Made
centro de
pesquisa em
macroeconomia
das desigualdades

Working Paper 01.10.2025 nº 032

Tax-financed green policies and income inequality in an agent-based model

Lucca Rodrigues,
Gilberto Tadeu Lima &
Pedro Romero Marques

Tax-financed green policies and income inequality in an agent-based model*

Lucca Gustafson Rodrigues[1,2], Gilberto Tadeu Lima[1,3], and Pedro Romero Marques[1]

[1]Research Center on Macroeconomics of Inequalities (Made/FEA-USP), Brazil
[2]Brazilian Development Bank (BNDES), Brazil
[3]Department of Economics, University of São Paulo (USP), Brazil

October 1, 2025

Abstract

Growing concern over the climate crisis has recently spurred decarbonization efforts across numerous economies. The overarching aim is to reconfigure productive systems so as to decouple carbon emissions from gross domestic product (GDP) growth. However, these structural shifts are inherently complex, meaning their full macroeconomic repercussions cannot be entirely anticipated in advance. This paper focuses on one key aspect: the impact on income distribution. It develops an agent-based model (ABM) to explore how different tax-financed green policies affect income inequality. The central question is whether—and under what conditions—it is possible to achieve GDP growth, reduced carbon emissions, and lower income inequality simultaneously. As decarbonization requires both financing and environmental policy instruments, this paper simulates various combinations of these tools. The simulations examine scenarios where tax instruments—either a carbon tax or a wealth tax—finance the following green policies: (i) price subsidy for the least polluting firms, (ii) public non-patented green R&D, (iii) subsidy for private green R&D, and

*This is a revised version of the original Working Paper published in September 11th, 2025. We gratefully acknowledge the insightful feedback received during discussions at the Research Center on Macroeconomics of Inequalities at the University of São Paulo (Made/FEA-USP). We also thank Instituto Clima e Sociedade, Co-Impact, Open Society Foundations, and Wellspring Philanthropic Fund for funding. The views expressed in this article are those of the authors and do not necessarily reflect the official position of any affiliated institutions.

(iv) green public procurement. While the carbon tax is both as a financing mechanism and an environmental policy tool, the wealth tax is primarily a means of income redistribution. Our findings show how this distinction crucially shapes the interplay between GDP growth, carbon emissions, and income distribution.

Resumo

A preocupação com a crise climática tem impulsionado a decarbonização de diversas economias. O objetivo central deste esforço é reconfigurar os sistemas produtivos de forma a dissociar as trajetórias das emissões de carbono e de crescimento do Produto Interno Bruto (PIB). Intrinsecamente complexas, essas transformações estão sujeitas à consequências macroeconômicas que não podem ser totalmente antecipadas. O presente artigo foca em um aspecto chave desse processo: o impacto sobre a distribuição de renda. Com base em um modelo baseado em agentes (ABM, na sigla em inglês), investiga-se como diferentes políticas de descarbonização, quando financiadas via tributação, impactam a desigualdade de renda. Especificamente, a pergunta central é se—e em quais condições—é possível fazer convergir crescimento do produto, redução das emissões de carbono e diminuição da desigualdade de renda. Como a descarbonização exige instrumentos de financiamento e de política ambiental, o artigo simula diferentes arranjos que combinam estas ferramentas. As simulações focam em dois instrumentos fiscais distintos, um imposto sobre carbono ou um imposto sobre riqueza. Estes tributos, por sua vez, financiam as seguintes políticas verdes: (i) subsídio de preço para as empresas menos poluentes, (ii) P&D público verde não patenteado, (iii) subsídio para P&D verde privado, e (iv) compras públicas verdes. Tanto o imposto sobre carbono quanto o imposto sobre a riqueza servem como instrumentos de financiamento da descarbonização, mas com características distintas. Enquanto o primeiro atua também como instrumento de política ambiental, o segundo funciona essencialmente como mecanismo redistributivo. Nossos resultados indicam que essa distinção é crucial para moldar a interação entre crescimento, emissões de carbono e distribuição de renda.

JEL Codes

E17, E25, O15, O44, Q56

1 Introduction

Continued greenhouse gas emissions have contributed to increasing global warming and the intensification of climate change-related hazards (IPCC, 2023). The seriousness of this fact appears to be increasingly recognized by actors across the global economic and political arena. A illustrative example is the changing discourse and policy priorities among developed economies following the COVID-19 pandemic. Once a general recession became apparent, these countries announced plans to pursue decarbonization as a way out of the crisis. In a familiar Keynesian tone—either explicitly or implicitly—many of them incorporated the notion of a "green new deal" and envisioned an economic recovery driven by the fossil fuel transition, with significant support from the public sector (Mastini et al., 2021).

Examples of these attempts include the United States' 2022 Inflation Reduction Act (IRA) and the European Union's 2024 Net-Zero Industrial Act (NZIA). They suggest, for example, that decarbonization strategies can be effectively coordinated by governments through a set of policy instruments such as regulations, public investments, green subsidies, public procurement, among others (Kleimann et al., 2023; European Parliament and Council of the European Union, 2024). Green growth—defined as the pursuit of GDP growth by decoupling carbon emissions—has therefore emerged as a central goal of contemporary macroeconomic policy.

On the one hand, the emerging global consensus around green economic growth cannot be overstated. It is well known that developed economies have largely relied on fossil fuels to promote economic growth during the past two centuries, and this dependency has demonstrably increased the pace of climate change. Any efforts to reduce reliance on these energy sources are thus welcome. On the other hand, green economic growth should not be viewed as a panacea. Absolute decoupling, i.e., completely diverging trajectories between economic growth and emissions, is a difficult process still unobserved (Vogel and Hickel, 2023). Furthermore, the substitution of fossil-fuel energy by renewable sources, the core driver of green growth, is likely to be truncated and unstable: energy transitions have historically been characterized by structural socioeconomic disruptions associated with the adoption of new technologies (Geels and Schot, 2007; Geels et al., 2017). Not surprisingly, some studies have pointed to the existence of a trilemma emerging from the aim of combining economic growth, decarbonization and distributional improvements (D'Alessandro et al., 2020; Oliveira and Lima, 2022).

The present paper investigates how distinct instruments employed in decarbonization strategies might influence the interaction between economic growth, income distribution and greenhouse gas (GHG) emissions. We resort to the development of an agent-based model (ABM), a modeling approach that considers the economy as a *complex evolving system*, wherein the interactions of multiple heterogeneous agents give rise to the emergence of aggregate properties that cannot be deduced by the simple aggregation of individual ones (Tesfatsion and Judd, 2006; Farmer and Foley, 2009; Dosi and Virgillito, 2021). ABMs seek a higher degree of realism by explicitly considering the economy as part of broader social and environmental systems that go beyond equilibrium analysis. Some key features of ABMs are heterogeneity in behavior along several dimensions, decentralized and uncoordinated interactions and path-dependent dynamics. In recent years, these models have been increasingly successfully developed to assess the potential consequences of decarbonization in different economies (Gerst et al., 2013; Isley et al., 2015; Safarzyńska and van den Bergh, 2017; Lamperti et al., 2018; Monasterolo and Raberto, 2018; Ponta et al., 2018; Foramitti et al., 2024).

Following these previous research efforts, we build an ABM centered on the impacts that productive and technological changes stemming from decarbonization might generate on the distribution of income of a stylized economy. Decarbonization is expressed by the falling trend in GHG emissions associated with a more environmentally friendly production. We do not specify the source of change (whether, for example, it stems from energy transition or other possible technological improvement that reduce emissions) in order to make our results and their substantive meaning and intuition as general as possible. Our ABM, unlike traditional Integrated Assessment Models (IAMs) used in climate change economics, does not include climate-economy feedback loops, particularly via a climate damage function (for an agent-based integrated assessment model, see Lamperti et al. (2018)). This methodological decision stems from the fact that such functions remain among the most *ad hoc* components in IAMs (Pindyck, 2013). Moreover, the economic impacts in the form of losses associated with climate change can vary significantly depending on location, social conditions, and existing infrastructure. By leaving climate damages aside, we focus exclusively on mitigation strategies rather than incorporating adaptation measures.

We argue that ABMs are particularly well suited for studying income inequality, as they allow for household-level heterogeneity, thereby broadening the analysis of the distributional consequences of climate policy (Safarzyńska and Van Den Bergh, 2022). To capture these distributive dynamics, we introduce a simplified wage bargaining process and a tripartite class structure in the household sector—comprising capitalists, direct workers, and indirect workers—following Rolim et al. (2023). This approach allows us to assess income distribution outcomes in terms of both personal and functional income inequality.

Since our ABM is designed to explore the consequences of different decarbonization strategies, the simulations consider potential financing and environmental policy alternatives. In the case of environmental policy, the model evaluates the effects of four instruments: a price subsidy for the least polluting firms, a research-support subsidy to encourage private R&D, non-patented green R&D, and public procurement directed toward the least polluting firms. These policies were chosen for their prominence in academic and public policy discussions and are considered within two distinct and also widely debated tax-financing scenarios. The first involves the implementation of a carbon tax—a widely recognized environmental policy tool. While it may help realign economic incentives to address externalities associated with environmental degradation and depletion, it also has the potential to generate additional public revenues to support decarbonization efforts. A carbon tax is therefore both an environmental policy and a financing instrument. The second scenario involves the introduction of a wealth tax—a distributive instrument proposed as a way to promote a more equitable decarbonization process (Chancel et al., 2024). Although not directly tied to environmental objectives, a wealth tax could influence the emission-intensive consumption patterns of top earners and contribute to a fairer distribution of income and wealth during the decarbonization process.

Although adopting a different analytical perspective, D'Alessandro et al. (2020) and Ravaioli et al. (2025) have already delineated similar questions using a relatively similar approach. Both articles compare transition scenarios in terms of GHG emissions and income distribution. Their results drew attention to the difficulties in finding win-win solutions, which tend to reaffirm the trilemma of economic growth, income inequality and carbon emissions. The main distinction of our paper—beyond differences in model structure and assumptions—lies in its focus on tax-financed decarbonization, the environmental policy instruments examined, and, most critically, our approach to inequality modeling based on endogenous wage bargain and a tripartite social-class structure.

A final remark concerns the importance of recognizing the effort undertaken in this paper as being in alignment with the field of Ecological Economics (EE). Although characterized by pluralism, EE is grounded on shared ontological and epistemological premises that are consistent with the points discussed and the method employed in this paper (Spash, 2012). First, EE recognizes that scientific knowledge is subject to radical uncertainty, particularly in relation to the environment. Second, it challenges traditional environmental economics by adopting hierarquical ontologies—biophysical, social, and economic—that interact with one another. Third, it assumes that reality is complex and characterized by emergent properties. Fourth, it is grounded in an ethical perspective that reaffirms social and environmental goals. Finally, EE has historically treated economic growth as a critical variable for assessing environmental issues from a macroeconomic perspective. This premise originates from the seminal works of Georgescu-Roegen and Herman Daly (Couix, 2019), and it remains alive and evolving as it incorporates contemporary discussions on environmental issues (Jackson, 2009; Victor, 2019; Rezai et al., 2013; Fontana and Sawyer, 2016; Dafermos et al., 2018; Alvarenga and Young, 2024).[1] That said, ABMs are widely and deservedly recognized as one of the most powerful modeling techniques in ecological macroeconomics (Monasterolo et al., 2019).

In addition to this introduction, the paper is organized as follows. Section 2 outlines the structure of the model, while Section 3 describes the decarbonization policies and tax-financing mechanisms considered in the simulation experiments. Section 4 presents and discusses the main simulation results of interest, while Section 5 recapitulates the key conclusions and offers final remarks.

2 Structure of the model

The model is populated by heterogeneous firms and households, a financial sector and the government. The economy consists of two distinct production sectors: the capital goods sector and the consumption goods sector. Capital goods firms hire labor, pay wages and dividends, and produce capital goods, which they sell to consumption goods firms for investment purposes. Consumption goods firms also hire labor, pay wages and dividends. They produce consumption goods for households and government demand. In order to finance their activities, consumption goods firms may need to take out loans from the financial sector. Firms adopt different production technologies based on specific market conditions and policy incentives.

[1] For an overview, see Hardt and O'Neill (2017) and the Special Issue edited by Rezai and Stagl (2016).

Firms' sales are taxed by the government. The modeling of the production sectors is inspired by Dosi et al. (2010); Lamperti et al. (2018).

We incorporate the households' social class division between capitalists, direct workers, researchers, and managers adopted by Rolim et al. (2023). Working households (direct workers, researchers, and managers) provide labor to both capital and consumption goods firms in exchange for wages, which are set through a simplified bargaining process. Capitalist households own the firms and receive dividends from their ownership. Households consume goods produced by the consumption goods firms and pay taxes. They also hold deposits in the financial sector. Each household belongs to a single social class.

