quells some of the economic distortions, especially if at medium levels and combined with a carbon tax. This combination also entails lower distributive impacts, even slightly redistributive in some cases, while in others, the lower net worth percentiles are worst off. Finally, we observe that government political preferences are relevant in affecting economic and distributive outcomes.

In the following, Section 2 describes briefly the extensions posed to the original MATRIX model. Section 3 discusses the choice of parameters and lists the proposed policy experiments. Section 4 presents the outcomes of the simulations and provides interpretations, while Section 5 concludes.

2 Model

The MATRIX model (*Multi-Agent model for Transition Risks*) is a multi-sector, multi-agent, integrated-assessment macroeconomic model designed to analyze the effects of energy and environmental policies on the climate and economic dynamics (Ciola et al., 2023; Turco et al., 2023; Bazzana et al., 2023). The model encompasses a diverse set of heterogeneous agents belonging to different sectors, such as households, corporates, banks, and public entities, interacting in decentralized markets.

The corporate sector comprises energy, capital, and final good firms, linked through empirically calibrated input-output relationships. Furthermore, two exogenous sectors provides firms with a fossil fuel and emission Abatement Technology (AbT), respectively, responding to demand with infinitely elastic supply.[1] Fossil fuel consumption by the corporate sector generates GHG emissions, contributing to the global average temperature rise through the carbon cycle.

[1]As in Ciola et al. (2023) and Turco et al. (2023), to preserve the stock-flow consistency of the model, we assume that the fossil rents are redistributed within the economy, partly to energy firms (to account for domestic fossil fuel production), and partly to households in proportion to their wealth. A similar procedure applies to abatement costs (see Bazzana et al., 2023).

Operating in decentralized markets characterized by uncertainty and incomplete information, economic agents make decisions based on strategic learning rules and adaptive expectations about relevant aggregate variables, such as inflation and growth rates. Consequently, the model generates endogenous fluctuations and out-of-equilibrium dynamics resulting from intra and inter-market coordination failures and feedback loops. The agent-based approach captures the intricate interplay of economic and environmental factors, allowing for a more nuanced understanding of the complex system under examination.

Lastly, the MATRIX model is a fully stock-flow consistent macroeconomic model, i.e., it adheres to the accounting principle that any change in a flow variable matches a corresponding variation in a stock, and each agent's asset corresponds to another agent's liability.

Figure 1 provides a visual representation of the overall functioning of the MATRIX model, offering insights into the flow of resources, the pivotal roles of key agents, and the intricate dynamics shaping the model's behavior.

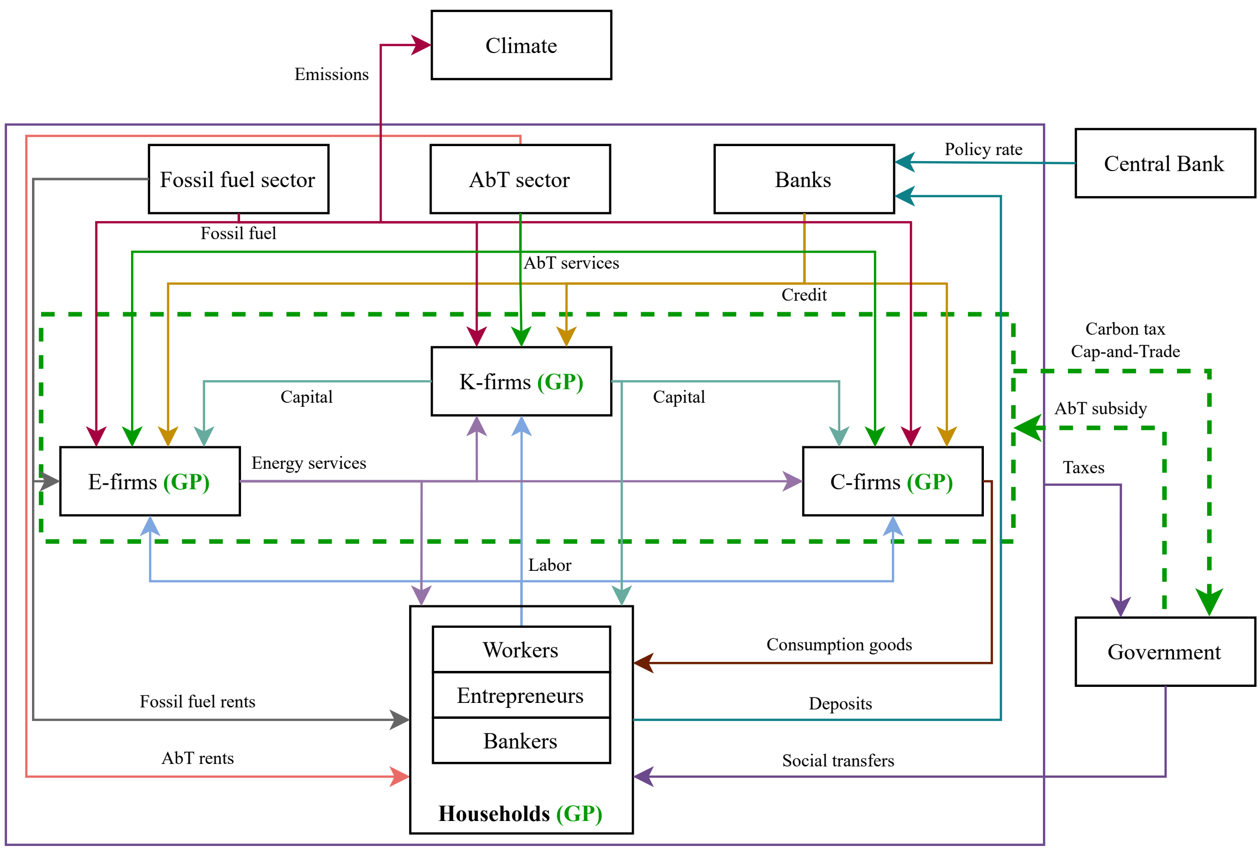

Figure 1: The MATRIX model and climate extensions

Starting from the bottom, the diagram illustrates that workers provide labor to energy (E), consumption (C), and capital (K) firms. The latter, in turn, employ labor alongside other inputs within a Constant Elasticity of Substitution (CES) production function to generate sector-specific goods. These goods either serve as intermediate inputs in other sectors (such as energy services and capital) or are directed for final consumption by households. Moving upwards, banks collect deposits and extend credit to firms and households whose expenditures exceed internal financial resources. The government collects taxes and distributes social transfers to low-income individuals. Simultaneously, the central bank sets the policy rate following an inertial Taylor rule.

To address climate change, the government can implement a carbon tax or a CaT mechanism. The primary objective of those policies is to assign a price to carbon emissions, thereby incentivizing firms to adopt cost-effective AbT and consequently decrease their emission intensity. At the same time, the government can also introduce a subsidy covering part of the abatement costs sustained by the corporate sector, thus further stimulating the investment in low-emission technology.

Even without explicit public policies, firms may also invest in low-carbon technologies due to consumers' Green Preferences (GP). Indeed, both households and firms, as demand units in various markets, may favor goods with lower emissions. This consumer behavior can impact firms' profitability and, through a strategic learning mechanism, influence their incentives to invest in low-carbon technologies, aligning with evolving market preferences for eco-friendly products.

In this paper, we extend the climate version of the model calibrated on the United States (US) economy (Ciola et al., 2023) to explore the role of both demand-driven green preferences and supply-side environmental policies in achieving the goal of net-zero emissions. The following section introduces the novel features incorporated into this new variant of the model, while the interested reader may refer to Ciola et al. (2023), Turco et al. (2023), and Bazzana et al. (2023) for an exhaustive description of the remaining parts.

2.1 Input demand and green preferences

Households In every period t, households $h = 1, \ldots, \mathcal{N}^H$ derive their utility from a basket of products $X_{h,t}$ comprising a final consumption good, capital, and energy services – denoted with $J_h = \{C, K, E\}$ hereafter – and defined through the CES function:

$$X_{h,t} = \left[\sum_{j \in J_h} \left(A_{j,h}\right)^{\frac{1}{\sigma_h}} \left(X_{j,h,t}\right)^{\frac{\sigma_h - 1}{\sigma_h}} \right]^{\frac{\sigma_h}{\sigma_h - 1}}, \tag{1}$$

where σ_h is the elasticity of substitution, and $X_{j,h,t}$ is the quantity of product $j \in J_h$ with consumption share $A_{j,h}$ and depreciation rate δ_j.

Each household h aims at maximizing the expected flow of current and future utility discounted by the intertemporal factor $\beta \in (0, 1)$:[2]

$$\max_{\left\{\left\{X_{j,h,t+s}\right\}_{j \in J_h}; D_{h,t+s}\right\}_{s=0}^{\infty}} \mathbb{E}_{h,t} \left[\sum_{s=0}^{\infty} \beta^s \log\left(X_{h,t}\right) \right], \tag{2}$$

under the budget constraint:

$$D_{h,t+s} + \sum_{j \in J_h} P_{j,t+s} X_{j,h,t+s} = Y^N_{h,t+s} + \left(1 + i^{CB}_{t+s-1}\right) D_{h,t+s-1} + \sum_{j \in J_h} \left(1 - \delta_j\right) P_{j,t+s} X_{j,h,t+s-1}, \tag{3}$$

[2] We denote with $\mathbb{E}_{y,t}[\cdot] = \mathbb{E}[\cdot \mid \mathcal{I}_{y,t}]$ the expected value conditional to the information set $\mathcal{I}$ of agent y at the time t.

where $D_{h,t+s}$ are demand deposits at the time $t+s$, i^{CB}_{t+s} is the risk-free interest rate set by the central bank, $P_{j,t+s}$ is the price of product j, and $Y^N_{h,t+s}$ is an exogenous nominal income (i.e., wages and corporate dividends).

Since households have limited processing capabilities, they approximate the optimal consumption budget of product j as follows:

$$H_{j,h,t} \approx A_{j,h} \left[1-\beta(1-\delta_j)\right]^{-\sigma_h} \left(\frac{\mathbb{E}_{h,t}[P_{j,t}]}{\mathbb{E}_{h,t}[P_t]}\right)^{1-\sigma_h} H_{h,t}, \tag{4}$$

where:

$$H_{h,t} = (1-\beta)(1+i^{CB}_{t+s-1})D_{t+s-1} + \bar{Y}^N_t + \sum_{j\in J_h} \mathbb{E}_{h,t}[P_{j,t}]\left(1-\delta_j\right) X_{j,h,t-1}, \tag{5}$$

is the aggregate consumption budget with:

$$\bar{Y}^N_{h,t} \approx (1-\beta)Y_{h,t} + \beta \frac{\mathbb{E}_{h,t}[P_t]}{\mathbb{E}_{h,t-1}[P_{t-1}]} \bar{Y}^N_{h,t-1}, \tag{6}$$

being the estimated nominal permanent income and:

$$\mathbb{E}_{h,t}[P_t] = \left\{\sum_{j\in J_h} A_{j,h}\left[1-\beta(1-\delta_j)\right]^{-\sigma_h} \left(\mathbb{E}_{h,t}[P_{j,t}]\right)^{1-\sigma_h}\right\}^{\frac{1}{1-\sigma_h}}, \tag{7}$$

the aggregate consumption price index.[3]

Firms After setting their desired price $P^*_{f,t+1}$ and quantity $Q^*_{f,t+1}$ for the subsequent period,[4] firms $f = 1, \ldots, \mathcal{N}^F$ compute their optimal demand for input (i.e, labor, energy services, capital, and fossil fuel, $J_f = \{N, E, K, O\}$) by minimizing the total purchase cost net of the expected recovery value:

$$\min_{\left\{X_{j,f,t+1}\right\}_{j\in J_f}} \mathbb{E}_{f,t}\left[\sum_{j\in J_f} P_{j,t}X_{j,f,t+1} - \frac{1}{1+i^{CB}_{t+1}} P_{j,t+1}(1-\delta_j)X_{j,f,t}\right], \tag{8}$$

under the production constraint:

$$Q^*_{f,t+1} = \left[\sum_{j\in J_f} \left(A_{j,f}\right)^{\frac{1}{\sigma_f}} \left(X_{j,f,t+1}\right)^{\frac{\sigma_f-1}{\sigma_f}}\right]^{\frac{\sigma_f}{\sigma_f-1}}, \tag{9}$$

where σ_f is the elasticity of substitution, and $X_{j,f,t+1}$ is the quantity of input j with factor share $A_{j,f}$ and depreciation rate δ_j.

[3]Moreover, we assume an irreversible investment constraint in the optimization problem. See Appendix A.1 for additional details.

[4]See Ciola et al. (2023) and Turco et al. (2023) for additional details.