The financial sector consists of a single commercial bank that collects deposits from firms and households and extends loans to consumption goods firms. In principle, the credit money supply is endogenous, but becomes constrained beyond a certain limit by the requirement for the commercial bank to comply with a simplified capital adequacy ratio. The financial sector also purchases government bonds, thus indirectly helping to finance fiscal operations. Lastly, the government collects taxes from firms and households and conducts fiscal spending through the purchase of consumption goods and the provision of unemployment benefits to working households. In the event of a fiscal deficit, the government issues bonds, which are absorbed by the financial sector. The government is also responsible for implementing decarbonization policies, such as carbon taxation, green subsidies to firms, a green public technology laboratory, and green public procurement, as explained in Section 3. The government can finance these policies through either a carbon tax on emissions from

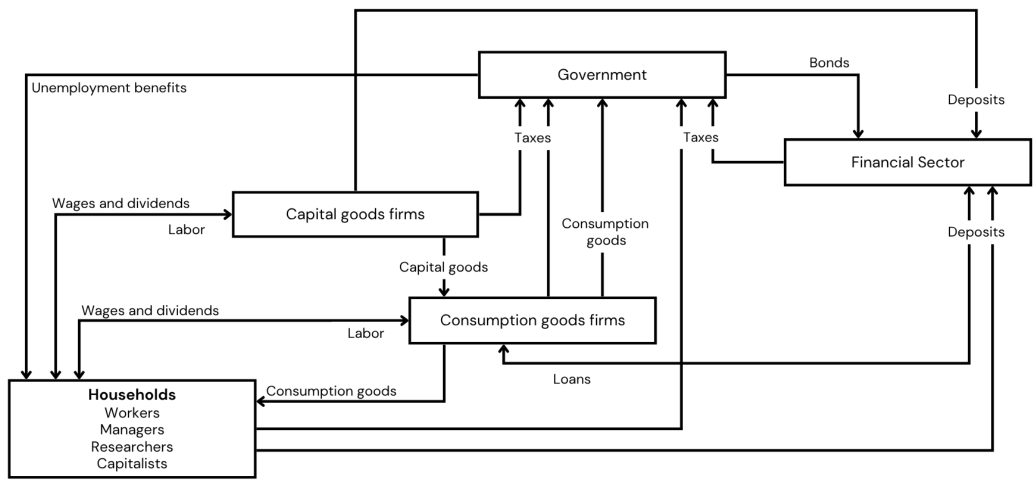


Figure 1: Model structure. *Note*: Unidirectional arrows point from the transferring sector to the receiving sector, while bidirectional arrows indicate flows in both ways

firms producing capital and consumption goods firms or a wealth tax on capitalist households. Figure 1 illustrates the schematic model structure and the interactions among the agents involved.

2.1 Sequence of events

In each simulation period, the sequence of events is the following:

1. Consumption goods firms set desired production levels and prices;

2. Consumption goods firms set investment demand;

3. Credit money market opens;

4. Nominal wages are set;
5. Labor market opens;
6. Production and research and development (R&D) activities are carried out;
7. Unemployment benefits and wages are paid;
8. Consumption goods market opens;
9. Taxes are paid;
10. Financial sector acquires government bonds;
11. New capital is delivered;
12. National accounts and statistics are computed.

2.2 Capital goods sector

The modeling of capital and consumption goods sectors is based on Lamperti et al. (2018) and conveniently—yet plausibly—adapted to incorporate a simplified version of the labor class division and wage bargaining process set forth in Rolim et al. (2023). Firms in the capital goods sector produce machines using direct workers. These workers are supervised by indirect workers hired as managers. For each ρ direct workers ($\rho > 1$), the firm needs to hire one manager (when the number of direct workers is not a multiple of ρ, the required number of managers is rounded up to maintain the established supervisory ratio; for instance, $\rho + 1$ direct workers would require two managers). Innovation is realized by indirect workers hired as researchers. We assume that each firm is owned by the same number σ of capitalists ($\sigma \geq 1$).

2.2.1 Innovation process

The technology of machines produced by capital goods firm i in period t is captured by its associated labor productivity (LP) and carbon intensity (CI), which are represented by four coefficients ($LP^K_{i,t}$, $LP^C_{i,t}$, $CI^K_{i,t}$, $CI^C_{i,t}$). While $LP^K_{i,t}$ stands for the labor productivity associated with producing the machine in the capital goods sector, $LP^C_{i,t}$ represents the labor productivity of using the machine in the consumption goods sector. Machines are also characterized by their carbon intensity, which is the ratio of emissions to output. The lower the carbon intensity, the more environmental friendly the machine is. Hence, $CI^K_{i,t}$ denotes the carbon intensity associated with producing the machine in the capital goods sector, while $CI^C_{i,t}$ represents the carbon intensity associated with using the machine in the consumption goods sector.

Firms in the capital goods sector pursue innovation to enhance labor productivity and reduce carbon intensity, aiming to improve price competitiveness and expand their market share. Firms invest in R&D a certain fraction $\nu \in (0, 1)$ of their past net profits $\Pi_{i,t-1}$ in the attempt to discover a new and improved technology:

$$RD_{i,t} = \nu \Pi_{i,t-1}, \tag{1}$$

with $\nu \in (0, 1)$. Innovation is a two step process. The first step captures the stochastic nature of technical change and determines whether a firm successfully innovates through a $Bernoulli(\theta^u_{i,t})$ draw, where $\theta^u_{i,t}$ is dependent on the level of R&D:

$$\theta^u_{i,t} = 1 - exp^{\zeta^u RD_{i,t}}, \tag{2}$$

with $\zeta^u > 0$, for $u \in \{LP, CI\}$. The second step determines the size of the technological advance via additional stochastic processes:

$$LP^K_{i,t} = LP^K_{i,t-1}(1 + \chi^{LP}_{K,i}), \tag{3}$$

$$LP^C_{i,t} = LP^C_{i,t-1}(1 + \chi^{LP}_{C,i}), \tag{4}$$

$$CI^K_{i,t} = CI^K_{i,t-1}(1 - \chi^{CI}_{K,i}), \tag{5}$$

$$CI^C_{i,t} = CI^C_{i,t-1}(1 - \chi^{CI}_{C,i}), \tag{6}$$

where $\chi^u_{G,i}$ and $\chi^u_{K,i}$ are independent draws from $Beta(\alpha, \beta)$ distributions over the support $[-\underline{x}^u, \overline{x}^u]$.

2.2.2 Cost and prices

Given the nominal labor cost with direct workers ($W^W_{i,t}$) and managers ($W^M_{i,t}$), the nominal unit cost of production of the capital goods produced by firm i is represented by:

$$c_{i,t} = (W^W_{i,t} + W^M_{i,t})\frac{1}{LP^K_{i,t}}. \tag{7}$$

Capital goods firms set the price of their machines ($p_{i,t}$) by applying an exogenously given constant mark-up rate ($\mu > 0$) over their nominal unit cost ($c_{i,t}$):

$$p_{i,t} = (1 + \mu)c_{i,t}. \tag{8}$$

Owing to the constant positive mark-up rate, capital goods firms consistently realize positive profits. Nominal wage determination follows a simplified version of that specified in Rolim et al. (2023) and is organized as follows. First, firms decide their desired nominal wage, which, for simplicity, is equal to the nominal wage paid in the previous period $W_{i,t-1}$. The wage bargained $W_{i,t}$ is a weighted average between firms' desired wage and workers' desired wage W_t^d:

$$W_{i,t} = \phi_t W_t^d + (1 - \phi_t)W_{i,t-1}, \tag{9}$$

where $\phi_t = \phi(1 - u_{t-1})$ is the endogenous workers' bargaining power set by institutional factors (ϕ) and the previous period unemployment rate (u_{t-1}). Managers' wage $W_{i,t}^M$ is set by applying a premium $\varrho > 0$ over direct workers wage:

$$W_{i,t}^M = (1 + \varrho)W_{i,t}. \tag{10}$$

Researchers receive the same wage as managers. There is downward rigidity in nominal wages in line with empirical evidence that firms rarely cut nominal wages (Dickens et al., 2007; Babecký et al., 2010).

2.2.3 Labor demand

Capital goods firms determine their demand for researchers ($\hat{L}^{RD}_{i,t}$) based on the available R&D budget, hiring the maximum number of researchers affordable at the prevailing research wage:

$$\hat{L}^{RD}_{i,t} = \frac{RD_{i,t}}{W^{M}_{i,t}}. \tag{11}$$

Note that capital goods are sold through orders from one period to the next. In this case, there is no capacity utilization constraint in the sector and orders equal production, conditioned on labor restraint. Demand for direct workers is determined by orders of capital goods $K_{i,t}$ directed to firm i by consumption goods firms:

$$\hat{L}^{W}_{i,t} = \frac{K_{i,t}}{LP^{K}_{i,t}}. \tag{12}$$

Each manager can supervise a fixed number $\rho > 1$ of direct workers. Thus, the demand for managers is given by:

$$\hat{L}^{M}_{i,t} = \frac{\hat{L}^{W}_{i,t}}{\rho}. \tag{13}$$

2.2.4 Profits

The amount of profits earned by capital goods firms ($\Pi_{i,t}$) in period t are equal to:

$$\Pi_{i,t} = p_{i,t}K_{i,t}(1-\tau) - c_{i,t}K_{i,t} - RD_{i,t}, \tag{14}$$

where τ is the tax rate on marginal sales. As noted earlier, expenditures on R&D

are limited by the previous period's profits, and each firm is owned by a fixed $\sigma \geq 1$ number of capitalists. Firms have a target share $\lambda \in (0, 1)$ to distribute dividends in each period ($Div_{i,t} = \lambda \Pi_{i,t} \geq 0$).

2.2.5 Emissions

The volume of emissions resulting from the production of capital goods by firm i in period t is given by:

$$E_{i,t} = K_{i,t} CI^{K}_{i,t}, \tag{15}$$

which depends on the level of production ($K_{i,t}$) and the corresponding carbon intensity ($CI^{C}_{i,t}$) of firm i.

2.3 Consumption goods sector

Firms in the consumption goods sector produce a homogeneous final good using capital ($K_{j,t}$) and labor ($L_{j,t}$) under constant returns to scale. The labor technical coefficient ($LP^{C}_{i,t}$) varies depending on the machine used, while the capital technical coefficient is constant and assumed to be equal to one:

$$Q^{max}_{j,t} = min[K_{j,t}, LP^{C}_{i,t} L_{j,t}]. \tag{16}$$

2.3.1 Investment and production decisions

The expected demand ($Q^{e}_{j,t}$) is adaptive (Dosi et al., 2020) and calculated as the average of the demand actually faced by the firm in the previous $H > 1$ periods:

$$Q^e_{j,t} = \frac{\sum_{h=1}^{H} Q_{j,t-h}}{H}, \tag{17}$$

where $Q_{j,t-h}$ is the demand actually faced by firm j in period $t-h$ and H is the total number of periods the firm takes into account when estimating the corresponding average. Their desired level of production $Q^d_{j,t}$ depends on the expected demand as well as on the desired inventories ($N^d_{j,t}$), and the actual stock of inventories ($N_{j,t-1}$):

$$Q^d_{j,t} = Q^e_{j,t} + N^d_{j,t} - N_{j,t-1}. \tag{18}$$

The desired inventories are calculated as a fraction $\iota \in (0,1)$ of the expected demand:

$$N^d_{j,t} = \iota Q^e_{j,t}. \tag{19}$$

Net investment demand is set through a flexible accelerator mechanism. Firms gradually adjust their desired capacity utilization (u^d_t) toward an exogenously given normal level (u^*), at a speed given by $\gamma_u \in (0,1)$, in addition to an autonomous component $\gamma_a \in (0,1)$:

$$I^d_{j,t} = \left[\gamma_a + \gamma_u(u^d_{j,t} - u^*)\right] K_{j,t-1}. \tag{20}$$

Consumption goods firms' desired capacity utilization depends on their capital stock ($K_{j,t-1}$) and their level of desired production:

$$u^d_{j,t} = \frac{Q^d_{j,t}}{K_{j,t-1}}. \tag{21}$$

Firms producing consumption goods select their capital goods suppliers by comparing the price and productivity of a subset of potential suppliers. The number of potential suppliers available to a consumption good firm varies each period and depends on the number of brochures it receives from capital goods firms. Each capital goods firm determines how many consumption good firms to send its brochures to based on the ratio of consumption good firms to capital goods firms, which is greater than one and even. This number of brochures is then randomly distributed across consumption good firms, so that the number of potential suppliers differs across firms in a given period. If a given consumption good firm receives two or more brochures, it will choose the machine that minimizes the expected nominal unit labor cost of its use in that period, as calculated using Equation (22) below—since, at the time this choice is made, the nominal wages of direct workers and managers have not yet been determined, the consumption good firm uses their values from the previous period. Meanwhile, if a given consumption good firm does not receive any brochures, it will purchase a machine from a randomly selected capital goods firm. Hence, consumption goods firms select their capital goods suppliers through a process of local search, shaped by limited information and bounded rationality. Instead of surveying the entire market to identify the globally optimal supplier, consumption goods firms consider only a limited subset of capital goods firms. This constrained search reflects consumption goods firms' bounded rationality, as decisions are made using heuristics and simple rules instead of full optimization. As a result, supplier choices represent not a global optimum, but a satisfactory decision that balances performance with informational and cognitive constraints.

2.3.2 Cost and prices

The nominal unit cost of production for consumption goods firm j is determined as follows:

$$c_{j,t} = (W^W_{j,t} + W^M_{j,t})\frac{1}{LP^C_{i,t}} + p_{i,t}, \tag{22}$$

where $p_{i,t}$ is the price of the machine with productivity $LP^C_{i,t}$ produced by capital goods firm i and used as input by consumption goods firm j. Meanwhile, $W^W_{j,t}$ is the wage paid to direct workers and $W^M_{j,t}$ is the wage paid to managers. Wage setting follows the same bargaining process as described for capital goods firms, recalling that $\phi_t = \phi(1-u_{t-1})$ is the endogenous workers' bargaining power and the bargained wage ($W_{j,t}$) is a weighted average between firms' desired wage ($W_{j,t-1}$) and workers' desired wage (W^d_t):

$$W_{j,t} = \phi_t W^d_t + (1-\phi_t)W_{j,t-1}. \tag{23}$$

Managers' wage $W^M_{j,t}$ is set by applying a premium $\varrho > 0$ over direct workers wage. The price of goods produced by consumption goods firms ($p_{j,t}$) is determined by applying a variable mark-up rate ($\mu_{j,t}$) over their nominal unit cost of production ($c_{j,t}$):

$$p_{j,t} = c_{j,t}(1 + \mu_{j,t}), \tag{24}$$

where the mark-up rate changes over time according to the evolution of firm's market share ($f_{j,t}$):

$$\mu_{j,t} = \mu_{j,t-1} \left[1 + \upsilon \frac{f_{j,t-1} - f_{j,t-2}}{f_{j,t-2}} \right], \tag{25}$$

with $\upsilon \in [0, 1]$. The competitiveness of consumption goods firms ($F_{j,t}$) depends on their price ($p^C_{j,t}$) and the level of unfilled demand ($Q^u_{j,t}$), weighted by their respective importance ω_1 and ω_2:

$$F_{j,t} = -\omega_1 p_{j,t} - \omega_2 Q^u_{j,t}, \tag{26}$$

with $\omega_1, \omega_2 > 0$. The average competitiveness in the consumption goods sector is given by:

$$\overline{F}_t = \sum F_{j,t} f_{j,t-1}. \tag{27}$$

The market share of the consumption goods firm j is determined by a quasi-replicator dynamic, which captures how this share varies over time based on relative performance:

$$f_{j,t} = f_{j,t-1} \left[1 + \kappa \frac{F_{j,t} - \overline{F}_t}{F_{j,t}} \right], \tag{28}$$

with $\kappa > 0$.

2.3.3 Profits and funding

The volume of profits earned by consumption goods firms ($\Pi_{j,t}$) in period t is given by:

$$\Pi_{j,t} = p_{j,t}Q_{j,t}(1-\tau) - W_tL_{j,t} - p_{i,t}I_{j,t} - r\Lambda_{j,t}, \tag{29}$$

where $p_{j,t}Q_{j,t}(1-\tau)$ is the firm's net sales income after taxes, $W_tL_{j,t}$ is the labor cost, $p_{i,t}I_{j,t}$ is the investment cost, and $r\Lambda_{j,t}$ is the financial cost of firm j. Borrowing takes place because consumption goods firms must finance their production costs. They follow a pecking order financing strategy, first utilizing their net worth ($NW_{j,t}$). If this is insufficient to cover total costs, they borrow external funds ($\Lambda_{j,t}$) from the bank at a constant, exogenously determined, interest rate $r > 0$. The net worth of firm j in period t is equal to:

$$NW_{j,t} = NW_{j,t-1} + \Pi_{j,t} - Div_{j,t}, \tag{30}$$

where $Div_{j,t} = \lambda\Pi_{j,t} \geq 0$ is the distributed profits of consumption goods firms to their $\sigma \geq 1$ capitalists owners. The credit money supply available to consumption goods firms may be subject to rationing, as detailed in the following subsection.

2.3.4 Emissions

The amount of emissions from the production of consumption goods of firm j in period t are equal to:

$$E_{j,t} = Q_{j,t} CI^C_{i,t}, \tag{31}$$

which depends on the level of production ($Q_{j,t}$) and its carbon intensity ($CI^C_{i,t}$), which is determined by the technological level of capital produced by capital goods firm i and used as input by consumption goods firm j.

2.4 Financial Sector

The financial sector is represented by a single commercial bank that collects deposits from firms and households and extends credit to firms. Its net worth is given by:

$$NW^{FS}_t = \Lambda_t + B_t - Dep_t + \Pi^{FS}, \tag{32}$$

where $\Lambda_t = \sum_j \Lambda_{j,t}$ is the aggregate credit supplied, B_t is the stock of public bonds held by the financial sector, Dep_t is the stock of deposits collected by the sector, and Π^{FS}_t denotes the profits of the sector, all in period t. The financial sector does not distribute dividends. The amount of profits earned by the financial sector (Π^{FS}_t) in period t are equal to the sum of interest paid on granted loans by the firms and interest paid by the government on public bonds:

$$\Pi^{FS}_t = \sum_j r\Lambda_{j,t} + r^* B_t. \tag{33}$$

The financial sector has no operational cost. The interest rate on granted loans (r) is an exogenously given constant determined by applying a constant spread ($\varsigma > 0$) over a fixed policy rate (r^*) set by the government:

$$r = (1 + \varsigma) r^*. \tag{34}$$

The credit money supply is limited by the net worth of the financial sector through a simplified Basel capital adequacy ratio (CAR):

$$\Lambda_t^{max} = \frac{NW_{t-1}^{FS}}{CAR}, \tag{35}$$

with $CAR > 0$.

2.5 Households

As previously mentioned, each household can assume one of four roles: direct worker, manager, researcher, or capitalist. These roles are category-specific and not fixed to individual agents. In other words, a household may serve as an indirect worker in one period and as a direct worker in the next. The labor supply is exogenously given and constant. If the demand for labor exceeds its supply, the constraint is equally shared across firms.

Wage setting is firm-specific but uniform across all workers within the same firm. Direct workers receive the wage $W_{i,t}^W$ or $W_{j,t}^W$ paid by the capital and consumption goods firms that hire them, respectively. The same applies to managers and researchers. Meanwhile, capitalists receive dividends based on firm ownership. Lastly, unemployed workers (L_t^U) receive an unemployment benefit (W_t^U) from the government.

The working class set their desired wage as described by the following equation:

$$W_t^d = W_{t-1}^d \left[1 + \psi_1 \frac{\Delta \overline{LP}_t^C}{\overline{LP}_{t-1}^C} + \psi_2 \frac{\Delta \pi_t}{\pi_{t-1}} \right], \tag{36}$$

with $\psi_1, \psi_2 > 0$, and where W_t^d is the desired nominal wage in period t, $\overline{LP}_{i,t}^C$ is the average labor productivity in the consumption goods sector in period t, and π_t is the inflation rate in the same the period. As mentioned earlier, the wage bargaining process is firm-specific.

Household consumption depends on their available income after taxation. The parameters $\tau_w \in (0,1)$ and $\tau_d \in (0,1)$ represent the marginal tax rate on wages and dividends, respectively. Aggregate consumption is given by:

$$C_t^W = c_W(1-\tau_w) \left\{ \sum_i \left[W_{i,t}^W L_{i,t}^W + W_{i,t}^M (L_{i,t}^M + L_{i,t}^{RD}) \right] + \sum_j \left[W_{j,t}^W L_{j,t}^W + W_{j,t}^M L_{j,t}^M + W_t^U L_t^U \right] \right\} + c_K(1-\tau_d) \left[\sum_i Div_{i,t} + \sum_j Div_{j,t} \right] \tag{37}$$

where the parameters $c_W \in (0,1)$ and $c_K \in (0,1)$ represent the marginal propensities to consume out of income for worker and capitalist households, respectively. All available income of households that is not consumed is then held in the form of bank deposits.

2.6 Government

The government conducts fiscal policy, while monetary policy is abstracted from by assuming a constant, exogenously given policy rate $r^* \in (0,1)$. The government has two sources of funding: taxes (T_t) and bonds (B_t). Taxes are set over sales, wages and dividends at the exogenous flat rate $\tau, \tau_w, \tau_d \in (0,1)$, respectively. Bonds ($B_t$) are considered risk-free and are purchased either by the financial sector at issuance or by the central bank. On the expenditures side, the government pays unemployment benefits ($W_t^U L_t^U$) and places an induced demand for consumption goods (ϵY_{t-1}), where $\epsilon \in (0,1)$. The government budget constraint is given by:

$$\begin{aligned} \tau \left(\sum_j p_{j,t} Q_{j,t} + \sum_i p_{i,t} K_{i,t} \right) + \\ \tau_w \left\{ \sum_i \left[W_{i,t}^W L_{i,t}^W + W_{i,t}^M (L_{i,t}^M + L_{i,t}^{RD}) \right] + \sum_j \left[W_{j,t}^W L_{j,t}^W + W_{j,t}^M L_{j,t}^M \right] \right\} + \\ \tau_d \left[\sum_i Div_{i,t} + \sum_j Div_{j,t} \right] + \Delta B_t = T_t + \Delta B_t = W_t^U L_t^U + \epsilon Y_{t-1} + r^* B_t. \end{aligned} \tag{38}$$

3 Decarbonization policies

We examine the macroeconomic effects of policies aimed at promoting technological shifts in the productive structure toward less carbon-intensive investment and output production. While environmental policies are essential for enabling and accelerating the decarbonization process, they can also lead to unintended adverse economic consequences. For instance, there is ongoing debate in academic and policy circles about whether it is possible to simultaneously reduce emissions *and* income inequality. Our research addresses this question by focusing on the intersection of environmental policy effectiveness and their socioeconomic impacts.

We examine four distinct environmental policy interventions: a price subsidy for the least polluting firms (Johnstone et al., 2010), a research-support subsidy to foster private innovation (Bai et al., 2019), public support to non-patented R&D (Mazzucato, 2011) and, finally, public procurement oriented to the least polluting firms (Krieger and Zipperer, 2022). The selected policies were chosen for the considerable prominence in the academic and public policy debates.[2]

The first is a price subsidy targeting the 25% least carbon-intensive capital goods firms. Under this environmental policy, the final price of a machine from these firms in Equation (8) is reduced to $\hat{p}_{i,t} = p_{i,t} - s_t$, making it more competitive. The price subsidy s_t is funded by the government and experimentally capped at 50% of the original price.

The second policy is a lump-sum research subsidy granted to all capital goods firms, which supplements their green R&D budgets in Equation (1) by an amount RD^S_t. As a result, the total green R&D budget of an individual capital goods firm i becomes $RD^{CI}_{i,t} = \nu\Pi_{i,t} + RD^S_t$. This research subsidy is thus allocated to hiring additional researchers dedicated to green innovation, thereby increasing the probability of discovering new, lower carbon intensity technologies.

The third environmental policy intervention examines whether public-sector-led research can more effectively address the challenges of decarbonization. Instead

[2] For an extensive survey of the links between environmental policy and technological innovation, see Popp (2019).

of distributing research subsidies to capital goods firms, this environmental policy entails establishing a publicly owned research lab that invests in non-patented green R&D, inspired specifically by the concept of the entrepreneurial state (Mazzucato, 2011; Dosi et al., 2023). The suggested government's innovation process mirrors that of the capital goods sector: the government hires researchers who have a certain probability of innovating and finding a new, lower carbon intensity coefficient. When the government is successful in finding such a new coefficient, the corresponding green technology then becomes freely available for use by any capital goods firm.[3]

The fourth environmental policy intervention involves a public procurement strategy, in which the government directs its demand for capital goods toward the 25% least carbon-intensive firms in the sector. The distribution of green public procurement is uniform across selected firms, irrespective of their relative price competitiveness.

A key analytical contribution of our work is the examination of how these policies are financed—an aspect often overlooked in the related (including the agent-based) modeling literature. We compare two distinct tax-based financing strategies, chosen for the prominence in the academic and public policy debates. The first is a carbon tax, widely considered the gold standard of climate policy owing to its potential ability to internalize the negative externalities of carbon emissions (World Bank, 2024). To implement a carbon tax, the government imposes a marginal rate $\tau_{ci} > 0$ on

[3]The government conducts its innovation process prior to the firm. The firm then undertakes its own innovation process, adopting the government's carbon intensity parameter if it represents an improvement over its own. This adoption occurs internally, as if the firm had discovered the improvement itself. Yet, the resulting final technology is still subject to comparison with existing capital vintages to assess its price competitiveness.

emissions from capital and consumption goods firms, which raises their nominal unit cost of production in Equations (7) and (22) by $\tau_{ci} CI^h_{i,t}$ for $h \in \{K, C\}$, respectively. Due to mark-up pricing by firms in both sectors, there is a tax shift to prices, leading to broader macroeconomic effects.