As for the households, firms have limited processing capabilities and approximate the optimal input budget as follows:

$$H_{j,f,t+1} \approx A_{j,f} \left[1 - \beta(1 - \delta_j)\right]^{-\sigma_f} \left(\mathbb{E}_{f,t}[P_{j,t}]\right)^{1-\sigma_f} \left(\mathbb{E}_{f,t}[\psi_{f,t}]\right)^{\sigma_f} Q^*_{f,t+1}, \tag{10}$$

where:

$$\mathbb{E}_{f,t}[\psi_{f,t}] = \left(\sum_{j \in J_f} A_{j,f} \left[1 - \beta(1 - \delta_j)\right]^{-\sigma_f} \left(\mathbb{E}_{f,t}[P_{j,t}]\right)^{1-\sigma_f}\right)^{\frac{1}{1-\sigma_f}}, \tag{11}$$

are the expected marginal costs. Moreover, if firms are financially constrained (i.e., deposits $D_{f,t}$ are below purchasing costs), they borrow additional funds from the banking sector and reduce their input demand if necessary.

Green Preferences Parallel to the consumed quantity, households and firms consider the associated environmental impact in their shopping decision. After defining the optimal consumption budget for each product j ($H_{j,y,t}$, with $y = \{h, f\}$), they search for the seller offering the best trade-off between the supplied amount of products/services and CO_2 emissions. In particular, the utility of consumers/firms increases with the purchased quantity $X_{j,y,t}$ but decreases with the related emission intensity $e_{j,y,t}$, namely:

$$U(X_{j,y,t}, e_{j,y,t} \mid s) = \log\left(X_{j,y,t}\right) - \chi_y e_{j,y,t} = \log\left(X_{s,t}\right) - \eta_y(1 - \hat{e}_{s,t}), \tag{12}$$

where $s \in \{1, \ldots, \mathcal{N}^j\}$ is the partner selected in market $j = \{E, C, K\}$ (thus implying $e_{j,y,t} = e_{s,t}$ and $X_{j,y,t} = X_{s,t}$), while $\eta_y = \chi_y e_{s,t^*}$ measures the semi-elasticity between the supplied amount $X_{s,t}$ and the percentage reduction $\hat{e}_{s,t}$ in the emission intensity of firm s from a baseline year t^* (i.e., $e_{s,t} = (1 - \hat{e}_{z,t})e_{s,t^*}$, see Section 2.2).[5]

Accordingly, when market $j = \{E, C, K\}$ opens in every period t, each buyer $y = \{h, f\}$ observes its old partner plus a new one with probability $\mathcal{Z}_y$ (or, alternatively, $\mathcal{Z}_y$ new partners if $\mathcal{Z}_y \in \mathbb{Z}$) and selects seller s over z if the former provides a higher utility, namely:

$$U(X_{j,y,t}, e_{j,y,t} \mid s) - U(X_{j,y,t}, e_{j,y,t} \mid z) = \log\left(\frac{X_{s,t}}{X_{z,t}}\right) - \eta(\hat{e}_{z,t} - \hat{e}_{s,t}) > 0, \tag{13}$$

where:

$$X_{w,t} = \min\left(\frac{H_{j,y,t}}{P_{w,t}}, Q_{w,t}\right), \tag{14}$$

is the supplied amount of products/services by firm $w \in \{s, z\} \subset \{1, \ldots, \mathcal{N}^j\}$. The latter depends on the purchasing power of buyer y given the sale price $P_{w,t}$ and the actual supply of goods $Q_{w,t}$ from seller w.

[5] We adopt this notation to have similar effects of GP on sectors characterized by different emission intensities, e.g., energy services and capital.

2.2 Emissions and abatement technology

Alongside other inputs, firms require a fossil fuel to supply goods and services, thus generating CO_2 emissions and contributing to global warming. In every period t, the simulated GHGs produced by domestic companies in the US are equal to:

$$E_t = \sum_{f=1}^{\mathcal{N}^F} E_{f,t} = \sum_{f=1}^{\mathcal{N}^F} e_{f,t} X_{O,f,t}, \tag{15}$$

where $X_{O,f,t}$ is the purchased quantity of fossil fuel by firm f, and $e_{f,t}$ is the related emission intensity.

At the same time, a stylized Rest Of the World (ROW) sector generates an exogenous amount of GHGs (E_t^{ROW}), whose values originate from a Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model (Dietz and Rosa, 1994, 1997). In particular, the forecasted paths of future ROW emissions (one for each replica of the MATRIX model) derive from a vector autoregression model estimated on the log differences of global real GDP per capita, population, and emission intensity.[6] Those values then enter the MATRIX model together with the simulated US emissions to obtain the global figure:

$$E_t^W = E_t + E_t^{ROW}, \tag{16}$$

which flow as an input into the HECTOR climate module (Hartin et al., 2015, 2016) to compute future temperature paths.

Lastly, firms can invest in a costly AbT to lower CO_2 production. This technology consists of a finite number of identical steps J^{AbT}, allowing a maximum percentage reduction in their emission intensity equal to $\hat{e}^{AbT}$. In particular, each step lowers the emission intensity of firms by the same amount (i.e., $\hat{e}^{AbT}/J^{AbT}$) but at a varying (increasing) Marginal Abatement Cost (MAC). Moreover, since emissions stem from fossil fuel consumption, abatement costs are proportional to their nominal purchased quantity and imply an additional expenditure for each company f equal to:

$$AC\left(\hat{e}_{f,t}\right) P_{O,t} X_{O,f,t} = \sum_{j=0}^{J_{f,t}^{AbT}} \frac{\hat{e}^{AbT}}{J^{AbT}} MAC\left(j \frac{\hat{e}^{AbT}}{J^{AbT}}\right) P_{O,t} X_{O,f,t}, \tag{17}$$

where $P_{O,t}$ is the producer price of the fossil fuel, $J_{f,t}^{AbT}$ is the chosen level of abatement (i.e., the selected number of abatement steps), and:

$$\hat{e}_{f,t} = J_{f,t}^{AbT} \frac{\hat{e}^{AbT}}{J^{AbT}} \implies e_{f,t} = \left(1 - \hat{e}_{f,t}\right) e_{f,t^*}, \tag{18}$$

is the realized percentage reduction in the emission intensity of firm f from a baseline year t^*.

[6] In other words, we generate different paths of future global emissions excluding the US and include them into the model. See Bazzana et al. (2023) for additional details.

2.3 Public finances

As a part of its normal operations, the government employs tax revenues (TAX_t) to subsidize low-income households (TRA_t), bail out banks (EXP_t), and pay interest on past debt issuances ($i^{CB}_{t-1}B_{t-1}$). Accordingly, the stock of public debt (B_t) accumulates following the rule:

$$B_t = (1 + i^{CB}_{t-1})B_{t-1} - F_t, \tag{19}$$

where:

$$F_t = TRA_t + EXP_t - TAX_t, \tag{20}$$

is the primary budget, and i^{CB}_{t-1} is the risk-free interest rate set by the central bank and paid on outstanding sovereign bonds.

Given the observed level of debt, the government sets the primary budget over GDP for the following period ($f_{t+1} = F_{t+1}/GDP_{t+1}$) such that the debt-to-GDP ratio ($b_{t+1} = B_{t+1}/GDP_{t+1}$) gradually converges to the long-term target b^* at a rate ρ^G, namely:

$$b_{t+1} = b_t + \rho^G(b^* - b_t), \tag{21}$$

which implies:

$$f_{t+1} = (1 - \rho^G)\left[\frac{1 + i^{CB}_t}{(1 + \mathbb{E}_t[g^N_t])(1 - \rho^G)} - 1\right] b_t - \rho^G b^*, \tag{22}$$

where $\mathbb{E}_t[g^N_t]$ is the expected growth rate of nominal GDP. In this way, it can guarantee the sustainability of public finances in the long run. Lastly, the government sets the desired amount of social spending for the subsequent period as a share of nominal GDP:

$$\tau^{TRA}_{t+1} = \max\left(\psi^G, -f_{t+1}\right), \tag{23}$$

where ψ^G is a minimum level of transfers to low-income households, and a tax rate achieving the budget target:

$$\tau^{TAX}_{t+1} = f_{t+1} - \tau^{TRA}_{t+1} = f_{t+1} - \max\left(\psi^G, -f_{t+1}\right). \tag{24}$$

Addressing climate change thus requires implementing new policies while considering their effects on public finances. On the one hand, the government can introduce a subsidy for firms investing in emissions reduction. In particular, it can sustain a share λ^{CA} of total abatement costs, thus generating an additional public expenditure equal to:

$$TRA^{CA}_t = \sum_{f=1}^{\mathcal{N}^F} \lambda^{CA} AC\left(\hat{e}_{f,t}\right) P_{O,t} X_{O,f,t}. \tag{25}$$

On the other hand, the government can collect additional revenues by i) directly imposing a carbon tax on national CO_2 emissions or ii) indirectly through a CaT mechanism. In the former case, it gradually introduces a carbon tax τ^{CA}_t such that:

$$\tau^{CA}_t = \begin{cases} \tau^{CA}_{t-1} + \epsilon^{CX} & \text{if } E_t \geq \overline{E}, \\ \tau^{CA}_{t-1} - \epsilon^{CX} & \text{otherwise,} \end{cases} \tag{26}$$

where ϵ^{CX} is the adjustment speed of the policy, and $\overline{E} = (1 - \eta^{CA})E_{t^*}$ is the long-term desired level of emissions, computed as a percentage reduction η^{CA} from a reference year t^*. In other words, an observed level of CO_2 emissions above (below) this threshold boosts an immediate increase (decrease) of the tax by an amount ϵ^{CX}.

Conversely, through the CaT mechanism, the government progressively lowers the maximum permitted level of CO_2 emissions $\overline{E}_t$ up to the desired level $\overline{E}$:

$$\overline{E}_t = \max\left(\overline{E}_{t-1} - \epsilon^{CaT} E_{t^*}, \overline{E}\right), \tag{27}$$

where the quarterly reduction $\epsilon^{CaT} E_{t^*}$ is computed as percentage ϵ^{CaT} of total emissions E_{t^*} in a reference year t^*. As a result, it receives an (implicit) carbon tax τ_t^{CA} from the sale of emission permits, namely:

$$\tau_t^{CA} = \left\{ \tau^{CA} \mid \sum_{f=1}^{\mathcal{N}^F} E_{f,t} = \overline{E}_t \right\} \text{ with } E_{f,t} = e_{f,t} X_{O,f,t} = e_{f,t} \frac{H_{O,f,t}}{P_{O,f,t}}, \tag{28}$$

where $H_{O,f,t}$ is the nominal budget for fossil fuel consumption of firm f at the time t, and:

$$P_{O,f,t} = \left[1 + \left(1 - \lambda^{CA}\right) AC\left(\hat{e}_{f,t}\right) + \tau_t^{CA} \varepsilon_{f,t}\right] P_{O,t}, \tag{29}$$

is the corresponding price. The latter depends on the producer price $P_{O,t}$, the carbon tax τ_t^{CA}, and the abatement cost $AC(\hat{e}_{f,t})$, net of the public subsidy $\lambda^{CA} AC(\hat{e}_{f,t})$, where $\varepsilon_{f,t} = e_{f,t}/e_{f^*,t^*}$ is the emission intensity of a company relative to a baseline sector/year $\{f^*, t^*\}$.[7] In other words, the CaT mechanism limits the maximum amount of CO_2 emissions by introducing a wedge between producer and consumer prices (equal to the emission permit), thus reducing the consumption of fossil fuels and GHGs production.

Lastly, the government collects carbon tax revenues based on firms' emissions $E_{f,t}$:

$$TAX_t^{CA} = \sum_{f=1}^{\mathcal{N}^F} \tau_t^{CA^*} E_{f,t} = \sum_{f=1}^{\mathcal{N}^F} \tau_t^{CA} \varepsilon_{f,t} P_{O,t} X_{O,f,t}, \tag{30}$$

where $\tau_t^{CA^*} = \tau_t^{CA} P_{O,t}/e_{f^*,t^*}$ is the implicit carbon tax set by the government.Accordingly, the fiscal budget over GDP relative to carbon tax revenues (TAX_t^{CA}) and abatement subsidies (TRA_t^{CA}) is equal to:

$$f_t^{CA} = \frac{TAX_t^{CA} - TRA_t^{CA}}{GDP_t}, \tag{31}$$

which we assume is immediately redistributed between social transfers and income taxation (i.e., it does not contribute to long-term debt sustainability) following the rule:

$$\bar{\tau}_{t+1}^{TRA} = \max\left(\psi^G, -f_{t+1}\right) + \phi^{CA} \max\left(0, f_t^{CA}\right) + \left(1 - \phi^{CA}\right) \min\left(0, f_t^{CA}\right), \tag{32}$$

and:

$$\tau_{t+1}^{TRA} = \max\left(\bar{\tau}_{t+1}^{TRA}, -f_{t+1} + f_t^{CA}\right), \tag{33}$$

[7] We adopt this specification since it allows a straightforward conversion of the carbon tax into real-world monetary units. See Section 3.

$$\tau_{t+1}^{TAX} = f_{t+1} - f_t^{CA} + \max\left(\bar{\tau}_{t+1}^{TRA}, -f_{t+1} + f_t^{CA}\right), \tag{34}$$

where ϕ^{CA} measures the policy-maker preference for social expenditure. When $\phi^{CA} = 1$, a positive balance from climate policies increases transfers to low-income households, while deficits are entirely financed through taxation. Conversely, when $\phi^{CA} = 0$, the government uses the extra resources to cut tax rates, while it decreases social spending below the minimum level ψ^G if additional funding is needed.