The second is a wealth tax, which has recently gained support as a tool to close the green financing gap while addressing both climate and income inequalities (Chancel et al., 2024). The wealth tax is implemented by applying a marginal rate $\tau_A > 0$ on capitalists' stock of wealth, but it is paid out of the flow of dividend income. This reduces available income and may lead to broader macroeconomic effects.

We simulate fiscally neutral scenarios with equivalent policy sizes to ensure comparability. In practice, the government sets a budgetary target to finance its policies and adjusts the tax rate accordingly to meet this revenue goal. The collected funds are then allocated to support the corresponding decarbonization interventions. Since each policy is paired with a dedicated revenue source that meets or exceeds its cost, the framework is fiscally neutral by design.[4]

4 Results

The results show the relative changes in selected variables after the specific environment policy was implemented. In the figures below, each simulated post-policy series is normalized by dividing it by its corresponding baseline value. Therefore, a ratio greater than one indicates an increase relative to the baseline, while a ratio less than

[4] As shown in the transaction flow matrix in Table 2 in Appendix A, the model developed in this paper is fully stock-flow consistent.

one indicates a decrease.[5]

Before examining each policy in detail, it is helpful and analytically informative to first revisit how the decarbonization process operates within the model's structure. This will facilitate the understanding of the results presented and discussed below. In our framework, decarbonization is primarily driven by technological change aimed at reducing the carbon intensity of economic production through decoupling. This process is shaped by economic incentives, such as price competition and policy support, which influence the pace and direction of innovation. Achieving decarbonization requires firms to innovate and develop technologies with lower carbon intensity. This innovation depends on the level of R&D effort undertaken by capital goods firms, which is influenced by their profitability and follows a stochastic process. Once a new technology is discovered, its adoption as the firm's dominant technological standard is determined by a comparison of nominal unit production costs, labor productivity, and carbon intensity relative to existing technologies. Capital goods firms then compete to sell their machines to consumption goods firms based on this cost-benefit analysis. It is important to note that availability of a cleaner technology alone is not sufficient to reduce the carbon intensity of production. It is only when these new machines are incorporated in the production processes of consumption goods firms that the innovation effectively diffuses throughout the economy. In the business-as-usual (BAU) scenario, there is no inherent incentive to the adoption of cleaner technologies beyond random chance. Nevertheless, the BAU scenario is calibrated to align with the empirically observed gradual reduction in carbon intensity (Hubacek

[5]The model validation procedures and results are described in Appendix B, whereas the parameter values in the baseline scenario are presented in Appendix D.

et al., 2021). As a result, the decarbonization process only accelerates when there is an economic incentive affecting one of the steps outlined above.

However, these economic incentives may lead to unintended consequences for income distribution and output growth. In the following sub-sections, we explore the potential emissions-distribution-growth trilemma across different combinations of tax-financing strategies and environmental policies. On the environmental front, we focus on two key aspects: the carbon intensity of production—which captures the degree of decoupling between economic activity and emissions—and total aggregate emissions, which constitute the primary target of environmental policies. Income distribution is evaluated from both a personal perspective, using the Gini Index, and a functional perspective, through the wage share of income. Finally, we consider the effect of the carbon intensity of production and total aggregate emissions on economic growth, which is both influenced by income distribution (Carvalho and Rezai, 2015; Rezai et al., 2018; Oliveira and Lima, 2022) and a driver of environmental impact, as higher levels of production generally lead to increased aggregate emissions (Vogel and Hickel, 2023).

4.1 Carbon tax financing

We begin by examining the first tax-financed scenario: the implementation of a carbon tax, which serves as both a financing and an environmental policy instrument. In our model, the carbon tax applies to the production activities of both consumption and capital goods firms. By increasing nominal unit production costs through tax shifting, the carbon tax raises the relative cost of carbon-intensive production,

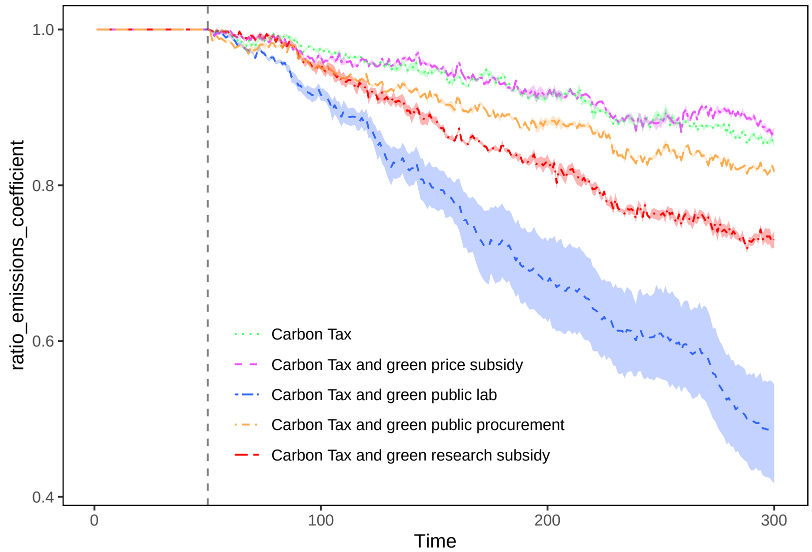


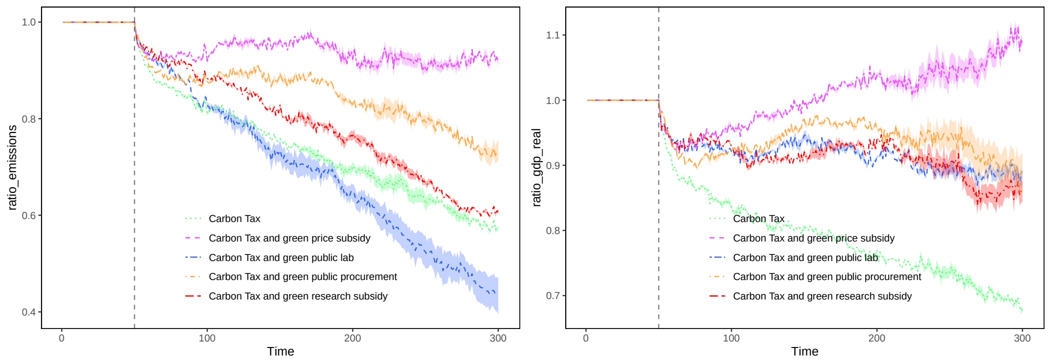
Figure 2: Carbon intensity coefficient ratio following policy intervention

Note: The vertical line marks the timing of the policy intervention. Each series represents the median of 50 Monte Carlo simulations per scenario, with the shaded are indicating the 95% confidence interval.

thereby creating economic incentives to adopt cleaner technologies. As a result, low-carbon machinery becomes more price competitive, encouraging its adoption and diffusion. Indeed, our results show that the carbon tax lowers the average carbon intensity of the economy (Figure 2). Additionally, we find that the carbon tax effectively reduces aggregate emissions (Figure 3a). However, it is important to note that the overall decline in aggregate emissions arises not only from lower carbon intensity in production, but also from a slowdown in economic growth (Figure 3b).

There are two main channels through which the carbon tax negatively impacts output growth. First, by raising the cost of new capital, the carbon tax slows technological adoption and diffusion, while also shifting technological change toward green innovation. As the relative importance of green innovation increases at the expense of productivity-enhancing innovation, economic growth decelerates, leading to a divergence in GDP levels between the baseline and the carbon tax scenario. Second, the carbon tax has adverse side effects on income distribution. Higher capital costs exert upward pressure on the consumer price index (Figure 4a). Acting as a cost shock, the carbon tax—combined with firms' mark-up pricing behavior—leads to a coordinated increase in final goods prices. Moreover, the decline in economic activity results in a higher unemployment rate (Figure 4b), which weakens workers' bargaining power. In this context, firms are able to pass the additional costs on to consumers, as real wages fail to keep up with inflation. At the aggregate level, this is reflected in a falling wage share (Figure 5a), as real wages lag behind rising profits. At the individual level, the carbon tax is inherently regressive, disproportionately affecting workers, who have a higher propensity to consume than capital owners. Additionally, higher profits lead to higher dividend payouts to capital owners, whose incomes higher than those of workers. These dynamics contribute to an increase in the Gini index (Figure 5b), highlighting the negative distributional effects of the carbon tax. In turn, this worsening income inequality feeds back into weaker aggregate demand, further dampening economic activity.

In summary, while the carbon tax contributes to emission reductions, the efficiency gains from technological improvements are modest. Most of the reduction in emissions results from a slowdown in economic activity, rather than from significant improvements in carbon intensity. However, when carbon taxation is combined with the policy interventions outlined in Section 3, a different set of outcomes emerges. First, we observe that carbon intensity of production is most significantly reduced



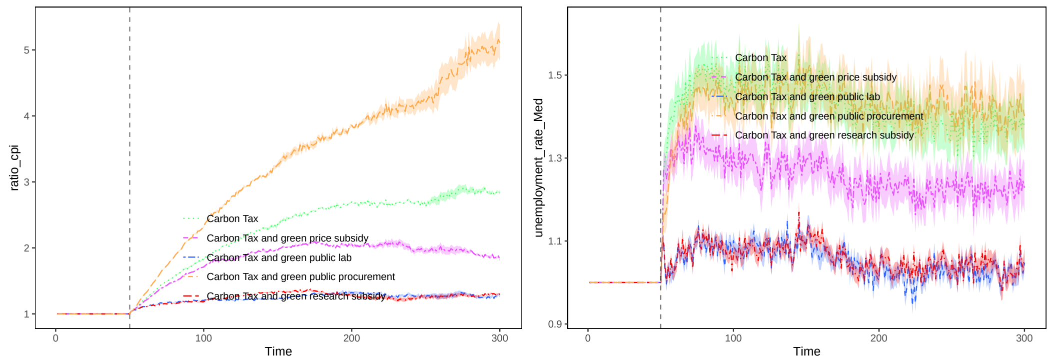
(a) Aggregate emissions (b) GDP

Figure 3: Aggregate emissions and GDP ratios following policy intervention

Note: The vertical line marks the timing of the policy intervention. Each series represents the median of 50 Monte Carlo simulations per scenario, with the shaded are indicating the 95% confidence interval.

when research-oriented policies are implemented (Figure 2). This result is intuitive, as the decarbonization process in our model depends on technological upgrading and the diffusion of less carbon-intensive machinery. From this perspective, policies that directly stimulate green innovation are the most effective at lowering firms' carbon intensity. Consistent with this, we find that a publicly owned research lab outperforms decentralized research subsidies. This is because, once a new green technology is developed through public research, it becomes immediately available to all firms due to its non-patented nature. This accelerates technological diffusion beyond what would occur under purely competitive market conditions. Importantly, this policy does not involve breaking existing private patents but rather leverages the government's coordination capacity to promote and disseminate strategic technologies.

When we examine the impact on aggregate emissions, we find that the combination of carbon taxation with a green public research lab results in the largest overall

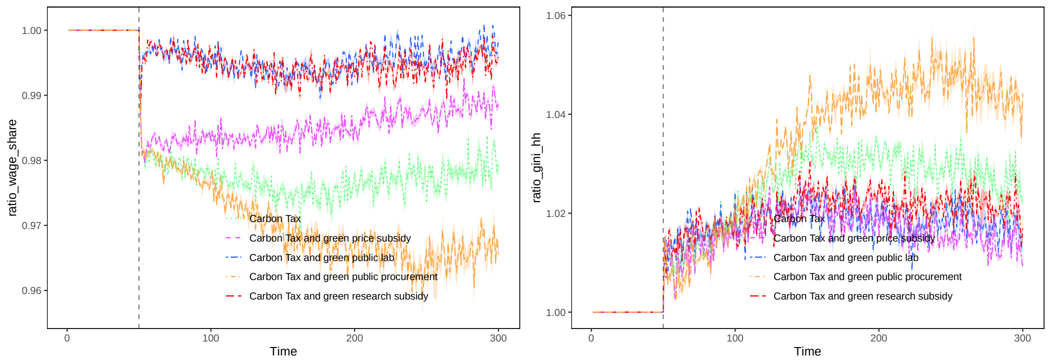


(a) Consumer price index (CPI) (b) Unemployment rate

Figure 4: Consumer price index and unemployment rate ratios following policy intervention

Note: The vertical line marks the timing of the policy intervention. Each series represents the median of 50 Monte Carlo simulations per scenario, with the shaded are indicating the 95% confidence interval.

reduction in aggregate emissions (Figure 3a). Interestingly, carbon taxation itself is the second most effective scenario, despite achieving a smaller reduction in the carbon intensity coefficient. This is primarily due to its previously noted recessive effect on economic activity. The GDP loss is smaller when carbon taxation is combined with other decarbonization policies, as evidenced by the reduced GDP divergence under the research subsidy and public procurement scenarios. This is due to rebound macroeconomic effects. These policies help offset the economic disincentives introduced by the carbon tax, as they are demand-stimulating interventions that improve the profitability of affected firms and encourage their R&D efforts, thereby supporting growth more broadly. In contrast, carbon taxation alone acts as a penalizing instrument, imposing costs without providing compensatory mechanisms to directly stimulate growth or innovation. Notably, the combination of a carbon tax



(a) Wage share

(b) Gini index

Figure 5: Wage share and Gini index ratios following policy intervention

Note: The vertical line marks the timing of the policy intervention. Each series represents the median of 50 Monte Carlo simulations per scenario, with the shaded are indicating the 95% confidence interval.

with a price subsidy is the only scenario in which GDP loss disappears over time. This outcome arises because the subsidy partially offsets the burden of the carbon tax, allowing capital goods firms to shift toward cleaner technologies without experiencing a significant loss in competitiveness. Because economic activity accelerates more rapidly than carbon intensity declines, the combination of a price subsidy with carbon taxation ultimately leads to an increase in aggregate emissions, despite improvements in green technology. This outcome highlights the limitations of relying solely on technological change for decarbonization (Victor, 2019).

The introduction of decarbonization policies also helps partially mitigate the regressive distributional effects of the carbon tax. Notably, in scenarios where research-oriented policies are implemented, income inequality is least affected. As shown in Figure 4a, these scenarios exhibit a moderate impact on the consumer price index, indicating that research and innovation play a key role in reducing inflationary pressures—an important factor in the distribution of real income (recall that in Figures (3a)-(9b), a ratio less than one indicates a decrease relative to the baseline, while a ratio greater than one indicates an increase).

Moreover, by stimulating increased R&D efforts and accelerating the pace of innovation, these policies expand the technological discovery space and boost productivity gains, partially mitigating the recessive consequences of the carbon tax. Due to the feedback loops between income inequality and aggregate demand, we observe improved outcomes across multiple dimensions—including a lower Gini index, a higher wage share, and stronger output growth. Overall, our findings suggest that research policies are among the most effective 'positive' interventions when paired with a carbon tax as a financing mechanism. They not only accelerate the decarbonization process but also help minimize its adverse effects on income inequality and economic growth.

4.2 Wealth tax financing

Recent discussions have emphasized the potential of using a wealth tax to finance decarbonization policies (Chancel et al., 2024). Unlike a carbon tax, a wealth tax is not intended to directly influence environmental outcomes directly, as it does not create direct incentives for firms to invest in or adopt cleaner technologies, nor does it encourage a shift to greener production choices. Its primary function is redistributive: by targeting the accumulated wealth of capitalists, it seeks to reduce income inequality. Our simulation results reflect this logic. When the wealth tax is implemented as a standalone policy, we observe no significant reduction in the carbon intensity of production (Figure 6). This supports the notion that, in the absence of green policy signals or technological incentives, firms tend to maintain their existing production structures and emissions profiles.

However, the wealth tax results in a noticeable improvement in personal income inequality, as evidenced by the decline in the Gini index (Figure 9b). This outcome reflects the redistributive nature of the wealth tax, which reallocates resources from wealthy households to the public sector. Nevertheless, since the generated tax revenues are not re-injected into the economy through increased public spending or decarbonization policies, the wealth tax exerts a contractionary effect on aggregate demand. As a result, overall economic activity slows (Figure 7b), leading to a moderate reduction in total emissions (Figure 7a).

It is important to note that even when combined with decarbonization policies, the overall impact of the wealth tax on the carbon intensity of production remains limited. These interventions yield weaker results compared to scenarios where a carbon tax is implemented. This outcome is fairly intuitive: without a cost-based economic disincentive such as a carbon tax, firms have little inherent motivation to transition to cleaner technologies. This suggest that indirect economic incentives are of limited effectiveness when firms act according to cost-benefit rationality. If cleaner technologies do not lower costs or increase profits, firms have minimal incentive to adopt them, even in the presence of subsidies or public investments. Naturally, this perspective is open to criticism, as the concept of a rational economic agent rarely reflects real-world behavior. However, regarding firm behavior, it is more reasonable to assume that, even if only in a stylized way, firms act according to a cost-benefit

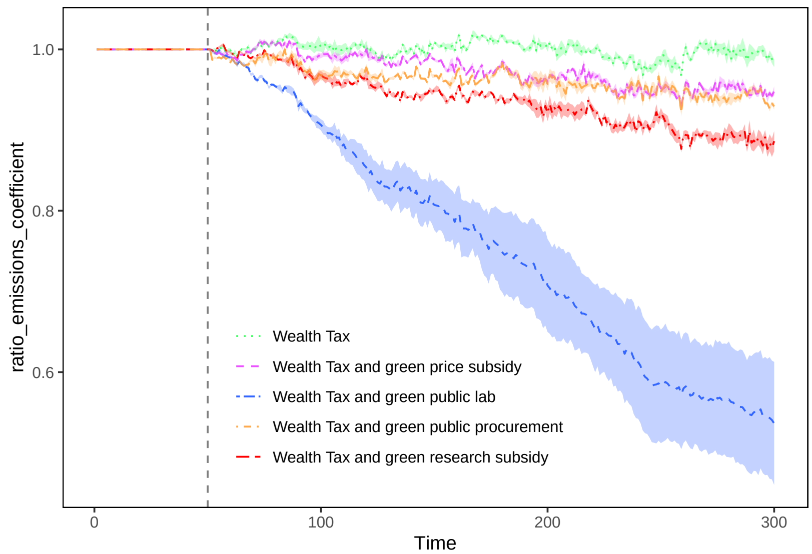


Figure 6: Carbon intensity coefficient ratio following policy intervention

Note: The vertical line marks the timing of the policy intervention. Each series represents the median of 50 Monte Carlo simulations per scenario, with the shaded are indicating the 95% confidence interval.

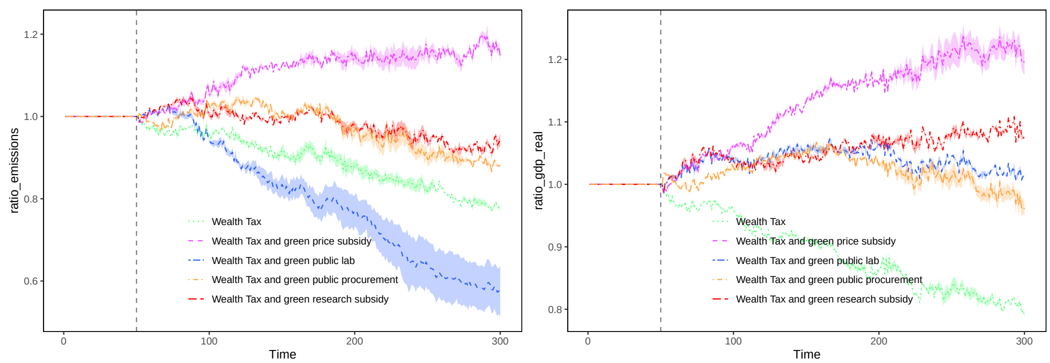
logic that places production costs at the center of their decision-making.[6]

However, despite the limited effectiveness of most simulated decarbonization interventions financed by a wealth tax, the outcome of the green public lab scenario stands out. Even when funded through a wealth tax, it significantly accelerates the reduction in the carbon intensity of production. The absence of cost-based economic incentives does not diminish its relative effectiveness, which relies on the easier diffusion of green technologies beyond competitive price dynamics. Once a new, less carbon-intensive innovation is developed, it becomes accessible to all firms, allowing

[6] A growing strand of literature on green transitions has sought to incorporate environmental preferences, social norms, or sustainability-oriented corporate strategies (e.g., (Dávila-Fernández et al., 2024)). While these approaches provide valuable insights, they fall outside the scope of the present analysis.

them to incorporate it into their own R&D processes. This underscores a broader insight: the diffusion of strategic technologies and knowledge depends heavily on cooperation rather than market competition alone. In this context, the government plays a crucial role as the sole economic agent capable of fostering such coordination. In our model, this is achieved through a publicly owned research lab and non-patented technologies. Evidence on the importance of public-led research on technological development supports this claim (Mazzucato, 2011; Mazzoleni and Nelson, 2007).

Examining the impact on aggregate emissions, we again confirm the effectiveness of the green public lab in accelerating decarbonization (Figure 7a). In contrast, the effects of other policy combinations are less pronounced, as they neither substantially improve the carbon intensity of production nor significantly reduce the economic growth rate. Notably, unlike the carbon tax policy mixes discussed in the preceding sub-section, the decarbonization interventions financed through the wealth tax are able to fully offset the contractionary effects of the tax on economic activity. This is largely due to the redistributive nature of the wealth tax: when its revenue is re-injected into the economy, it compensates for the initial aggregate demand reduction caused by the tax. In contrast, the carbon tax, when applied in isolation, not only suppresses aggregate demand but also exacerbates income inequality. This deterioration in income distribution further undermines aggregate demand, reinforcing the recessionary dynamics. In this context, the price subsidy intervention stands out as the scenario in which GDP growth rates increases the most following the shock. However, emissions rise despite the green intent of the intervention due to rebound effects from the stronger economic activity.



(a) Aggregate emissions (b) GDP

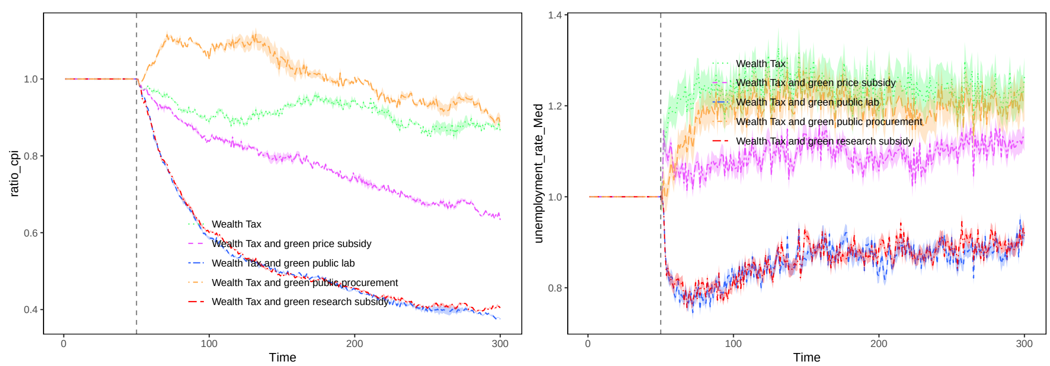
Figure 7: Aggregate emissions and GDP ratios following policy intervention

Note: The vertical line marks the timing of the policy intervention. Each series represents the median of 50 Monte Carlo simulations per scenario, with the shaded are indicating the 95% confidence interval.

Lastly, as previously noted, income inequality outcomes improve across all wealth tax financing scenarios. The impact on the Gini index is clear and consistent: taxing wealthy capitalists with accumulated savings reduces personal income inequality (Figure 9b). In contrast, the effect on the wage share is less straightforward (Figure 9a). While most scenarios show a modest increase in the wage share, the effect is most significant when research policies are implemented alongside the wealth tax. This outcome can be attributed to labor market dynamics and inflationary effects.

The primary factor driving the increase in the wage share is the decline in the consumer price index relative to the baseline (Figure 8a). Because of nominal wage rigidity, falling prices lead to higher real wages. This dynamic allows the wage share to rise even when worker bargaining power is weakened, as reflected in higher unemployment rates (Figure 8b). The green procurement scenario illustrates this mechanism well: initially, inflationary pressure from procurement offsets any potential gains in the wage share.

However, as the consumer price index gradually declines over time, the wage share begins to rise, even though unemployment remains stable and above the baseline. In contrast, scenarios that combine wealth taxation with research policies benefit from both a lower consumer price index and falling unemployment, leading to the most significant increase in the wage share. This underscores the complex interplay between inflation, labor market dynamics, and income distribution across different policy mixes.



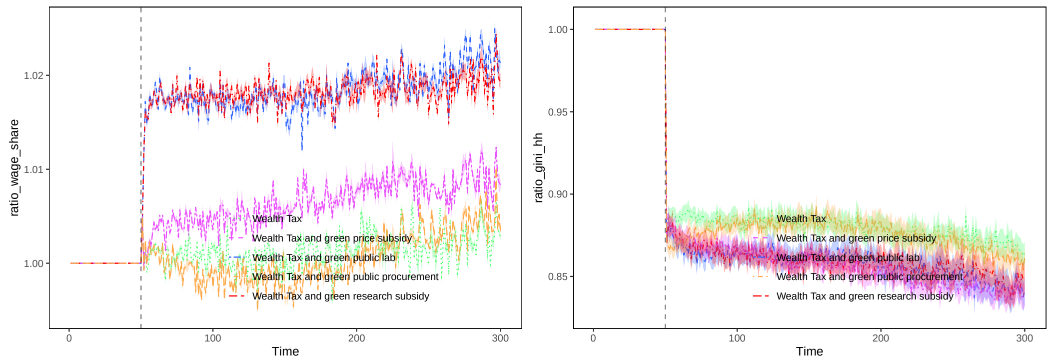
(a) Consumer price index (CPI)

(b) Unemployment rate

Figure 8: Consumer price index and unemployment rate ratios following policy intervention.