2.4 Abatement decision

We conclude this section by describing firms' abatement decisions. As shown before, each company has different incentives to invest in AbT. On the one hand, a lower emission intensity may increase the attractiveness of a firm (deter customers' flights towards competitors) through GP and improve its profitability (avoid its default). On the other hand, GHGs raise production costs when a carbon tax or a CaT mechanism is in place. Therefore, to assess the strength of profit and cost motives on the abatement decision, we introduce an endogenous learning mechanism by which firms observe the behavior of competitors and copy the most profitable strategies.

In every period t, each firm f compares its profits $\Pi_{f,t}$ with those of a competitor S chosen with probability:

$$\Pr(s = S) = \frac{\exp\left(-\omega^{AbT}\Delta_{f,S,t}\right)}{\sum_{s\neq f=1}^{\mathcal{N}^F}\exp\left(-\omega^{AbT}\Delta_{f,s,t}\right)} \tag{35}$$

where $\Delta_{f,s,t} = |y_{f,t} - y_{s,t}|$ measures the absolute distance between firms in terms of nominal production, and ω^{AbT} captures the intensity of choice. If the competitor displays higher profitability, the firm copies its strategy (i.e., the abatement level). On the contrary, it explores the surroundings of its current abatement level by increasing or decreasing it by equal chance, namely:

$$J_{f,t+1}^{AbT} = \begin{cases} J_{S,t}^{AbT} & \text{if } \{\Pi_{S,t} \geq \Pi_{f,t}\}, \\ J_{f,t}^{AbT} + 1 & \text{if } \{\Pi_{S,t} < \Pi_{f,t}\} \wedge \{U(0,1) \geq 0.5\}, \\ J_{f,t}^{AbT} - 1 & \text{if } \{\Pi_{S,t} < \Pi_{f,t}\} \wedge \{U(0,1) < 0.5\}. \end{cases} \tag{36}$$

3 Calibration and policy experiments

3.1 Calibration

The new version of the model introduces the possibility for households to consume a wider variety of goods, calibrates the emissions of the MATRIX model to the US economy, and introduces an updated MAC function. This Section describes the new calibration, while Table B.1 in Appendix A.2 summarizes the values of the remaining parameters.

Input demand and emission intensity To update the factor shares in the new version of the MATRIX model, we calibrate them from the annual IO tables of the U.S. Bureau of Economic Analysis between 2010 and 2019. In particular, we divide the original NAICS activities of the database between consumption (C) and capital (K) goods depending on their relative weight on final uses and associate the energy (E) sector with the category "Utilities" in the original tables. Further, we assume that only households purchase final goods, there are no intra-sector exchanges, and the fossil fuel sector coincides with the sum of the economic activities "Petroleum and coal products" and "Oil and gas extraction". Subsequently, we compute the factor shares by computing the relative weight of each input/product on total costs/expenditure. At the same time, we derive the relative emission intensity of each sector from the Carbon Dioxide Emissions From Energy Consumption tables of the U.S. Energy Information Administration using 2019 as a reference year and consumption (C) goods as baseline sector $\{f^* = C, t^* = 2019\}$. Moreover, the dataset allows us to calculate the conversion factor of the carbon tax from model quantities to real-world monetary values: $P_{O,t}/e_{f^*,t^*} = 288$ USD/tCO_2. Table 1 summarizes the obtained results together with the elasticity of substitution, assumed to be equal to 0.25 as in previous model versions.

Table 1: CES function parameters

		Consumption (C)	**Capital** (K)	**Energy** (E)	**Households** (H)
Number of agents	$\mathcal{N}^y$	100	60	10	1180*
Final good	$A_{C,y}$				0.92
Labor	$A_{N,y}$	0.73	0.90	0.64	
Capital	$A_{K,y}$	0.21		0.08	
Energy	$A_{E,y}$	0.02	0.04		0.02
Fossil fuel	$A_{O,y}$	0.04	0.06	0.28	
Elasticity of substitution	σ_y	0.25	0.25	0.25	0.25
Relative emission intensity	ε_y	1.00	1.00	0.80	

*: 1000 workers plus 170 entrepreneurs and 10 bankers.

Abatement technology As in Foramitti et al. (2021), we assume an AbT identical for all firms and composed of $J^{AbT} = 40$ steps up to a maximum reduction in the emission intensity equal to 200% (i.e., $\hat{e}^{AbT} = 2$). In other words, adopting a more efficient AbT diminishes emissions by five percentage points ($\hat{e}^{AbT}/J^{AbT} = 0.05$), also allowing for carbon capture when exceeding the 100% threshold. Moreover, we set companies' intensity of choice equal to $\omega^{AbT} = 10$ to ensure homogeneity in firms' comparison. Lastly, we derive the MAC curve from Barrage and Nordhaus (2023):

$$MAC\left(\hat{e}_{f,t}\right) = \alpha^{AbT}\left(\hat{e}_{f,t}\right)^{\beta^{AbT}} \text{ with } \alpha^{AbT} = 1.92 \text{ and } \beta^{AbT} = 1.6, \tag{37}$$

which points to a backstop price of 696 USD/tCO2 in 2019 nominal values.

3.2 Policy experiments

The objective of this work is to investigate whether different policies or consumers' GP can prompt the transition towards net zero emissions and the related economic and distributional impacts.

We start by assessing the effects of increasing GPs in households (HGP) and all sectors (i.e., households and firms – AGP) consumption choices. Assuming a representative agent setting with a single homogeneous good, the structure of preferences in (12) implies the following price elasticity:

$$\frac{dP}{d\hat{e}}\frac{\hat{e}}{P} = \eta_y \hat{e} \text{ with } y = \{h, f\}, \tag{38}$$

and an optimal abatement level:

$$\eta_y = \nu_O \left[1 + AC(\hat{e})\right]^{-\sigma} MAC(\hat{e}), \tag{39}$$

where ν_O is the initial fossil fuel expenditure over GDP, σ is the elasticity of substitution of the CES production function, while $AC(\hat{e})$ and $MAC(\hat{e})$ are total and marginal abatement costs. Accordingly, we set $\eta_H = \{0.025, 0.050, 0.075, 0.100\}$ in the HGP scenario and $\eta_H = \eta_F = \{0.025, 0.050, 0.075, 0.100\}$ with $F = \{E, C, K\}$ in the AGP experiment, corresponding approximately to a 36%, 56%, 74%, and 91% abatement level, respectively.

At the same time, we explore the role of public policies in stimulating investments to achieve net-zero emissions. In the baseline scenario, we assume a 99% reduction target ($\eta^{CA} = 0.99$) together with a balanced political preference regarding the distribution of the additional revenues/expenditures between taxes and social transfers ($\phi^{CA} = 0.5$).[8] We then investigate the effects of two different policies. On the one hand, we analyze the gradual introduction of a carbon tax (CX) at different speeds $\varepsilon^{CX} = \{0.01, 0.02, 0.03, 0.04\}$, and implying an annual increase in the price of emissions between 11 and 44 USD/tCO_2. On the other hand, we assess the effects of a steady reduction in the maximum level of GHGs through a CaT mechanism by assuming an annual contraction rate between 1% and 4% of initial emissions, namely: $\varepsilon^{CaT} = \{0.01/4, 0.01/3, 0.01/2, 0.01/1\}$.

Lastly, we conclude by investigating the interaction of those policies and preferences with a government subsidy to abatement costs. In particular, we compare the results of four different scenarios characterized by zero ($\lambda^{CA} = 0.0$, AZ), medium ($\lambda^{CA} = 0.5$, AM), high ($\lambda^{CA} = 1.0$, AH), and ultrahigh ($\lambda^{CA} = 1.1$, AU) public support to firms investing in emission reduction. Further, we analyze the obtained results under redistributive (RE, $\phi^{CA} = 1.0$) and laissez-faire (LF, $\phi^{CA} = 0.0$) political preferences. Table 2 provides a summary of the overall experiments.

Table 2: Policy and preference experiments

Label	Policy/Preference	Parameters
HGP	Households Green Preferences	$\eta_H = \{0.025, 0.050, 0.075, 0.100\}$
AGP	All sectors Green Preferences	$\eta_H = \eta_F = \{0.025, 0.050, 0.075, 0.100\}$ with $F = \{E, C, K\}$
CX	Carbon taX	$\varepsilon^{CX} = \{0.01, 0.02, 0.03, 0.04\}$
CaT	Cap-and-Trade	$\varepsilon^{CaT} = \{0.01/4, 0.01/3, 0.01/2, 0.01/1\}$
{AZ, AM, AH, AU}	Abatement subsidy: Zero (AZ), Medium (AM), High (AH), and Ultrahigh (AU)	$\lambda^{CA} = \{0.0, 0.5, 1.0, 1.1\}$
{·, RE, LF}	Political preference: baseline (·), Redistribution (RE), and Laissez-Faire (LF)	$\phi^{CA} = \{0.5, 1.0, 0.0\}$

4 Results and discussion

4.1 Baseline experiments

We begin by assessing the baseline scenarios, i.e., HGP, AGP, CX, and CaT, for different intensities of the policy/preference. Figure 2 depicts the evolution of CO_2 emissions after

[8] This assumption holds in all experiments unless otherwise defined.

2020, the assumed starting year of the experiments. The plots show the value generated from 250 independent Monte Carlo simulations, measured as the percentage difference from a Business-As-Usual (BAU) context, i.e., a reference scenario without environmental extensions.

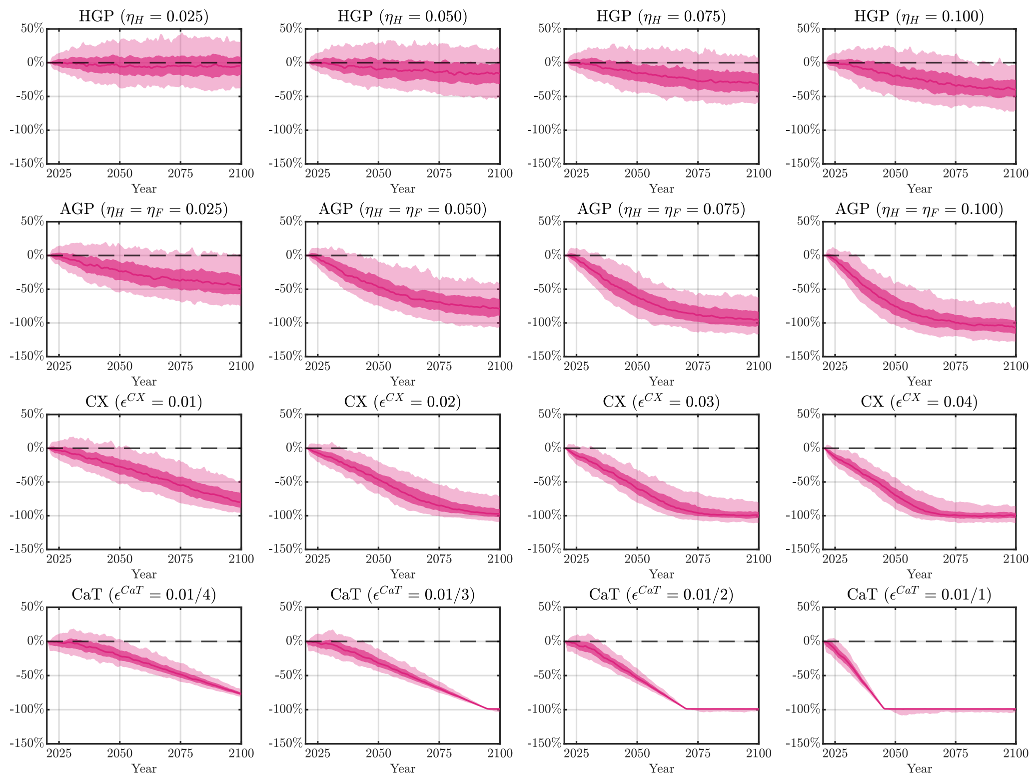

Figure 2: Evolution of national emissions

Note: percentage deviation of national emissions from BAU under different policies/preferences (rows) and policy/preference intensities (columns). Medians (solid lines), 50%, and 90% confidence intervals (shaded areas) computed on 250 independent replicas of the model.