Note: The vertical line marks the timing of the policy intervention. Each series represents the median of 50 Monte Carlo simulations per scenario, with the shaded are indicating the 95% confidence interval.

The simulation results presented and discussed so far are summarized in Table 1, which ranks tax-financing instruments and their combinations with environmental policies in decreasing order of effectiveness for each outcome of interest. A *decrease* is the desired outcome for the carbon intensity coefficient, aggregate emissions, the



(a) Wage share (b) Gini index

Figure 9: Wage share and Gini index ratios following policy intervention.

Note: The vertical line marks the timing of the policy intervention. Each series represents the median of 50 Monte Carlo simulations per scenario, with the shaded are indicating the 95% confidence interval.

Gini index, the unemployment rate, and the CPI, while an *increase* is preferred for GDP and the wage share in turn. The business-as-usual baseline is shown in black. Scenarios in which the average performance exhibits a deviation from the latter in the *desired direction* are highlighted in green. Those exhibiting deviations in the *opposite direction* are highlighted in red. The scenarios are ranked from the best-performing (1) to the worst-performing (11). For example, as shown in the second column, both tax-financing mechanisms—whether used alone or combined with an environmental policy—succeed in reducing carbon intensity, with the combination of a carbon tax and a public research lab doing non-patented green R&D being the most effective.[7]

[7] To further understand the model's behavior and ensure the robustness of the results, Appendix C presents a global sensitivity analysis based on joint variations of key parameters.

Scenario	Carbon intensity	GHG emissions	GDP	Gini index	Wage share	Unemployment rate	CPI
Business as usual (BAU)	11	10	5	6	6	3	6
Wealth tax	10	6	10	5	4	8	4
Wealth tax + Price subsidy	9	11	1	1	3	6	3
Wealth tax + Public procurement	8	7	6	4	5	7	5
Wealth tax + Research subsidy	7	9	2	3	2	2	2
Carbon tax + Price subsidy	6	8	3	7	9	9	9
Carbon tax	5	2	11	10	10	10	10
Carbon tax + Public procurement	4	5	7	11	11	11	11
Carbon tax + Research subsidy	3	4	9	9	8	5	7
Wealth tax + Public research lab	2	3	4	2	1	1	1
Carbon tax + Public research lab	1	1	8	8	7	4	8

Table 1: Relative effectiveness of tax-financing mechanisms and their combinations with environmental policies across outcomes of interest.

Note: Scenarios with average performance exhibiting a change from the BAU baseline in the desired direction are highlighted in green, while those exhibiting a change from BAU in the opposite direction are highlighted in red. The scenarios are ranked from the best-performing (1) to the worst-performing (11).

5 Conclusion

Decarbonization entails changes in productive structures that are likely to result in unintended and unforeseen socioeconomic consequences. From an optimistic perspective, a low-carbon economy can be achieved by combining emission reductions with sustained economic growth and decreasing income inequality. This vision has gained global prominence, as various stakeholders have called for a "green and just transition". However, a more pessimistic outlook emerges from the specialized literature, highlighting significant trade-offs associated with decarbonization, particularly when considering economic growth and income distribution. Specifically, evidence suggests the existence of a trilemma involving lower carbon emissions, reduced income inequality, and economic growth.

This article addresses some of the complexities underlying the trilemma hypothesis. Using an agent-based with a simplified wage bargaining process and a tripartite class structure, it simulates the combined impacts of financing and environmental policy instruments that could drive decarbonization on personal and functional income distribution. The simulations focus on two distinct tax-financing instruments—a carbon tax and a wealth tax—and four different green policy instruments: price subsidy for the least polluting firms, public non-patented green R&D, subsidy for private green R&D, and green public procurement.

Table 1, presented in the preceding section, summarizes the potential and actual trade-offs and trilemmas among boosting economic activity, reducing carbon intensity and aggregate emissions, and lowering income inequality. In fact, the only combinations of tax-financing mechanisms and environmental policies that achieve all these desirable outcomes are: (1) a wealth tax coupled with funding for a public research lab focused on non-patented green R&D, and (2) a wealth tax combined with a lump-sum research subsidy granted to capital goods firms, with the former proving to be the most effective on average.

At this point, two main conclusions are worth highlighting. First, although not a typical environmental policy instrument, the wealth tax can be an effective means of financing the transition to low-carbon economies when combined with other interventions. Compared to the carbon tax, it provides an inherent redistributive mechanism from the outset, reducing the risks of unintended consequences that may exacerbate income inequality. Second, as green innovation emerges as a key driver of decarbonization, it is important to recognize that it can be fostered through various institutional arrangements between public and private entities. The choice of such arrangements is not neutral, as it presents different opportunities for mitigating the contradictions of the decarbonization trilemma.

References

Alvarenga, M. and Young, C. E. F. (2024). Principles for building a post-Keynesian environmental macroeconomics: Revisiting Keynes in times of crises 1. In *Environment and Ecology in the History of Economic Thought*, pages 107–122. Routledge.

Babecký, J., Du Caju, P., Kosma, T., Lawless, M., Messina, J., and Rönn, T. (2010). Downward nominal and real wage rigidity: Survey evidence from european firms. *Labour Economics*, 17(3):323–334.

Bai, Y., Song, S., Jiao, J., and Yang, R. (2019). The impacts of government r&d subsidies on green innovation: Evidence from chinese energy-intensive firms. *Journal of cleaner production*, 233:819–829.

Barth, E., Bryson, A., Davis, J. C., and Freeman, R. (2016). It's where you work: Increases in the dispersion of earnings across establishments and individuals in the united states. *Journal of Labor Economics*, 34(S2):S67–S97.

Caiani, A., Godin, A., Caverzasi, E., Gallegati, M., Kinsella, S., and Stiglitz, J. E. (2016). Agent based-stock flow consistent macroeconomics: Towards a benchmark model. *Journal of Economic Dynamics and Control*, 69:375–408.

Carlin, W. and Soskice, D. (2014). *Macroeconomics: Institutions, Instability, and the Financial System.* Oxford University Press.

Carvalho, L. and Rezai, A. (2015). Personal income inequality and aggregate demand. *Cambridge Journal of Economics*, 40(2):491–505.

Caverzasi, E. and Godin, A. (2015). Post-keynesian stock-flow-consistent modelling: a survey. *Cambridge Journal of Economics*, 39(1):157–187.

Chancel, L., Bothe, P., and Voituriez, T. (2024). The potential of wealth taxation to address the triple climate inequality crisis. *Nature Climate Change*, 14(1):5–7.

Cioppa, T. M. and Lucas, T. W. (2007). Efficient nearly orthogonal and space-filling latin hypercubes. *Technometrics*, 49(1):45–55.

Couix, Q. (2019). Natural resources in the theory of production: the georgescu-roegen/daly versus solow/stiglitz controversy. *The European Journal of the History of Economic Thought*, 26(6):1341–1378.

Dafermos, Y., Nikolaidi, M., and Galanis, G. (2018). Climate change, financial stability and monetary policy. *Ecological Economics*, 152:219–234.

Dávila-Fernández, M. J., Sordi, S., and Cafferata, A. (2024). How do you feel about going green? modelling environmental sentiments in a growing open economy. *Journal of Economic Interaction and Coordination*, 19(4):649–687.

Dickens, W. T., Goette, L., Groshen, E. L., Holden, S., Messina, J., Schweitzer, M. E., Turunen, J., and Ward, M. E. (2007). How wages change: micro evidence from the international wage flexibility project. *Journal of Economic Perspectives*, 21(2):195–214.

Doda, B. (2014). Evidence on business cycles and CO2 emissions. *Journal of Macroeconomics*, 40:214–227.

Dosi, G. (2005). Statistical regularities in the evolution of industries: a guide through some evidence and challenges for the theory. Technical report, LEM working paper series.

Dosi, G., Fagiolo, G., and Roventini, A. (2010). Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles. *Journal of Economic Dynamics and Control*, 34(9):1748–1767.

Dosi, G., Lamperti, F., Mazzucato, M., Napoletano, M., and Roventini, A. (2023). Mission-oriented policies and the "entrepreneurial state" at work: An agent-based exploration. *Journal of Economic Dynamics and Control*, 151:104650.

Dosi, G., Napoletano, M., Roventini, A., Stiglitz, J. E., and Treibich, T. (2020). Rational heuristics? Expectations and behaviors in evolving economies with heterogeneous interacting agents. *Economic Inquiry*, 58(3):1487–1516.

Dosi, G. and Virgillito, M. E. (2021). In order to stand up you must keep cycling: Change and coordination in complex evolving economies. *Structural Change and Economic Dynamics*, 56:353–364.

D'Alessandro, S., Cieplinski, A., Distefano, T., and Dittmer, K. (2020). Feasible alternatives to green growth. *Nature Sustainability*, 3(4):329–335.

European Parliament and Council of the European Union (2024). REGULATION (EU) 2024/1735 OF THE EUROPEAN PARLIAMENT AND OF THE COUN-

CIL of 13 June 2024 on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724. Official Journal of the European Union, L, 1735.

Fagiolo, G., Guerini, M., Lamperti, F., Moneta, A., and Roventini, A. (2019). Validation of agent-based models in economics and finance. In Beisbart, C. and Saam, N., editors, *Computer Simulation Validation: Fundamental Concepts, Methodological Frameworks, and Philosophical Perspectives*, pages 763–787. Springer.

Farmer, J. D. and Foley, D. (2009). The economy needs agent-based modelling. *Nature*, 460(7256):685–686.

Fontana, G. and Sawyer, M. (2016). Towards post-keynesian ecological macroeconomics. *Ecological Economics*, 121:186–195.

Foramitti, J., Savin, I., and van den Bergh, J. C. (2024). How carbon pricing affects multiple human needs: An agent-based model analysis. *Ecological Economics*, 217:108070.

Geels, F. W. and Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy*, 36(3):399–417.

Geels, F. W., Sovacool, B. K., Schwanen, T., and Sorrell, S. (2017). Sociotechnical transitions for deep decarbonization. *Science*, 357(6357):1242–1244.

Gerst, M. D., Wang, P., Roventini, A., Fagiolo, G., Dosi, G., Howarth, R. B., and Borsuk, M. E. (2013). Agent-based modeling of climate policy: An introduction to the engage multi-level model framework. *Environmental modelling & software*, 44:62–75.

Godley, W. and Lavoie, M. (2016). *Monetary economics: an integrated approach to credit, money, income, production and wealth*. Springer.

Hardt, L. and O'Neill, D. W. (2017). Ecological macroeconomic models: assessing current developments. *Ecological economics*, 134:198–211.

Hubacek, K., Chen, X., Feng, K., Wiedmann, T., and Shan, Y. (2021). Evidence of decoupling consumption-based CO2 emissions from economic growth. *Advances in Applied Energy*, 4:100074.

IPCC (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland.

Isley, S. C., Lempert, R. J., Popper, S. W., and Vardavas, R. (2015). The effect of near-term policy choices on long-term greenhouse gas transformation pathways. *Global Environmental Change*, 34:147–158.

Jackson, T. (2009). *Prosperity without growth: Economics for a finite planet*. Routledge.

Johnstone, N., Haščič, I., and Popp, D. (2010). Renewable energy policies and technological innovation: evidence based on patent counts. *Environmental and resource economics*, 45(1):133–155.

Kleimann, D., Poitiers, N., Sapir, A., Tagliapietra, S., Véron, N., Veugelers, R., and Zettelmeyer, J. (2023). Green tech race? The US inflation reduction act and the EU net zero industry act. *The World Economy*, 46(12):3420–3434.

Krieger, B. and Zipperer, V. (2022). Does green public procurement trigger environmental innovations? *Research Policy*, 51(6):104516.

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., and Sapio, A. (2018). Faraway, so close: Coupled climate and economic dynamics in an agent-based integrated assessment model. *Ecological Economics*, 150:315–339.

Maestri, V. and Roventini, A. (2012). Stylized facts on business cycles and inequality. Technical report, Technical Report, AIAS, Amsterdam Institute for Advanced Labour Studies.

Mastini, R., Kallis, G., and Hickel, J. (2021). A green new deal without growth? *Ecological Economics*, 179:106832.

Mazzoleni, R. and Nelson, R. R. (2007). Public research institutions and economic catch-up. *Research policy*, 36(10):1512–1528.

Mazzucato, M. (2011). The entrepreneurial state. *Soundings*, 49(49):131–142.

Monasterolo, I. and Raberto, M. (2018). The EIRIN flow-of-funds behavioural model of green fiscal policies and green sovereign bonds. *Ecological Economics*, 144:228–243.

Monasterolo, I., Roventini, A., and Foxon, T. J. (2019). Uncertainty of climate policies and implications for economics and finance: An evolutionary economics approach. *Ecological Economics*, 163:177–182.