Starting from HGP in the first row, net zero transition is unattainable if the driving force is solely consumer behavior. Indeed, only C-firms react to the change in household GPs (see Figure 3), and even their strongest form (i.e., $\eta_H = 0.100$) slightly impacts national emissions, generating a maximum contraction of only 40% in 2100. Conversely, the picture changes dramatically in the AGP scenario. In this case, as shown in the second row of Figure 2, introducing GPs also in the corporate sector leads to a 50% drop in CO_2 emissions even in the presence of a low pro-environmental attitude ($\eta_H = \eta_F = 0.025$). Moreover, the economy can reach NZE in 2075 if GPs are at their maximum level ($\eta_H = \eta_F = 0.100$). Indeed, given the prominent role of corporates in the overall demand for intermediate inputs, a switch in their purchasing behavior towards less polluting products generates a significant incentive for producers to invest in AbT. As seen in the second row of Figure 3, all sectors contribute to GHG reduction, with the most fossil-intensive firms, i.e., energy companies, drastically

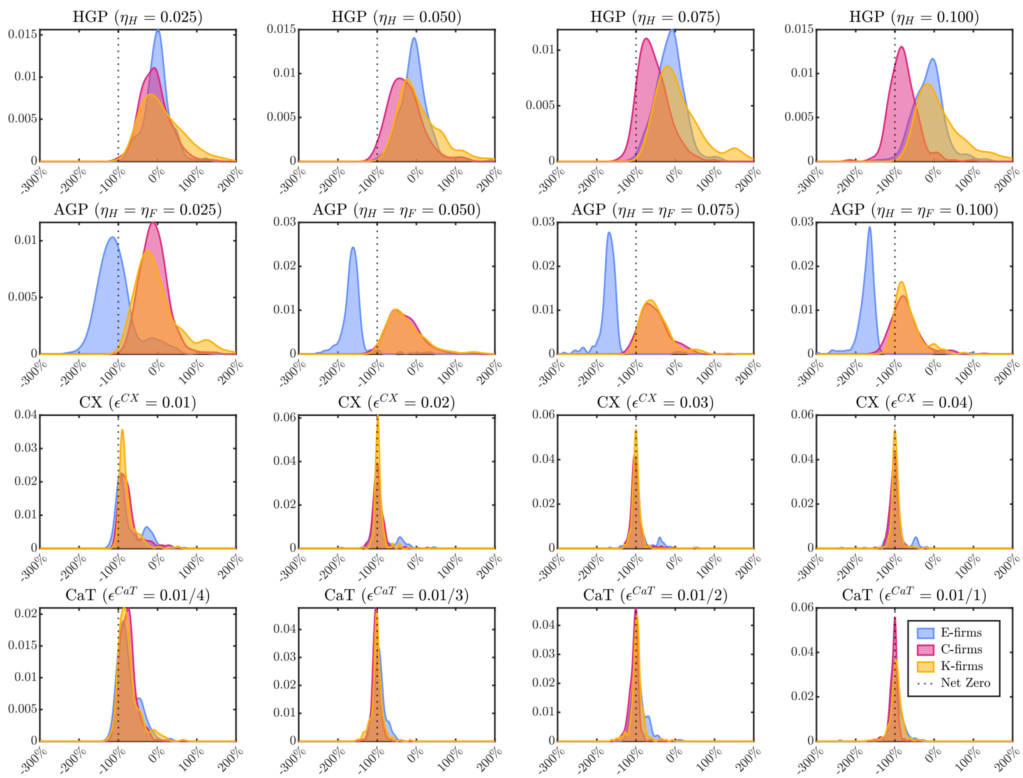

Figure 3: Sectoral emissions in 2100

Note: distribution of sectoral emissions in terms of percentage deviation from BAU by the end of the century under different policies/preferences (rows) and policy/preference intensities (columns). Kernel densities computed on 250 independent replicas of the model.

diminishing their emissions well below the NZE threshold and becoming net absorbers.

Going back to Figure 2, the third row displays the CX scenarios for different adjustment speeds of the tax, while the last row depicts the decline in emissions due to the implementation of a CaT mechanism with increasing reduction rates. Both policies allow the system to reach carbon neutrality by the end of the century, even for low adjustment speeds. Moreover, from Figure 2, it seems that the CaT scheme is more effective from an environmental viewpoint since it steers the system toward NZE more quickly by imposing stricter constraints. Lastly, looking at sectoral effects by 2100 in Figure 3, the two policies are substantially equivalent and, contrary to HGP and AGP, they reduce emissions by the same percentage in all firms.

Table 3 shows the main reference variables in 2050 and 2100. As seen before, the HGP scenario fails to achieve NZE even under the assumption of a very high engagement of final consumers ($\eta_H = 0.100$, with emission reduction equal to -19.1% by 2050 and -38.6% by 2100) but generates negligible economic effects. Conversely, in the AGP experiment with low environmental awareness ($\eta_H = \eta_F = 0.025$), the system already attains a 25% reduction in emissions by 2050, which rises further to 45.2% in 2100. Those results amplify when all agents have strong GPs ($\eta_H = \eta_F = 0.100$), reaching -75.9% in 2050 and -106.9% in 2100.

Table 3: Policy and preference effects in 2050 and 2100

Policy/Agents' preferences		Real GDP		GDP Deflator		Real Wage		National Emissions		Carbon Tax USD/tCO_2		Prob. Econ. Instability
HGP	$\eta_H = 0.025$	−1.2%	−1.5%	5.9%	−2.7%	−0.5%	−0.5%	−7%	−6%	0	0	2%
	$\eta_H = 0.050$	−0.8%	−0.2%	1.5%	−3.3%	−0.7%	−2.1%	−10%	−16%	0	0	4%
	$\eta_H = 0.075$	−1.0%	−1.9%	−2.5%	−5.8%	−0.6%	−2.2%	−16%	−33%	0	0	2%
	$\eta_H = 0.100$	0.2%	−2.3%	−0.6%	−16.5%	−0.8%	−3.0%	−19%	−39%	0	0	1%
AGP	$\eta_H = \eta_F = 0.025$	1.6%	−0.3%	6.7%	25.6%	−1.5%	−3.7%	−24%	−45%	0	0	3%
	$\eta_H = \eta_F = 0.050$	−1.6%	−4.0%	30.3%	81.4%	−3.7%	−9.0%	−47%	−79%	0	0	1%
	$\eta_H = \eta_F = 0.075$	−1.7%	−3.2%	46.4%	100.6%	−5.2%	−11.3%	−62%	−95%	0	0	1%
	$\eta_H = \eta_F = 0.100$	−1.8%	−5.5%	58.9%	82.5%	−6.4%	−12.4%	−76%	−107%	0	0	3%
CX	$\epsilon^{CX} = 0.01$	−1.9%	−3.7%	20.4%	13.6%	−5.6%	−9.1%	−27%	−81%	343	919	3%
	$\epsilon^{CX} = 0.02$	−3.0%	−2.3%	32.4%	13.6%	−8.7%	−10.4%	−47%	−97%	685	1,572	4%
	$\epsilon^{CX} = 0.03$	−5.0%	−3.6%	27.0%	13.4%	−10.8%	−9.8%	−61%	−99%	1,028	1,650	4%
	$\epsilon^{CX} = 0.04$	−3.4%	−6.5%	26.9%	13.4%	−11.4%	−10.4%	−70%	−100%	1,371	1,578	6%
CaT	$\epsilon^{CaT} = 0.01/4$	−1.4%	−6.4%	13.9%	11.1%	−1.5%	−4.7%	−21%	−77%	183	895	4%
	$\epsilon^{CaT} = 0.01/3$	−1.7%	−6.3%	15.4%	3.7%	−2.7%	−6.1%	−32%	−99%	358	1,687	6%
	$\epsilon^{CaT} = 0.01/2$	−4.5%	−5.8%	12.5%	7.6%	−4.1%	−3.7%	−54%	−99%	900	1,242	8%
	$\epsilon^{CaT} = 0.01/1$	−14.3%	−3.4%	−27.2%	−25.3%	0.2%	0.1%	−99%	−99%	2,271	1,044	35%

Note: deviation of selected variables from BAU in 2050 (white columns) and 2100 (shaded columns) under different policies/agents' preferences. Median values computed on 250 independent replicas of the model.

Nevertheless, this complete transition to net zero is associated with a 5.5% fall in real GDP and an 82.5% increase in the GDP deflator. Indeed, by investing in AbT, companies must sustain higher production costs, translating into higher prices and lower sales. Moreover, the resulting growth in the cost of living significantly affects workers, whose real wages fall by up to 12.4% in the worst-case scenario.

Analyzing now the CX experiment, while it is highly efficient in transitioning the economy toward NZE, it requires a very high value of the carbon tax (around 1,600 USD/tCO_2). On the one hand, the chosen functional form of the MAC curve implies higher costs than in previous versions (Nordhaus, 2008; Clarke et al., 2009; Ackerman and Bueno, 2011). On the other hand, the endogenous learning mechanism, by reflecting potential limits in corporates' adoption speed of new technology and slowing down investments in AbT, requires the government to act aggressively to stimulate firms to reduce emissions. As in the AGP scenario, the resulting increase in production costs raises prices (+13%), thus lowering real GDP (−6.5%) and wages (−10.0%).

Lastly, the CaT scenario produces environmental and economic dynamics similar to the CX for low and medium adjustment speeds ($\epsilon^{CaT} = 0.01/4$ and $\epsilon^{CaT} = 0.01/3$). Conversely, if the policymaker decides to reduce emissions faster ($\epsilon^{CaT} = 0.01/2$ and $\epsilon^{CaT} = 0.01/1$), the system experiences a minor reduction in real wages, accompanied by a lower inflationary pressure (see Table 3, last rows). Indeed, by imposing a rigid constraint on the maximum quantity of emissions, the CaT mechanism strictly limits the purchase of fossil fuel by firms not investing in AbT. As a result, a too-fast reduction in the permitted level of GHGs, by not giving companies sufficient time to adopt less polluting technology, pushes corporates to replace fossil fuel with other production factors like labor. While that prevents the shrinkage of real wages observed in the other scenarios, the imperfect substitutability between those inputs generates higher economic instability (Table 3, last column) because of the unavoidable production limits it introduces in the short term and, as a result, lower inflation.[9]

[9] We define the probability of economic instability as the percentage of simulations in which public debt exceeds 500% of nominal GDP.

4.2 Abatement subsidies

In the previous section, we show that the system can reach NZE by the end of the century by either implementing stringent policies (CX or CaT) or through a very strong (and possibly irrealistic) pro-environmental attitude of all agents (AGP). Moreover, the transition to a low-carbon economy comes with significant costs. For this reason, we now investigate the interaction of those policies/preferences with a government subsidy to abatement costs. The idea is to see if it can limit the negative consequences of the energy transition or increase its speed. In particular, we compare the results of four different scenarios characterized by zero ($\lambda^{CA} = 0.0$, AZ), medium ($\lambda^{CA} = 0.5$, AM), high ($\lambda^{CA} = 1.0$, AH), and ultrahigh ($\lambda^{CA} = 1.1$, AU) public support to firms investing in AbT.

Table 4 shows that the economy can reach NZE by the end of the century also in the case of medium/high HGPs if the government strongly subsides investments in emission abatement (i.e., $\eta_H = 0.075$ and $\eta_H = 0.100$ with AH and AU). Moreover, while easing the financial constraints of firms, the additional public expenditure stimulates aggregate demand, thus increasing production (Table 5), prices (Table 6), and labor demand, with a consequent growth in real wages (Table 7). Similarly, subsidies anticipate the achievement time of the NZE target in the AGP scenario, reaching this objective around the middle of the century even for low and medium GPs when the subsidy is at its maximum (Table 4, $\eta_H = \eta_F = 0.025$ and $\eta_H = \eta_F = 0.050$ with AU). At the same time, the system does not reach zero emissions by 2100 only for low levels of public engagement and political effort (Table 4, $\eta_H = \eta_F = 0.025$ and $\eta_H = \eta_F = 0.050$ with AZ). Lastly, subsidies increase aggregate demand, production (Table 5), prices (Table 6), and real wages (Table 7) as in the HGP experiment.

Table 4: NZE year

Policy/Agents' preferences		Abatement subsidy			
		AZ	AM	AH	AU
HGP	$\eta_H = 0.025$	2100*	2100*	2100*	2100*
	$\eta_H = 0.050$	2100*	2100*	2100*	2090
	$\eta_H = 0.075$	2100*	2100*	2093	2081
	$\eta_H = 0.100$	2100*	2100*	2081	2073
AGP	$\eta_H = \eta_F = 0.025$	2100*	2100*	2078	2068
	$\eta_H = \eta_F = 0.050$	2100*	2078	2057	2055
	$\eta_H = \eta_F = 0.075$	2078	2062	2052	2050
	$\eta_H = \eta_F = 0.100$	2063	2055	2047	2046
CX	$\epsilon^{CX} = 0.01$	2100*	2100*	2078	2074
	$\epsilon^{CX} = 0.02$	2088	2079	2067	2064
	$\epsilon^{CX} = 0.03$	2075	2069	2060	2059
	$\epsilon^{CX} = 0.04$	2066	2062	2057	2055
CaT	$\epsilon^{CaT} = 0.01/4$	2100*	2100*	2100*	2100*
	$\epsilon^{CaT} = 0.01/3$	2097	2096	2094	2089
	$\epsilon^{CaT} = 0.01/2$	2073	2073	2070	2070
	$\epsilon^{CaT} = 0.01/1$	2049	2049	2048	2048

Table 5: Real GDP

Policy/Agents' preferences		Abatement subsidy			
		AZ	AM	AH	AU
HGP	$\eta_H = 0.025$	−1.5%	0.3%	1.9%	0.6%
	$\eta_H = 0.050$	−0.2%	−2.4%	−0.1%	0.6%
	$\eta_H = 0.075$	−1.9%	1.4%	0.2%	2.3%
	$\eta_H = 0.100$	−2.3%	−0.8%	2.3%	−0.5%
AGP	$\eta_H = \eta_F = 0.025$	−0.3%	0.5%	0.7%	−0.2%
	$\eta_H = \eta_F = 0.050$	−4.0%	−0.4%	−1.1%	1.1%
	$\eta_H = \eta_F = 0.075$	−3.2%	0.0%	2.1%	−1.4%
	$\eta_H = \eta_F = 0.100$	−5.5%	−3.5%	−0.4%	1.4%
CX	$\epsilon^{CX} = 0.01$	−3.7%	2.5%	0.9%	0.7%
	$\epsilon^{CX} = 0.02$	−2.3%	1.2%	0.5%	2.6%
	$\epsilon^{CX} = 0.03$	−3.6%	0.9%	0.5%	−2.8%
	$\epsilon^{CX} = 0.04$	−6.5%	0.0%	−1.9%	−1.5%
CaT	$\epsilon^{CaT} = 0.01/4$	−6.4%	−1.8%	−1.7%	0.8%
	$\epsilon^{CaT} = 0.01/3$	−6.3%	−1.9%	−0.5%	−1.0%
	$\epsilon^{CaT} = 0.01/2$	−5.8%	−1.7%	−2.1%	−3.1%
	$\epsilon^{CaT} = 0.01/1$	−3.4%	4.4%	1.7%	3.9%

Note: year of NZE achievement (left table) and percentage deviation of real GDP from BAU by the end of the century (left table) for different policies/agents' preferences (rows) and abatement subsidy levels (columns). Median values computed on 250 independent replicas of the model. Year 2100* indicates NZE after the end of the century.

The two environmental policies CX and CaT have comparable dynamics in terms of convergence speed to the NZE target, real wages, and carbon tax levels (see Tables 4, 7, and 8) but have different impacts on real GDP and inflation (see Tables 5 and 6). In most cases, the year of NZE achievement is before 2100 for both policies, but abatement subsidies lead to early attainment of the zero emissions target only in the CX scenario (Table 4). Further, the carbon tax decreases with the share of abatement costs covered by the public sector since, as expected, the two policies are complementary (Table 8). Lastly, while real wages grow with government expenditure in both experiments (Table 7), the CX scenario differs from the CaT policy in terms of aggregate dynamics (Tables 5 and 6). Indeed, the former follows HGP and AGP, with subsidies increasing aggregate demand and prices. On the contrary, the production constraints imposed by the CaT mechanism also hold in the presence of subsidies to abatement costs, thus limiting the extent of the additional public expenditure.

Table 6: GDP deflator

Policy/Agents' preferences		Abatement subsidy			
		AZ	AM	AH	AU
HGP	$\eta_H = 0.025$	−2.7%	−0.8%	3.7%	14.0%
	$\eta_H = 0.050$	−3.3%	−10.2%	18.9%	17.1%
	$\eta_H = 0.075$	−5.8%	2.5%	22.3%	23.4%
	$\eta_H = 0.100$	−16.5%	−0.5%	21.1%	33.7%
AGP	$\eta_H = \eta_F = 0.025$	25.6%	24.7%	36.8%	23.4%
	$\eta_H = \eta_F = 0.050$	81.4%	61.0%	70.0%	69.2%
	$\eta_H = \eta_F = 0.075$	100.6%	64.3%	91.5%	73.1%
	$\eta_H = \eta_F = 0.100$	82.5%	76.2%	93.4%	71.1%
CX	$\epsilon^{CX} = 0.01$	13.6%	11.3%	22.1%	20.9%
	$\epsilon^{CX} = 0.02$	13.6%	−1.6%	22.9%	20.1%
	$\epsilon^{CX} = 0.03$	13.4%	0.9%	27.8%	27.9%
	$\epsilon^{CX} = 0.04$	13.4%	18.1%	35.9%	28.1%
CaT	$\epsilon^{CaT} = 0.01/4$	11.1%	2.1%	3.2%	−2.8%
	$\epsilon^{CaT} = 0.01/3$	3.7%	11.9%	1.8%	11.4%
	$\epsilon^{CaT} = 0.01/2$	7.6%	2.7%	11.0%	14.8%
	$\epsilon^{CaT} = 0.01/1$	−25.3%	−23.7%	−4.3%	−6.3%

Table 7: Real wage

Policy/Agents' preferences		Abatement subsidy			
		AZ	AM	AH	AU
HGP	$\eta_H = 0.025$	−0.5%	−0.7%	0.0%	1.3%
	$\eta_H = 0.050$	−2.1%	−0.7%	0.4%	1.3%
	$\eta_H = 0.075$	−2.2%	−1.9%	0.4%	2.3%
	$\eta_H = 0.100$	−3.0%	−2.9%	0.5%	3.2%
AGP	$\eta_H = \eta_F = 0.025$	−3.7%	−3.8%	1.5%	4.2%
	$\eta_H = \eta_F = 0.050$	−9.0%	−6.0%	2.7%	4.9%
	$\eta_H = \eta_F = 0.075$	−11.3%	−7.6%	2.4%	4.7%
	$\eta_H = \eta_F = 0.100$	−12.4%	−8.3%	2.0%	4.4%
CX	$\epsilon^{CX} = 0.01$	−9.1%	−6.6%	−1.5%	0.3%
	$\epsilon^{CX} = 0.02$	−10.4%	−6.5%	−0.6%	2.0%
	$\epsilon^{CX} = 0.03$	−9.8%	−6.9%	0.5%	3.3%
	$\epsilon^{CX} = 0.04$	−10.4%	−6.0%	0.4%	4.3%
CaT	$\epsilon^{CaT} = 0.01/4$	−4.7%	−3.8%	0.2%	0.6%
	$\epsilon^{CaT} = 0.01/3$	−6.1%	−2.9%	−0.8%	1.0%
	$\epsilon^{CaT} = 0.01/2$	−3.7%	−0.7%	3.5%	4.8%
	$\epsilon^{CaT} = 0.01/1$	0.1%	3.4%	5.6%	8.9%

Note: percentage deviation of GDP deflator (left table) and real wage (right table) from BAU by the end of the century for different policies/agents' preferences (rows) and abatement subsidy levels (columns). Median values computed on 250 independent replicas of the model.

Table 8: Carbon tax

Policy/Agents' preferences		Abatement subsidy			
		AZ	AM	AH	AU
HGP	$\eta_H = 0.025$	0	0	0	0
	$\eta_H = 0.050$	0	0	0	0
	$\eta_H = 0.075$	0	0	0	0
	$\eta_H = 0.100$	0	0	0	0
AGP	$\eta_H = \eta_F = 0.025$	0	0	0	0
	$\eta_H = \eta_F = 0.050$	0	0	0	0
	$\eta_H = \eta_F = 0.075$	0	0	0	0
	$\eta_H = \eta_F = 0.100$	0	0	0	0
CX	$\epsilon^{CX} = 0.01$	919	919	475	343
	$\epsilon^{CX} = 0.02$	1,572	1,077	328	190
	$\epsilon^{CX} = 0.03$	1,650	924	95	0
	$\epsilon^{CX} = 0.04$	1,578	841	0	0
CaT	$\epsilon^{CaT} = 0.01/4$	895	697	151	0
	$\epsilon^{CaT} = 0.01/3$	1,687	852	0	0
	$\epsilon^{CaT} = 0.01/2$	1,242	585	0	0
	$\epsilon^{CaT} = 0.01/1$	1,044	398	0	0

Table 9: National emissions

Policy/Agents' preferences		Abatement subsidy			
		AZ	AM	AH	AU
HGP	$\eta_H = 0.025$	−6%	−11%	−38%	−71%
	$\eta_H = 0.050$	−16%	−31%	−76%	−116%
	$\eta_H = 0.075$	−33%	−43%	−95%	−142%
	$\eta_H = 0.100$	−39%	−57%	−118%	−159%
AGP	$\eta_H = \eta_F = 0.025$	−45%	−60%	−122%	−169%
	$\eta_H = \eta_F = 0.050$	−79%	−100%	−183%	−224%
	$\eta_H = \eta_F = 0.075$	−95%	−118%	−206%	−251%
	$\eta_H = \eta_F = 0.100$	−107%	−135%	−213%	−266%
CX	$\epsilon^{CX} = 0.01$	−81%	−91%	−126%	−167%
	$\epsilon^{CX} = 0.02$	−97%	−102%	−136%	−193%
	$\epsilon^{CX} = 0.03$	−99%	−101%	−140%	−201%
	$\epsilon^{CX} = 0.04$	−100%	−102%	−143%	−201%
CaT	$\epsilon^{CaT} = 0.01/4$	−77%	−76%	−75%	−79%
	$\epsilon^{CaT} = 0.01/3$	−99%	−99%	−108%	−127%
	$\epsilon^{CaT} = 0.01/2$	−99%	−99%	−123%	−171%
	$\epsilon^{CaT} = 0.01/1$	−99%	−99%	−130%	−217%

Note: carbon tax in 2019 USD/tCO_2 (left table) and percentage deviation of national emissions from BAU (right table) by the end of the century for different policies/agents' preferences (rows) and abatement subsidy levels (columns). Median values computed on 250 independent replicas of the model.

Finally, looking at the distributive consequences of the policies, it seems they come with a cost in most cases (Figure 4). While zero or medium abatement subsidies (AZ and AM) produce a negligible or, at maximum, slightly redistributive impact on workers' net worth, high levels of public support for firms investing in emission reduction (AH and AU) always have strong regressive effects. Indeed, public expenditure, by promoting investments in AbT and causing an extraordinary contraction in CO_2 emissions (Table 9), boosts abatement rents, which are then distributed to households depending on their net worth. That, together with the parallel increase in the cost of living (Table 6), raises inequality among workers, with the wealthier 50% of the population gaining at the expense of the poorer 50%. The only exception is the CaT mechanism (Figure 4, last row) that limits the negative consequences of the policy on the poorest workers by boosting aggregate labor demand.