Okun, A. M. (1963). *Potential GNP: its measurement and significance*. Cowles Foundation for Research in Economics at Yale University.

Oliveira, G. and Lima, G. T. (2022). Economic growth as a double-edged sword: The pollution-adjusted Kaldor-Verdoorn effect. *Ecological Economics*, 199:107449.

Piketty, T. (2014). *Capital in the twenty-first century*. Harvard University Press.

Pindyck, R. S. (2013). Climate change policy: What do the models tell us? *Journal of Economic Literature*, 51(3):860–872.

Ponta, L., Raberto, M., Teglio, A., and Cincotti, S. (2018). An agent-based stock-flow consistent model of the sustainable transition in the energy sector. *Ecological Economics*, 145:274–300.

Popp, D. (2019). Environmental policy and innovation: A decade of research. Working Paper 25631, National Bureau of Economic Research.

Ravaioli, G., Lamperti, F., Roventini, A., and Domingos, T. (2025). Tackling emissions and inequality: policy insights from an agent-based model. *Journal of Economic Behavior Organization*, 237:107188.

Rezai, A. and Stagl, S. (2016). Ecological macroeconomics: Introduction and review. *Ecological Economics*, 121:181–185.

Rezai, A., Taylor, L., and Foley, D. (2018). Economic growth, income distribution, and climate change. *Ecological Economics*, 146:164–172.

Rezai, A., Taylor, L., and Mechler, R. (2013). Ecological macroeconomics: An application to climate change. *Ecological Economics*, 85:69–76.

Rolim, L. N., Baltar, C. T., and Lima, G. T. (2023). Income distribution, productivity growth, and workers' bargaining power in an agent-based macroeconomic model. *Journal of Evolutionary Economics*, 33(2):473–516.

Safarzyńska, K. and van den Bergh, J. C. (2017). Integrated crisis-energy policy: Macro-evolutionary modelling of technology, finance and energy interactions. *Technological Forecasting and Social Change*, 114:119–137.

Safarzyńska, K. and Van Den Bergh, J. C. (2022). ABM-IAM: optimal climate policy under bounded rationality and multiple inequalities. *Environmental Research Letters*, 17(9):094022.

Salle, I. and Yıldızoğlu, M. (2014). Efficient sampling and meta-modeling for computational economic models. *Computational Economics*, 44:507–536.

Sobol, I. M. (2001). Global sensitivity indices for nonlinear mathematical models and their monte carlo estimates. *Mathematics and Computers in Simulation*, 55(1-3):271–280.

Spash, C. L. (2012). New foundations for ecological economics. *Ecological Economics*, 77:36–47.

Stanley, M. H., Buldyrev, S. V., Havlin, S., Mantegna, R. N., Salinger, M. A., and Stanley, H. E. (1995). Zipf plots and the size distribution of firms. *Economics letters*, 49(4):453–457.

Stock, J. H. and Watson, M. W. (1999). Business cycle fluctuations in us macroeconomic time series. *Handbook of Macroeconomics*, 1:3–64.

Stockhammer, E. (2017). Determinants of the wage share: A panel analysis of advanced and developing economies. *British Journal of Industrial Relations*, 55(1):3–33.

Tesfatsion, L. and Judd, K. L. (2006). *Handbook of computational economics: Agent-based computational economics*, volume 2. Elsevier.

Victor, P. (2019). *Managing without growth: Slower by design, not Disaster*. Advances in Ecological Economics. Edward Elgar Publishing, 2nd edition.

Vogel, J. and Hickel, J. (2023). Is green growth happening? An empirical analysis of achieved versus paris-compliant CO_2–GDP decoupling in high-income countries. *The Lancet Planetary Health*, 7(9):e759–e769.

Windrum, P., Fagiolo, G., and Moneta, A. (2007). Empirical validation of agent-based models: Alternatives and prospects. *Journal of Artificial Societies and Social Simulation*, 10(2):8.

World Bank (2024). Carbon pricing dashboard. Accessed: 2025-04-25.

A Transaction flow matrix

Stock-flow consistent models have gained prominence in the related literature in recent years.[8] This approach utilizes specific social accounting matrices to ensure that every payment flow originates from and is directed to a particular sector. Each financial stock is recorded as both an asset for one agent and a liability for another, eliminating any leakages. This framework provides a fundamental consistency check with the structure of national accounts (Godley and Lavoie, 2016). Caiani et al. (2016) offer a methodological recommendation to integrate agent-based modeling (which captures micro-level behavior) with stock-flow consistency (which ensures macro-level coherence). They argue that combining these two approaches helps overcome the inherent limitations of each, since accounting consistency is enforced at the most detailed level to capture the full structural interrelatedness of agents' balance sheets. The model developed in this paper is fully stock-flow consistent, and Table 2 presents the corresponding transaction flow matrix.

[8]For a comprehensive survey, see Caverzasi and Godin (2015).

	Households	**Consumption Goods Firms**	**Capital Goods Firms**	**Financial Sector**	**Government**	Sum
Consumption	$-C_t^W$	$+\sum_j p_{j,t} Q_{j,t}$			$-\epsilon Y_{t-1}$	0
Investment		$-\sum_j p_{i,t} I_{j,t}$	$+\sum_i p_{i,t} K_{i,t}$			0
Wages	$+\sum_i [W_{i,t}^W L_{i,t}^W + W_{i,t}^M (L_{i,t}^M + L_{i,t}^{RD})]$ $+\sum_j [W_{j,t}^W L_{j,t}^W + W_{j,t}^M L_{j,t}^M]$	$-\sum_j \left[W_{j,t}^W L_{j,t}^W + W_{j,t}^M L_{j,t}^M\right]$	$-\sum_i \left[W_{i,t}^W L_{i,t}^W + W_{i,t}^M (L_{i,t}^M + L_{i,t}^{RD})\right]$			0
Dividends	$+\sum_i Div_{i,t} + \sum_j Div_{j,t}$	$-\sum_i Div_{i,t}$	$-\sum_j Div_{j,t}$			0
Interest on loans		$-\sum_j r\Lambda_{j,t}$		$+r\Lambda_t$		0
Unemployment benefits	$+W_t^U L_t^U$				$-W_t^U L_t^U$	0
Taxes	$-\tau_w \left\{\sum_i \left[W_{i,t}^W L_{i,t}^W + W_{i,t}^M (L_{i,t}^M + L_{i,t}^{RD})\right] + \sum_j \left[W_{j,t}^W L_{j,t}^W + W_{j,t}^M L_{j,t}^M\right]\right\}$ $-\tau_d \left[\sum_i Div_{i,t} + \sum_j Div_{j,t}\right]$	$-\tau \sum_j p_{j,t} Q_{j,t}$	$-\tau \sum_i p_{i,t} K_{i,t}$		$+T_t$	0
Δ Loans		$+\sum_j \Lambda_{j,t}$		$-\Lambda_t$		0
Δ Deposits	$-\Delta Dep_t^W$	$-\sum_j \Delta Dep_{j,t}$	$-\sum_i \Delta Dep_{i,t}$	$+\Delta Dep_t$		0
Δ Government bonds				$-\Delta B_t$	$+\Delta B_t$	0
Government bonds interest				$+r^* B_t$	$-r^* B_t$	0
Sum	0	0	0	0	0	0

Table 2: Transaction flow matrix

B Model validation

The model is calibrated using an indirect calibration approach to produce time series that qualitatively align with real-world data (Windrum et al., 2007). In practice, this method begins with validation objectives and then calibrates the model by identifying parameters that are consistent with those validation outcomes. Model construction involves the following procedures. First, the modeller selects a set of stylized facts and macroeconomic regularities that she aims to reproduce with the model. Matching simulated data and real-world stylized facts is a standard practice for model validation in the agent-based modeling literature (Fagiolo et al., 2019). Following this approach, the model is constructed to closely reflect real microeconomic behavioral evidence and maintain theoretical consistency. Rather than directly fitting parameters to data, the parameters are systematically explored and selected based on their capacity to reproduce the targeted stylised facts. Finally, within the validated parameter space, the modeller analyzes the model's underlying causal mechanisms.

The model is simulated for 350 periods, with the first 50 warm-up steps excluded from the analysis. The final series thus cover 300 periods. This section presents the median results from 50 Monte Carlo simulations of the baseline scenario.[9] The baseline parametrization represents the model under the business-as-usual scenario, with no green policy intervention.

Figure 10 illustrates that the model is capable of generating sustained economic growth with fluctuations for the main aggregate variables —output, consumption,

[9]We use median values instead of averages because the variables in the Monte Carlo experiment do not necessarily follow a normal distribution.

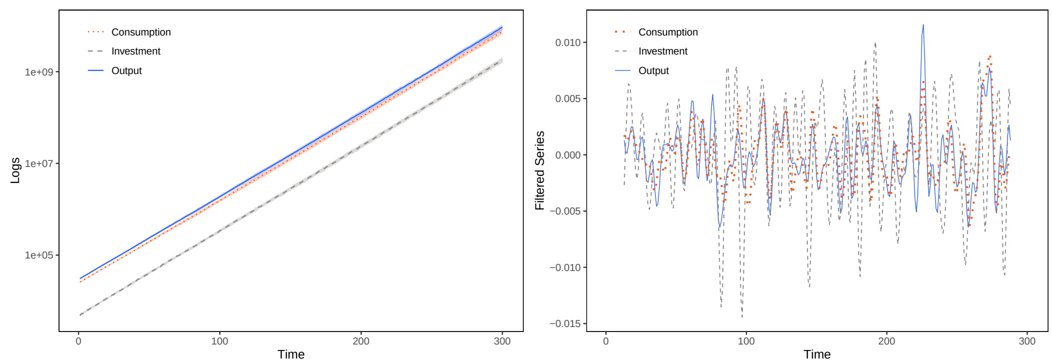


Figure 10: Output, consumption, and investment: trend and cyclical components

Note: Results are based on the median of 50 Monte Carlo runs. Cyclical components are extracted using a bandpass filter with parameters (6,32,12). Trend series are expressed in logarithms. The shaded area represents the 95% confidence interval.

and investment. Table 3 shows the cross-correlations between the cyclical components of aggregate output and components of aggregate demand, derived using the bandpass filter. A negative correlation in period t indicates that the variable is countercyclical, while a positive value suggests it is procyclical. The timing of the peak correlation reveals whether the variable lags, coincides with, or leads output. The results indicate that both consumption and investment are procyclical (Carlin and Soskice, 2014; Stock and Watson, 1999). Investment leads output, while consumption moves coincidentally with it, consistent with findings from other agent-based models (e.g., (Rolim et al., 2023). The unemployment rate is found to be countercyclical and to lag behind output (Okun, 1963). Finally, we observe a positive correlation between aggregate output and aggregate emissions (Doda, 2014).

The model also reproduces stylized facts related to income inequality. Table 4 presents the cross-correlation structure between the Gini index and selected macroeconomics variables. In line with Maestri and Roventini (2012), we find that higher

Variable	$t-3$	$t-2$	$t-1$	t	$t+1$	$t+2$	$t+3$
Consumption	0.274	0.557	0.777	0.822	0.661	0.375	0.096
Investment	-0.135	-0.053	0.115	0.266	0.305	0.211	0.054
Unemployment	-0.061	-0.093	-0.059	0.010	0.066	0.071	0.033
Emissions	0.099	0.169	0.189	0.161	0.102	0.046	0.017

Table 3: Cross-correlation structure between GDP and selected variables at different lags

output and investment are correlated with lower income inequality, as measured by the Gini index. Moreover, our results confirm that unemployment is positively and strongly correlated with the Gini index Maestri and Roventini (2012). The funcional and personal distributions of income are correlated, with the wage share showing a strong negative correlation with the Gini index. Lastly, as shown in Figure 11, the baseline parametrization captures both the rising trend in income inequality Piketty (2014) and the decline in the wage share observed in many advanced economies over recent decades Stockhammer (2017). For a comprehensive overview of the correlation structure among the model's variables, see Figure 12.