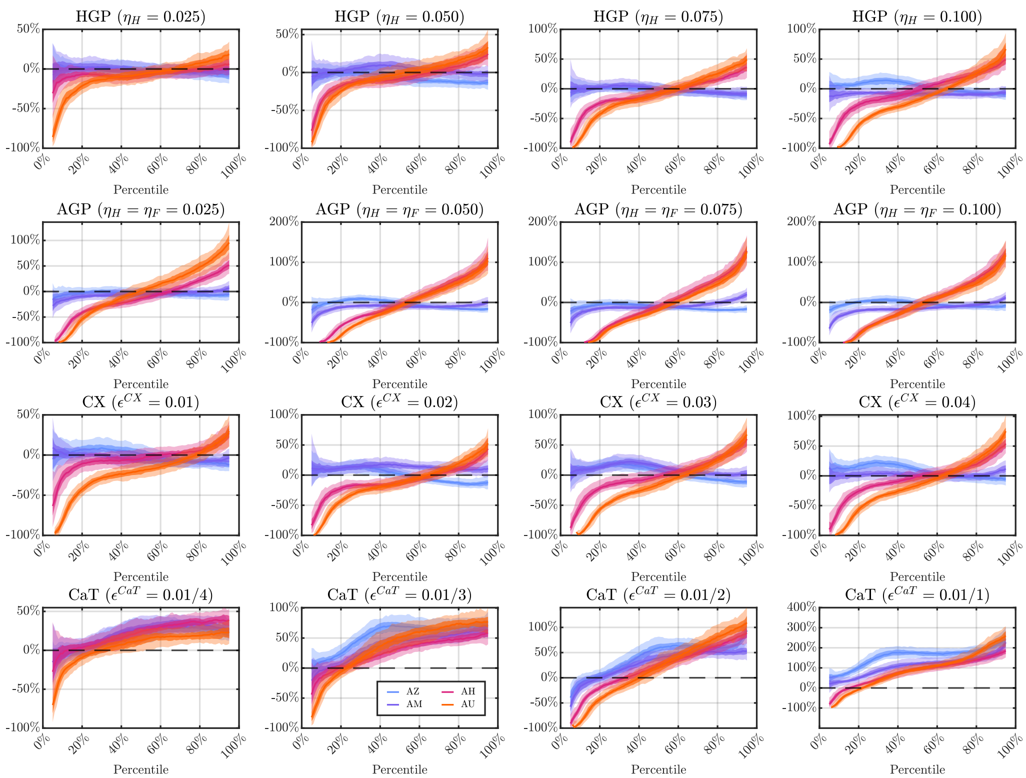

Figure 4: Shift in workers' net worth distribution

Note: percentage change in workers' real net worth from BAU for different distribution percentiles under different policies/preferences (rows), policy/preference intensities (columns), and abatement subsidy levels (colors). Medians (solid lines), 50%, and 90% confidence intervals (shaded areas) computed on 250 independent replicas of the model.

Conversely, the distributional consequences of subsidies on firms' net worth are less pronounced (Figure B.1 in Appendix A.3, HGP, AGP, and CX scenarios). Indeed, zero or medium public support for companies reducing emissions (AZ and AM) has an effect similar to that of workers (i.e., negligible or slightly redistributive), while high levels of abatement subsidy (AZ and AM) reduce firms' equity evenly. Lastly, in line with the previous analysis, by limiting the purchase of fossil fuel and constraining the production possibility of corporates, the CaT mechanism hurts companies profits, with smaller enterprises bearing most of the costs (Figure B.1 in Appendix A.3, last row).

4.3 Political preferences

Until now, we have assumed that the government evenly distributes the additional revenues or expenditures related to climate policies between social transfers and taxation reduction (i.e., $\phi^{CA} = 0.5$). In this section, we explore the economic and distributional effects of the energy transition under two extreme political preferences. On the one hand, we investigate a situation in which the policy-maker favors increasing social transfers over tax reductions (RE, with $\phi^{CA} = 1$). In this case, it raises taxes when needing additional resources to subsidize AbT costs (i.e., when $f_t^{CA} < 0$) and transfers green budget surpluses to low-income families when available (i.e., when $f_t^{CA} > 0$). On the other hand, we assume a political class that prefers tax cuts over raising social spending (LF, with $\phi^{CA} = 0$). In other words, the government employs the net additional revenues from climate policy to reduce taxes first (i.e., when $f_t^{CA} > 0$) or diminishes transfers to low-income families when needing supplementary budgetary resources (i.e., when $f_t^{CA} < 0$). Lastly, we limit the testing of those two scenarios only to zero and 100% AbT subsidies (AZ and AH) as sufficiently representative of the policy experiments analyzed above.

While political preferences do not seem to affect environmental and economic dynamics in the absence of abatement subsidies (RE–AZ and LF–AZ), introducing public support for firms investing in AbT reduces the time required for the system to reach the NZE target (Table 10), diminishes total CO_2 emissions (Table 11) and limits the economic costs of the energy transition (Tables 12 and 13) in both scenarios (RE–AH and LF–AH). Nevertheless, favoring tax cuts over social spending produces better economic performances, with real wages always above the BAU scenario when the government subsidizes abatement costs (LF–AH). Indeed, the combined effect of tax cuts and additional public expenditure boosts aggregate demand, thus raising production, labor demand, and inflation (see Tables 12, 13, and 14, last column). At the same time, increasing social expenditure at the cost of higher tax rates generates lower incentives to expand production in the presence of AbT subsidies (RE–AH) but avoids inflationary spirals (see Tables 12 and 14, second column). However, that comes at the price of higher instability in private and public finances (Table 15, first and second columns).

Table 10: Net-zero year

Policy/Agents' preferences		Policy combination			
		RE – AZ	RE – AH	LF – AZ	LF – AH
HGP	$\eta_H = 0.025$	2100*	2100*	2100*	2100*
	$\eta_H = 0.050$	2100*	2100*	2100*	2100*
	$\eta_H = 0.075$	2100*	2091	2100*	2088
	$\eta_H = 0.100$	2100*	2084	2100*	2084
AGP	$\eta_H = \eta_F = 0.025$	2100*	2076	2100*	2077
	$\eta_H = \eta_F = 0.050$	2100*	2058	2100*	2059
	$\eta_H = \eta_F = 0.075$	2078	2052	2078	2052
	$\eta_H = \eta_F = 0.100$	2063	2048	2062	2048
CX	$\epsilon^{CX} = 0.01$	2100*	2079	2100*	2080
	$\epsilon^{CX} = 0.02$	2086	2068	2089	2068
	$\epsilon^{CX} = 0.03$	2074	2061	2073	2060
	$\epsilon^{CX} = 0.04$	2067	2057	2066	2057
CaT	$\epsilon^{CaT} = 0.01/4$	2100*	2100*	2100*	2100*
	$\epsilon^{CaT} = 0.01/3$	2097	2094	2097	2094
	$\epsilon^{CaT} = 0.01/2$	2073	2070	2073	2071
	$\epsilon^{CaT} = 0.01/1$	2049	2048	2049	2048

Table 11: National emissions

Policy/Agents' preferences		Policy combination			
		RE – AZ	RE – AH	LF – AZ	LF – AH
HGP	$\eta_H = 0.025$	−4.9%	−31.0%	−6.3%	−31.1%
	$\eta_H = 0.050$	−16.4%	−77.4%	−16.8%	−82.0%
	$\eta_H = 0.075$	−32.8%	−100.0%	−33.6%	−103.5%
	$\eta_H = 0.100$	−39.1%	−114.4%	−37.6%	−121.0%
AGP	$\eta_H = \eta_F = 0.025$	−45.2%	−124.5%	−45.3%	−121.6%
	$\eta_H = \eta_F = 0.050$	−78.7%	−179.8%	−78.8%	−183.2%
	$\eta_H = \eta_F = 0.075$	−95.4%	−203.1%	−94.8%	−212.6%
	$\eta_H = \eta_F = 0.100$	−106.9%	−215.6%	−106.9%	−221.2%
CX	$\epsilon^{CX} = 0.01$	−79.0%	−125.2%	−78.4%	−125.6%
	$\epsilon^{CX} = 0.02$	−97.5%	−138.6%	−96.9%	−137.5%
	$\epsilon^{CX} = 0.03$	−99.0%	−143.3%	−99.9%	−143.0%
	$\epsilon^{CX} = 0.04$	−99.9%	−143.0%	−99.3%	−147.4%
CaT	$\epsilon^{CaT} = 0.01/4$	−77.2%	−74.5%	−77.3%	−74.5%
	$\epsilon^{CaT} = 0.01/3$	−98.9%	−107.2%	−98.9%	−108.0%
	$\epsilon^{CaT} = 0.01/2$	−98.9%	−121.3%	−98.9%	−123.6%
	$\epsilon^{CaT} = 0.01/1$	−98.9%	−129.3%	−98.9%	−133.0%

Note: year of NZE achievement (left table) and percentage deviation of national emissions from BAU by the end of the century (right table) for different policies/agents' preferences (rows) and policy combinations (columns). Median values computed on 250 independent replicas of the model.

These aggregate dynamics are partially mitigated by a redistribution of net worth among families towards the poorer percentiles. Figure 5 shows that employing the additional funds from climate policy to finance social expenditure significantly reduces workers inequality (RE–AZ vs LF–AZ) or limits the regressive effects of AbT subsidies (RE–AZ vs LF–AZ). Moreover, also firms seem to benefit from this political choice, with a lower contraction in

Table 12: Real GDP

Policy/Agents' preferences		Policy combination			
		RE – AZ	RE – AH	LF – AZ	LF – AH
HGP	$\eta_H = 0.025$	−1.6%	1.9%	−1.5%	4.1%
	$\eta_H = 0.050$	−0.2%	0.6%	−0.2%	3.4%
	$\eta_H = 0.075$	−2.2%	0.4%	−2.6%	3.5%
	$\eta_H = 0.100$	−2.5%	−0.4%	−2.1%	1.6%
AGP	$\eta_H = \eta_F = 0.025$	−0.5%	0.2%	−0.6%	0.6%
	$\eta_H = \eta_F = 0.050$	−4.0%	−1.2%	−4.0%	2.3%
	$\eta_H = \eta_F = 0.075$	−3.6%	0.0%	−3.6%	1.9%
	$\eta_H = \eta_F = 0.100$	−6.0%	−3.4%	−5.6%	3.0%
CX	$\epsilon^{CX} = 0.01$	−3.9%	0.7%	−3.6%	4.6%
	$\epsilon^{CX} = 0.02$	−3.2%	2.9%	−4.4%	0.5%
	$\epsilon^{CX} = 0.03$	−3.3%	0.6%	−3.3%	3.4%
	$\epsilon^{CX} = 0.04$	−4.8%	2.3%	−1.0%	3.6%
CaT	$\epsilon^{CaT} = 0.01/4$	−5.7%	1.7%	−5.4%	−1.2%
	$\epsilon^{CaT} = 0.01/3$	−8.7%	−3.3%	−5.8%	−1.8%
	$\epsilon^{CaT} = 0.01/2$	−5.1%	−2.9%	−5.2%	0.4%
	$\epsilon^{CaT} = 0.01/1$	−5.4%	1.6%	−7.4%	3.0%

Table 13: Real wage

Policy/Agents' preferences		Policy combination			
		RE – AZ	RE – AH	LF – AZ	LF – AH
HGP	$\eta_H = 0.025$	−0.7%	−0.6%	−0.4%	0.1%
	$\eta_H = 0.050$	−2.1%	−0.2%	−2.0%	1.6%
	$\eta_H = 0.075$	−2.2%	−1.7%	−2.2%	2.2%
	$\eta_H = 0.100$	−2.9%	−1.1%	−2.9%	1.5%
AGP	$\eta_H = \eta_F = 0.025$	−3.8%	−1.9%	−3.7%	2.8%
	$\eta_H = \eta_F = 0.050$	−8.7%	−1.9%	−8.6%	1.7%
	$\eta_H = \eta_F = 0.075$	−11.3%	−3.2%	−11.3%	2.3%
	$\eta_H = \eta_F = 0.100$	−12.4%	−4.4%	−12.4%	1.0%
CX	$\epsilon^{CX} = 0.01$	−10.2%	−3.5%	−8.9%	−0.6%
	$\epsilon^{CX} = 0.02$	−10.9%	−3.1%	−10.1%	1.1%
	$\epsilon^{CX} = 0.03$	−11.9%	−2.9%	−9.0%	2.6%
	$\epsilon^{CX} = 0.04$	−11.9%	−3.4%	−9.2%	1.3%
CaT	$\epsilon^{CaT} = 0.01/4$	−6.1%	−1.7%	−4.4%	−0.2%
	$\epsilon^{CaT} = 0.01/3$	−8.7%	−1.8%	−7.6%	0.0%
	$\epsilon^{CaT} = 0.01/2$	−2.8%	1.4%	−2.5%	3.8%
	$\epsilon^{CaT} = 0.01/1$	0.8%	5.1%	−0.5%	6.5%

Note: percentage deviation of real GDP (left table) and real wage (right table) from BAU by the end of the century for different policies/agents' preferences (rows) and policy combinations (columns). Median values computed on 250 independent replicas of the model.

Table 14: GDP deflator

Policy/Agents' preferences		Policy combination			
		RE – AZ	RE – AH	LF – AZ	LF – AH
HGP	$\eta_H = 0.025$	−1.5%	−5.0%	−0.5%	13.1%
	$\eta_H = 0.050$	−3.3%	−5.5%	1.1%	33.1%
	$\eta_H = 0.075$	−6.1%	−10.5%	−2.6%	46.6%
	$\eta_H = 0.100$	−16.4%	−6.7%	−16.2%	41.0%
AGP	$\eta_H = \eta_F = 0.025$	25.6%	5.6%	28.3%	87.3%
	$\eta_H = \eta_F = 0.050$	81.4%	−2.2%	81.7%	100.9%
	$\eta_H = \eta_F = 0.075$	100.5%	−11.0%	101.5%	111.7%
	$\eta_H = \eta_F = 0.100$	82.5%	−16.1%	87.5%	123.4%
CX	$\epsilon^{CX} = 0.01$	3.1%	−10.5%	28.0%	46.5%
	$\epsilon^{CX} = 0.02$	−3.8%	−14.0%	20.8%	58.5%
	$\epsilon^{CX} = 0.03$	−12.5%	−16.3%	32.0%	76.6%
	$\epsilon^{CX} = 0.04$	−16.0%	−9.1%	27.2%	65.3%
CaT	$\epsilon^{CaT} = 0.01/4$	5.0%	−3.2%	3.7%	7.1%
	$\epsilon^{CaT} = 0.01/3$	15.5%	−8.1%	13.8%	35.5%
	$\epsilon^{CaT} = 0.01/2$	22.8%	−13.2%	3.7%	44.5%
	$\epsilon^{CaT} = 0.01/1$	−26.7%	−33.7%	−20.0%	21.0%

Table 15: Prob. of econ. instability

Policy/Agents' preferences		Policy combination			
		RE – AZ	RE – AH	LF – AZ	LF – AH
HGP	$\eta_H = 0.025$	2%	2%	2%	2%
	$\eta_H = 0.050$	5%	3%	5%	2%
	$\eta_H = 0.075$	2%	2%	2%	3%
	$\eta_H = 0.100$	1%	2%	2%	1%
AGP	$\eta_H = \eta_F = 0.025$	3%	2%	3%	2%
	$\eta_H = \eta_F = 0.050$	1%	3%	1%	2%
	$\eta_H = \eta_F = 0.075$	1%	2%	1%	2%
	$\eta_H = \eta_F = 0.100$	3%	4%	3%	1%
CX	$\epsilon^{CX} = 0.01$	12%	6%	2%	2%
	$\epsilon^{CX} = 0.02$	15%	8%	2%	2%
	$\epsilon^{CX} = 0.03$	20%	8%	2%	2%
	$\epsilon^{CX} = 0.04$	24%	7%	2%	2%
CaT	$\epsilon^{CaT} = 0.01/4$	5%	6%	2%	2%
	$\epsilon^{CaT} = 0.01/3$	14%	15%	4%	14%
	$\epsilon^{CaT} = 0.01/2$	19%	22%	2%	16%
	$\epsilon^{CaT} = 0.01/1$	42%	32%	29%	26%

Note: percentage deviation of GDP deflator from BAU (left table) and probability of economic instability (right table) by the end of the century for different policies/agents' preferences (rows) and policy combinations (columns). Median values computed on 250 independent replicas of the model.

their real net worth in the presence of public support to CO_2 reduction (RE–AZ vs LF–AZ, see Figure B.2 in Appendix A.3).

5 Concluding remarks

In this study, we investigate the impact of GPs on the transition towards a NZE economy and compare it with different climate policies. To accomplish this, we enhance the integrated assessment MATRIX model (Ciola et al., 2023; Turco et al., 2023; Bazzana et al., 2023) by modifying consumers' preference structure to incorporate goods' implicit emissions. Further, we extend this pro-environmental behavior to firms in the model. Through simulations, we analyze the evolution of the economy under different levels of green attitudes and examine the outcomes against scenarios with different climate policies. Specifically, we consider a carbon tax with varying adjustment speeds and a Cap-and-Trade mechanism with different emissions reduction targets. We compare the scenarios evaluating the degree of emissions reduction in 2050 and 2100, the average percentage variation of real GDP, real wages, and

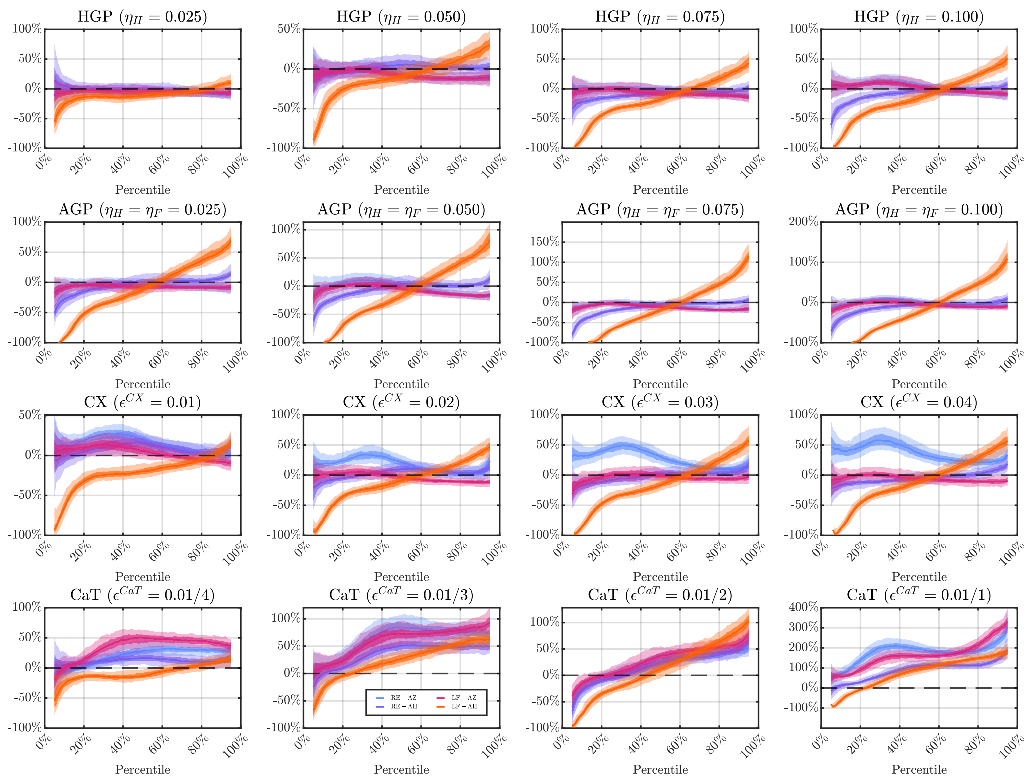

Figure 5: Shift in workers' net worth distribution

Note: percentage change in workers' real net worth from BAU for different distribution percentiles under different policies/preferences (rows), policy/preference intensities (columns), and policy combinations (colors). Medians (solid lines), 50%, and 90% confidence intervals (shaded areas) computed on 250 independent replicas of the model.

GDP deflator from a reference BAU scenario, and the probability of economic instability. For each experiment, we also consider the sectoral variation in emission intensities and analyze the distributive impacts in households' and firms' net worth. Lastly, we explore the combined effects of original policies with an abatement subsidy, also considering possible interactions with varied political preferences.

If no policy is in effect, the economy cannot achieve NZE solely through household GPs. Indeed, final consumers represent only a small fraction of total purchases in energy and capital goods markets and do not generate sufficient incentives for firms operating in those sectors to invest in less polluting technology. Accordingly, when also companies internalize GPs, thus preferring goods and services with a lower environmental impact, CO_2 emissions decrease significantly. In particular, when both households and firms exhibit the highest level of GPs, reaching a net-zero scenario becomes attainable by 2075. Lastly, both the carbon tax and the CaT mechanisms can achieve net-zero emissions if the adjustment speed is sufficiently high.

When examining the effects on macroeconomic variables, all scenarios display a decrease in real GDP, an increase in the GDP deflator, and a reduction in real wages. Moreover, the CaT policy appears to magnify those effects due to its inherent rigidity. The cause of the economic downturn stems from firms passing additional abatement costs to consumers, thus decreasing their total sales and income. High subsidy levels can make NZE achievable even with a moderate level of environmental awareness and can mitigate real GDP losses for certain carbon tax levels. However, this approach raises distributional concerns, as the average real wage increases at the expense of redistributing wealth away from lower-income households. Such issues can be mitigated by implementing an intermediate subsidy level or preferring social transfers over taxation when allocating additional revenues/expenditures from climate policies. Nevertheless, while the latter also benefits firms in the lower percentiles of net worth, it can undermine the stability of public finances.

This study highlights several limitations that can be addressed in future research endeavors. Firstly, the evaluation of emission reductions is conducted within a single national unit, thereby failing to account for feedback from global climate change and local climate damages that could impact the economy. Secondly, the GPs in this study are treated as exogenous variables to establish well-defined scenarios. However, they could be further explored and endogenized by incorporating insights from the literature on opinion dynamics. Thirdly and lastly, the study represents the reduction in emissions through a generalized abatement sector. Future studies may consider substituting this approach with endogenous technological progress and more explicit green sectors focused on renewable energy production.

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A Appendix

A.1 Households input demand

Households $h = 1, \dots, \mathcal{N}^H$ derive their utility from the consumption of final goods, capital, and energy services – denoted with $J_h = \{C, K, E\}$ hereafter – given the sequence of expected prices $\{\{\mathbb{E}_{h,t}[P_{j,t+s}]\}_{j \in J_h}\}_{s=0}^{\infty}$, risk-free interest rate $\{\mathbb{E}_{h,t}[i_{t+s}^{CB}]\}_{s=0}^{\infty}$, and nominal income $\{\mathbb{E}_{h,t}[Y_{h,t+s}^N]\}_{s=0}^{\infty}$. In every period t, each consumer h maximizes the flow of current and future utility, discounted by the intertemporal factor $\beta \in (0,1)$:

$$\max_{\left\{\{X_{j,h,t+s}\}_{j \in J_h}; D_{h,t+s}\right\}_{s=0}^{\infty}} \mathbb{E}_{h,t}\left[\sum_{s=0}^{\infty} \beta^s \log\left\{\left[\sum_{j \in J_h} (A_{j,h})^{\frac{1}{\sigma_h}} (X_{j,h,t+s})^{\frac{\sigma_h - 1}{\sigma_h}}\right]^{\frac{\sigma_h}{\sigma_h - 1}}\right\}\right], \tag{40}$$

under the budget constraint:

$$D_{h,t+s} + \sum_{j \in J_h} P_{j,t+s} X_{j,h,t+s} = Y_{h,t+s}^N + \left(1 + i_{t+s-1}^{CB}\right) D_{h,t+s-1} + \sum_{j \in J_h} (1 - \delta_j) P_{j,t+s} X_{j,h,t+s-1}, \tag{41}$$

and the irreversible investments condition:

$$(1 - \delta_j) X_{j,h,t+s-1} \leq X_{j,h,t+s}, \tag{42}$$

where $D_{h,t+s}$ are demand deposits at the time $t + s$, σ_h is the elasticity of substitution, and $X_{h,j,t+s}$ is the consumed quantity of good j with factor share $A_{j,h}$ and depreciation rate δ_j. The optimal solution implies the following consumption budget for each product j:

$$H_{h,j,t} = A_{j,h}\left[1 - \frac{(1 + \mathbb{E}_{h,t}[\pi_{j,t}])(1 - \delta_j)}{(1 + \mathbb{E}_{h,t}[i_t^{CB}])}\right]^{-\sigma_h} \left(\frac{\mathbb{E}_{h,t}[P_{j,t}] - \mu_{j,t}}{\mathbb{E}_{h,t}[P_t]}\right)^{-\sigma_h} \frac{\mathbb{E}_{h,t}[P_{j,t}]}{\mathbb{E}_{h,t}[P_t]} H_{h,t}, \tag{43}$$

where $\mu_{j,t}$ is the Lagrange multiplier associated with (42), and:

$$\mathbb{E}_{h,t}[\pi_{j,t}] = \mathbb{E}_{h,t}\left[\frac{P_{j,t+1} - P_{j,t}}{P_{j,t}}\right], \tag{44}$$

is the expected inflation rate. At the same time, the aggregate nominal consumption budget is equal to:

$$H_t = (1 - \beta)(1 + i_{t+s-1}^{CB}) D_{t+s-1} + \bar{Y}_t^N + \sum_{j \in J_h} \mathbb{E}_{h,t}[P_{j,t}] (1 - \delta_j) X_{j,t-1}, \tag{45}$$

with:

$$\bar{Y}_t^N = (1 - \beta)\left\{Y_{h,t} + \lim_{s \to \infty} \sum_{n=1}^{s-1} \mathbb{E}_{h,t}\left[\prod_{z=1}^{n} \frac{Y_{h,t+j}}{1 + i_{t+z-1}^{CB}}\right]\right\}, \tag{46}$$

being the discounted flow of future nominal income and:

$$\mathbb{E}_{h,t}[P_t] = \left\{\sum_{j \in J_h} A_{j,h}\left[1 - \frac{(1 + \mathbb{E}_t[\pi_{j,t}])(1 - \delta_j)}{(1 + \mathbb{E}_t[i_t^{CB}])}\right]^{-\sigma_h} \mathbb{E}_{h,t}[P_{j,t}] \left(\mathbb{E}_{h,t}[P_{j,t}] - \mu_{j,t}\right)^{-\sigma_h}\right\}^{\frac{1}{1 - \sigma_h}}, \tag{47}$$

the aggregate consumption price index. Following Ciola et al. (2023), we assume that households have limited processing capabilities and adopt the simplifying assumption:

$$\frac{1+\mathbb{E}_t[\pi_{j,t}]}{1+\mathbb{E}_t[i_t^{CB}]} \approx \frac{1}{1+\mathbb{E}_t[r_t^{CB}]} \approx \beta \tag{48}$$

to approximate (43), (46), and (47) as follows:

$$H_{h,j,t} \approx A_{j,h}\left[1-\beta(1-\delta_j)\right]^{-\sigma_h}\left(\frac{\mathbb{E}_{h,t}[P_{j,t}]-\mu_{j,t}}{\mathbb{E}_{h,t}[P_t]}\right)^{-\sigma_h}\left(\frac{\mathbb{E}_{h,t}[P_{j,t}]}{\mathbb{E}_{h,t}[P_t]}\right)H_{h,t}, \tag{49}$$

$$\bar{Y}_t^N \approx (1-\beta)Y_{h,t} + \beta\frac{\mathbb{E}_{h,t}[P_t]}{\mathbb{E}_{h,t-1}[P_{t-1}]}\bar{Y}_{t-1}^N, \tag{50}$$

$$\mathbb{E}_{h,t}[P_t] = \left\{\sum_{j=1}^{J} A_{j,h}\left[1-\beta(1-\delta_j)\right]^{-\sigma_h}\mathbb{E}_{h,t}[P_{j,t}]\left(\mathbb{E}_{h,t}[P_{j,t}]-\mu_{j,t}\right)^{-\sigma_h}\right\}^{\frac{1}{1-\sigma_h}}, \tag{51}$$