Variable	$t-3$	$t-2$	$t-1$	t	$t+1$	$t+2$	$t+3$
GDP	0.074	0.067	0.027	-0.044	-0.127	-0.185	-0.180
Investment	0.001	0.043	0.013	-0.040	-0.058	-0.011	0.079
Unemployment	0.077	0.241	0.336	0.296	0.123	-0.087	-0.218
Wage share	0.041	0.003	-0.105	-0.221	-0.257	-0.181	-0.028

Table 4: Cross-correlation structure between the Gini index and selected variables at different lags

Lastly, the model successfully reproduces microeconomic stylized facts commonly found in the agent-based modeling literature, capturing the heterogeneity of firms that emerges during the simulations. The Zipf plot in Figure 13a shows that real

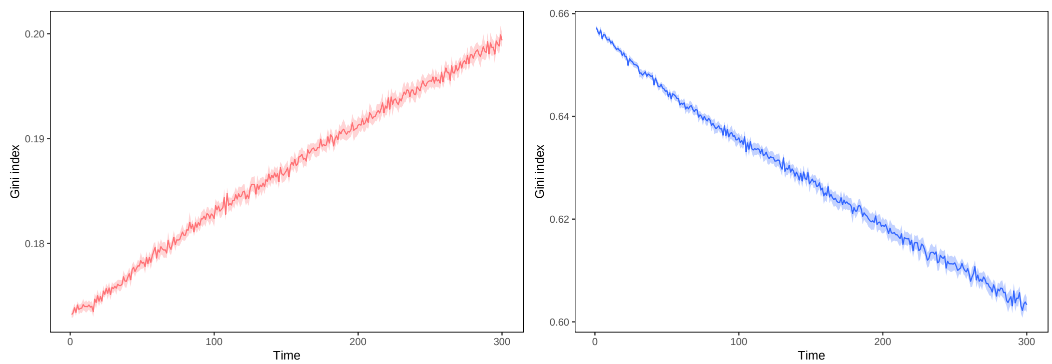


Figure 11: Gini index and Wage share

Note: Results are based on the median of 50 Monte Carlo simulations. The shaded area represents the 95% confidence interval.

sales of consumption goods firms exhibit a heavy-tailed distribution, which closely approximates a log-normal fit—consistent with the findings of Stanley et al. (1995). Moreover, the model captures persistent and significant productivity differentials (Barth et al., 2016; Dosi, 2005), particularly in terms of carbon intensity. As shown in Figure 13b, the distribution of carbon intensity across firms exhibits substantial dispersion. Notably, the most efficient firm consistently achieves a carbon intensity well below the median, highlighting a clear performance gap.

C Sensitivity analysis

To further understand the model's behavior and ensure the robustness of our results, we conduct a global sensitivity analysis by exploring joint variations of key parameters. We adopt the methodology proposed by Salle and Yıldızoğlu (2014), in which a meta-model is estimated using a parsimonious sampling of possible parameters com-

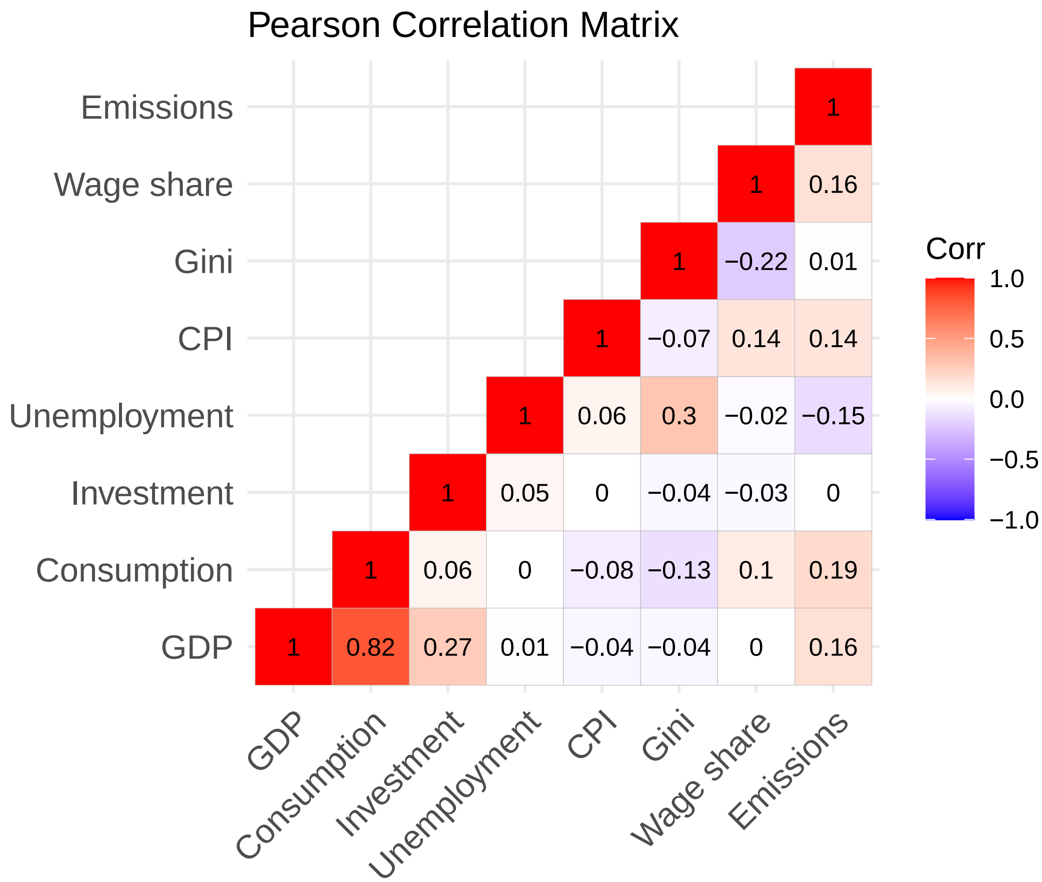
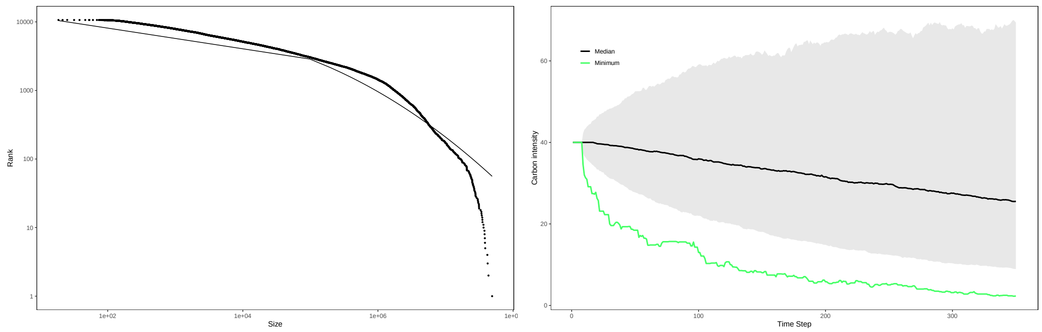


Figure 12: Pearson correlation matrix

binations within the selected domain. This approach uses the Nearly Orthogonal Latin Hypercube (NOLH) sampling method (Cioppa and Lucas, 2007) as the design of experiment (DoE). We use 27 DoE samples and 10 external validation samples to construct the Sobol decomposition Sobol (2001) and estimate the meta-model, which relates model parameters to the variables of interest.[10] The parameters included in the analysis are listed in Table 5, which presents the results by decomposing the variance into direct effects and interaction effects. Each row corresponds to a model

[10]The sample size is obtained from Salle and Yıldızoğlu (2014).



(a) Sales distribution (pooled) (b) Carbon intensity

Figure 13: Stylized microeconomic facts (consumption goods sector)

Note: Each series represents the median of 50 Monte Carlo simulations per scenario, with the shaded indicating the 95% quantile interval.

parameter, while each pair of columns represents one of the five key outcome variables: the Gini index, unemployment rate, carbon intensity, GDP growth rate, and consumer price index.

In the case of the Gini index, the most influential parameter is the wage premium (ϱ), which accounts for more than half of the total variation in income inequality. This suggests that differences in wage premia between direct workers and managers/researchers are a dominant mechanism shaping income inequality in the model. Accordingly, most of the observed personal income inequality arises from disparities between household classes, rather than from the micro-level wage bargaining dynamics.

For the unemployment rate, the model is particularly sensitive to two parameters: the target size of government spending (ϵ) and the R&D reinvestment rate (ν). Each of these parameters accounts for roughly 30% of the variance in unemployment. The relatively low interaction effects suggest that these two drivers operate largely independently and in opposing directions: greater public sector participation increases aggregate demand, thereby reducing unemployment, while a higher R&D reinvestment rate boosts innovation and enhances labor-saving technologies, which in turn raises the unemployment rate.

Turning to carbon intensity, the analysis reveals a strong concentration of sensitivity around the R&D reinvestment rate (ν). This highlights a tight connection between innovation and the carbon intensity of production, as the model's decarbonization process depends on technological upgrading and diffusion of less carbon-intensive machinery. Similarly, the GDP growth rate is also highly influenced by ν. By stimulating greater R&D efforts and accelerating the pace of innovation, this parameter expands the technological discovery space and enhances productivity gains, ultimately supporting higher economic growth in the long term.

Lastly, the determinants of the consumer price index reflect a traditional conflict inflation narrative. The parameter representing workers' bargaining power (ϕ) emerges as the most significant driver, accounting for 54.8% of the variance in the consumer price index through direct , with an additional 13.2% explained by interaction effects. The R&D reinvestment rate (ν) also plays a substantial role, contributing 25.2% of the variance. On one hand, ϕ captures workers' efforts to maintain real wages in line with productivity and inflation, potentially leading to wage-push inflation. On the other hand, ν reflects firms' strategies to boost labor productivity and profitability by reducing dependence on labor through technological innovation.

Parameter (Sections)	Gini Index		Unemployment		Carbon Intensity		GDP Growth rate		CPI	
	Direct	Interact.	Direct	Interact.	Direct	Interact.	Direct	Interact.	Direct	Interact.
ν (2.2.1)	0.139	0.005	0.305	0.001	**0.896**	0.002	**0.845**	0.022	0.252	0.132
γ_a (2.3.1)	0.112	0.001	0.104	0.013	0.031	0.001	0.042	0.010	0.000	0.002
γ_u (2.3.1)	0.004	0.043	0.018	0.001	0.006	0.001	0.001	0.001	0.026	0.006
ϵ (2.6)	0.081	0.001	**0.317**	0.001	0.006	0.001	0.018	0.003	0.008	0.002
ϕ (2.2.2, 2.3.2)	0.084	0.000	0.109	0.001	0.009	0.001	0.020	0.003	**0.548**	0.132
ϱ (2.2.2, 2.3.2)	**0.506**	0.036	0.034	0.012	0.039	0.001	0.024	0.015	0.026	0.009
σ (2.2, 2.2.3, 2.3.3)	0.048	0.005	0.080	0.002	0.007	0.002	0.002	0.019	0.000	0.001

Table 5: Variance decomposition (direct and interaction effects)

D Parameters in baseline scenario

Parameter	Description (Sections)	Value
ρ	Managers-to-direct-workers ratio (2.2, 2.2.2)	2
σ	Capitalist-to-firm ratio (2.2, 2.2.3, 2.3.3)	1
ν	R&D reinvestment rate (2.2.1)	0.5
ζ^{LP}	R&D productivity parameter (2.2.1)	0.5
ζ^{CI}	Green R&D productivity parameter (2.2.1)	0.4
α	Alpha parameter of the Beta distribution for innovation (2.2.1)	3
β	Beta parameter of the Beta distribution for innovation (2.2.1)	3
$\underline{x}^{LP}$	Lower bound of labor productivity innovation (2.2.1)	-0.25
$\overline{x}^{LP}$	Upper bound of labor productivity innovation (2.2.1)	0.35
$\underline{x}^{CI}$	Lower bound of carbon intensity innovation (2.2.1)	-0.145
$\overline{x}^{CI}$	Upper bound of carbon intensity innovation (2.2.1)	0.15
μ	Mark-up rate of capital goods firms (2.2.2)	0.5
ϕ	Workers' institutional bargaining power parameter (2.2.2, 2.3.2)	0.6
ϱ	Researchers and managers wage premium (2.2.2, 2.3.2)	0.5

Parameter	**Description**	**Value**
τ	Tax rate on marginal sales (2.2.4, 2.3.3)	0.15
λ	Target dividends share (2.2.4, 2.3.3)	0.2
H	Number of lags in the expected demand of consumption goods firms (2.3.1)	4
ι	Desired inventories share (2.3.1)	0.15
γ_a	Autonomous component in investment function (2.3.1)	0.1
γ_u	Speed of adjustment of capacity utilization in investment function (2.3.1)	0.3
u^*	Normal level of capacity utilization (2.3.1)	0.8
υ	Adjustment parameter of the mark-up rate of consumption goods firms (2.3.2)	0.04
ω_1	Weight of price competitiveness (2.3.2)	1
ω_1	Weight of unfilled demand competitiveness (2.3.2)	1
κ	Market share quasi-replicator parameter (2.3.2)	1
r^*	Interest rate (2.4, 2.6)	0.1
ς	Interest rate spread (2.4)	0.1
r	Interest rate on granted loans (2.3.3, 2.4)	0.11
CAR	Capital adequacy ratio (2.4)	16
ψ_1	Sensitivity of workers' desired wage to labor productivity (2.5)	1
ψ_2	Sensitivity of workers' desired wage to inflation(2.5)	1
τ_w	Marginal tax rate on wages (2.5, 2.6)	0.1
τ_d	Marginal tax rate on dividends (2.5, 2.6)	0.05

Parameter	**Description**	**Value**
c_W	Propensity to consume out of wage income (2.5)	1
c_K	Propensity to consume out of dividends (2.5)	0.9
ϵ	Government induced consumption parameter (2.6)	0.25