Lastly, if deposits $D_{h,t}$ are below the optimal budget $H_{h,t}$, households reduce their consumption proportionally, namely:

$$\max_{\{X_{j,h,t}\}_{j\in J_h}} \mathbb{E}_{h,t}\left[\left(\sum_{j\in J_h}(A_{j,h})^{\frac{1}{\sigma_h}}(X_{j,h,t})^{\frac{\sigma_h-1}{\sigma_h}}\right)^{\frac{\sigma_h}{\sigma_h-1}}\right], \tag{52}$$

under the budget constraint:

$$\sum_{j\in J_h} P_{j,t}X_{j,h,t} = D_{h,t}, \tag{53}$$

and the irreversible investments condition:

$$(1-\delta_j)\,X_{j,h,t-1} \leq X_{j,h,t}, \tag{54}$$

which implies:

$$H_{h,j,t} = \frac{A_{j,h}E_{h,t}[P_{j,t}]\left(\mathbb{E}_{h,t}[P_{j,t}]-\mu_{j,t}\right)^{-\sigma_h}}{\sum_{j\in J_h} A_{j,h}E_{h,t}[P_{j,t}]\left(\mathbb{E}_{h,t}[P_{j,t}]-\mu_{j,t}\right)^{-\sigma_h}}D_{h,t}, \tag{55}$$

where $\mu_{j,t}$ is the Lagrange multiplier associated with (54).

A.2 MATRIX model parameters

Variable	Description	Value
β^F	Firms discount rate	0.985
μ^F	Firms dividend payout ratio	$1-\beta^F$
γ^{PQ}	Maximum size of price-quantity exploration	0.10
ζ^Q	Speed of adjustment: quantity	0.75
ζ^P	Speed of adjustment: price	0.75
ω	Intensity of choice	10
$\mathcal{N}^C$	Number of C-firms	100
$A_{N,C}$	Input share: labor (C)	0.73
$A_{K,C}$	Input share: capital (C)	0.21
$A_{E,C}$	Input share: energy (C)	0.02
$A_{O,C}$	Input share: fossil fuel (C)	0.04
δ_C	Depreciation rate of consumption goods	1
σ_C	Elasticity of substitution (C)	0.25
$\mathcal{Z}_C$	Search rate of new partners (C)	4
$\mathcal{N}^E$	Number of E-firms	10
$A_{N,E}$	Input share: labor (E)	0.64
$A_{K,E}$	Input share: capital (E)	0.08
$A_{O,E}$	Input share: fossil fuel (E)	0.28
δ_E	Depreciation rate of energy services	1
σ_E	Elasticity of substitution (E)	0.25
$\mathcal{Z}_E$	Search rate of new partners (E)	4
$\mathcal{N}^K$	Number of K-firms	60
$A_{N,K}$	Input share: labor (K)	0.90
$A_{E,K}$	Input share: energy (K)	0.04
$A_{O,K}$	Input share: natural resource (K)	0.06
δ_K	Depreciation rate of phisical capital	0.05/4
σ_K	Elasticity of substitution (K)	0.25
$\mathcal{Z}_K$	Search rate of new partners (K)	4
ν^O	Foreign natural resource expenditure over GDP	0.055
δ_O	Foreign natural resource depreciation rate	1
η^O	Share of foreign natural resource going to E-firms	1

Variable	Description	Value
β	Households discount rate	0.993
χ	Marginal propensity to consume out of wealth	$1-\beta$
$\mathcal{N}^W$	Number of workers	1000
ρ^W	Wage stickiness	0.61
θ^W	Insider-outsider bargaining power	0.67
ι^W	Inflation anchoring	0.75
δ_N	Depreciation rate of labor	1
$\mathcal{Z}_N$	Search rate of new jobs by unemployed	10
$\mathcal{N}^H$	Number of households	1180
$A_{C,H}$	Consumption share: final good (H)	0.92
$A_{E,H}$	Consumption share: energy (H)	0.02
$A_{K,H}$	Consumption share: capital (H)	0.06
σ_H	Elasticity of substitution (H)	0.25
$\mathcal{Z}_H$	Search rate of new partners (H)	0.25
$\mathcal{N}^B$	Number of banks	10
γ^B	Capital adequacy ratio	0.08
ω^B	Risk weighting	1
κ^B	Maximum single exposure to borrowers	0.25
ϱ^B	Interest rate setting parameter: bank financial soundness	0.029/4
ρ^B	Interest rate setting parameter: firm leverage	0.017/4
ι^B	Interest rate setting parameter: share of aggregate NPL	0.001/4
θ^B	Share of loans repaid at each time-step	0.0125
$\mathcal{Z}_B$	Search rate of new banks	0.2
p^*	Inflation target	0.02/4
u^*	Target unemployment rate	0.057
r^*	Steady state real interest rate	$1/\beta-1$
λ^p	Monetary policy rule weights: inflation	2.03
λ^u	Monetary policy rule weights: unemployment	0.08
ρ^{CB}	Speed of adjustment of the monetary policy rule	0.81
b^*	Target debt-GDP ratio	0.75
ρ^G	Speed of adjustment to target debt-GDP ratio	0.007
ψ^G	Share of social expenditures	0.066

Source: Ciola et al. (2023); Turco et al. (2023); Bazzana et al. (2023).

Table B.1: MATRIX model parameters

A.3 Additional Figures

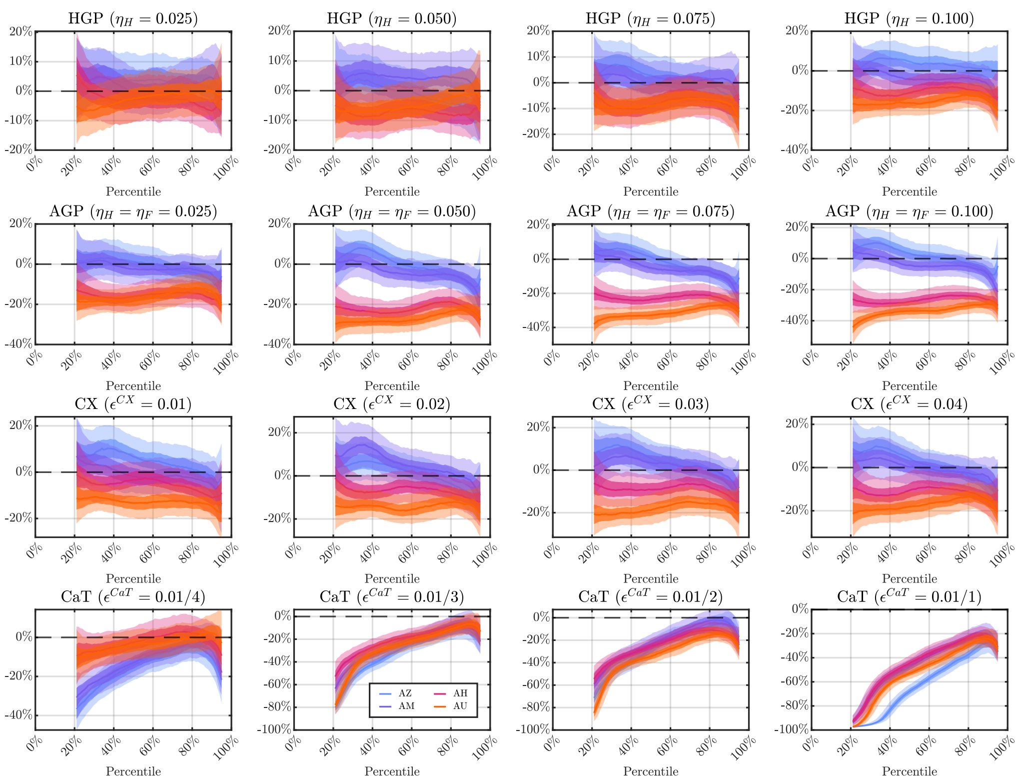

Figure B.1: Shift in firms' net worth distribution

Note: percentage change in firms' real net worth from BAU for different distribution percentiles under different policies/preferences (rows), policy/preference intensities (columns), and abatement subsidy levels (colors). Medians (solid lines), 50%, and 90% confidence intervals (shaded areas) computed on 250 independent replicas of the model. Percentiles below 20% removed to improve graphical clarity.

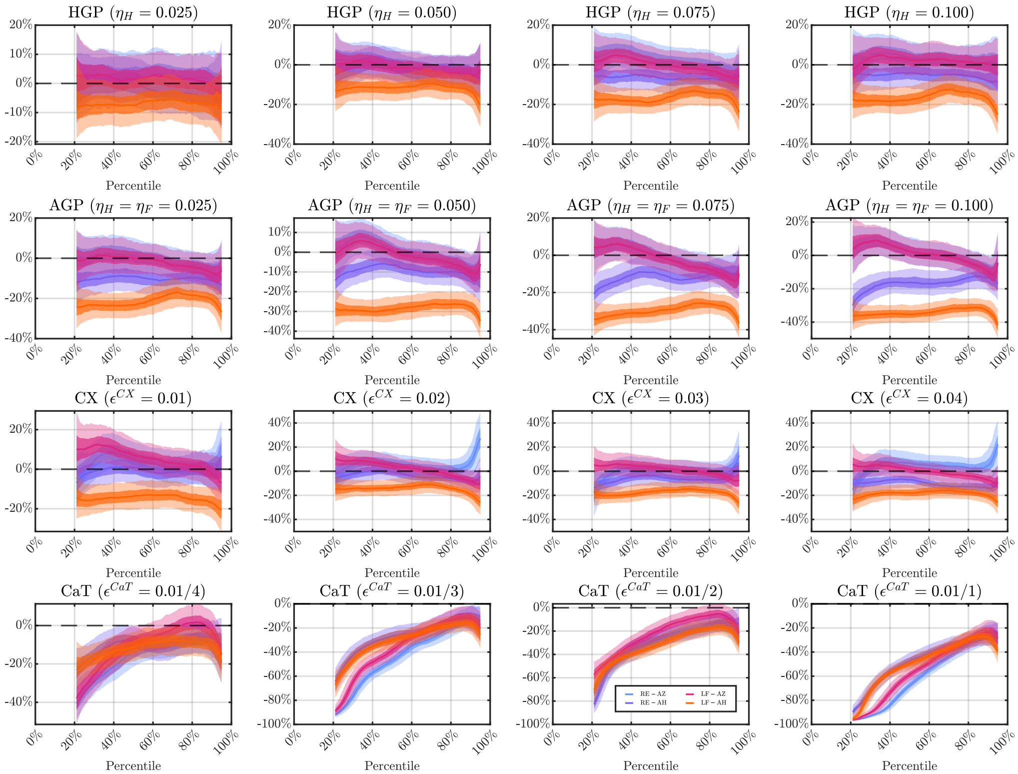

Figure B.2: Shift in firms' net worth distribution

Note: percentage change in firms' real net worth from BAU for different distribution percentiles under different policies/preferences (rows), policy/preference intensities (columns), and policy combinations (colors). Medians (solid lines), 50%, and 90% confidence intervals (shaded areas) computed on 250 independent replicas of the model. Percentiles below 20% removed for clarity.

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