Inequality along the European green transition *

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Abstract

The EU aims for 42.5% green energy consumption by 2030. What are the effects of the European green transition on inequality? We answer this question using a heterogeneous-agent model with non-homothetic preferences for energy and non-energy goods, calibrated to European data. We study the impact of an increase in carbon taxes designed to meet the EU target under different revenue-recycling strategies. Redistributing tax revenues via uniform transfers reduces consumption inequality, shifts the welfare burden to high-income households, but leads to significant output losses. Subsidizing green energy producers boosts energy production, reduces output losses, and requires a smaller carbon tax to meet the EU target. However, it increases consumption and income inequality, with the highest welfare costs borne by low-income and asset-poor households. Our findings highlight key trade-offs between equity and efficiency in green transition policies.

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JEL codes: Q43, Q52, E6

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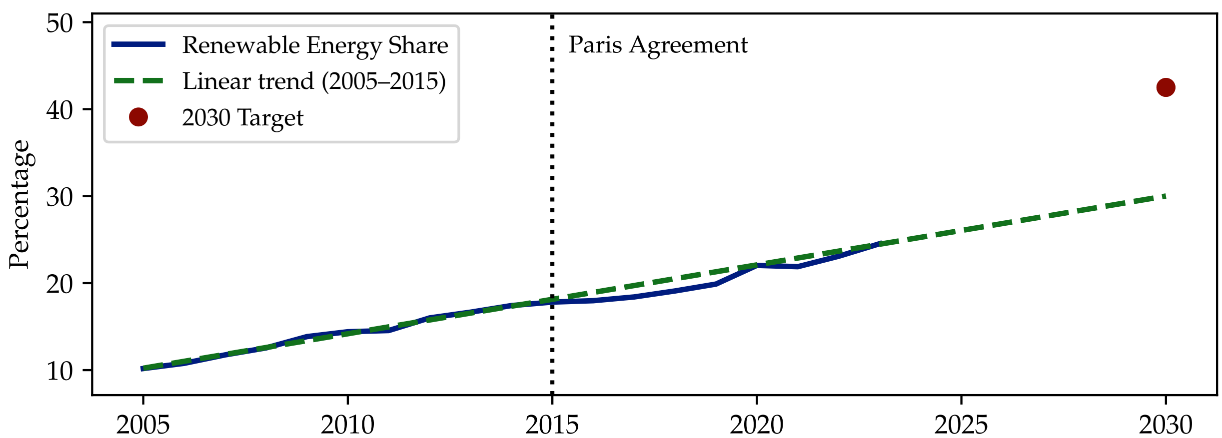
1 Introduction

The transition to a greener economy is one of the European Union's most urgent and complex challenges. The EU has set ambitious goals to significantly reduce carbon dioxide emissions and substantially increase the share of renewable energy. Figure 1 illustrates the trajectory of renewable energy consumption in Europe over the past two decades, along with the EU's target of achieving 42.5% renewable energy consumption by 2030.[1] Given current trends, reaching this target appears increasingly challenging.

Figure 1: Share of energy consumption from renewable sources in Europe.



Note. Data from the European Environmental Agency. Linear trend fitted to 2005–2015 data and extrapolated to 2030.

While renewable energy targets are crucial for mitigating climate change, they also pose significant socio-economic challenges, because the costs of the green transition are likely not to be equally shared across households. For example, if the green transition leads to higher energy prices, it would disproportionately impact lower-income households, who typically spend a larger share of their income on energy.

The novelty of this paper is to explore the distributional effects of the green transition in the European Union. Specifically, assuming the EU increases its carbon tax to reach its renewable energy consumption target, we investigate the distributional consequences of different uses of the revenues of the carbon tax. Our results reveal significant trade-offs between equity and efficiency in green transition policies.

To study the aggregate and distributional effects of the green transition, we develop an incomplete markets general equilibrium model where households face idiosyncratic income risk. Following Aiyagari (1994), income risk is only partially mitigated through savings in physical capital. We extend this classical framework by incorporating two essential features for understanding the

[1] The revised Renewable Energy Directive EU/2023/2413 raised the EU's binding renewable energy target for 2030 to a minimum of 42.5%, up from the previous 32%, with an aspiration to reach 45%. The directive took effect across all EU countries on 20 November 2023 (see here).

broader implications of the green transition. First, we introduce both green and non-green energy producers, enabling us to capture the dynamic effects of the green transition on energy production and consumption.

Second, we introduce non-homothetic preferences over energy and non-energy goods. Following Boppart (2014), we adopt preferences that give rise to a Price-Independent Generalized Linear (PIGL) demand system. This specification generates nonlinear Engel curves, consistent with empirical evidence that lower-income households allocate a larger share of their consumption to energy than higher-income households, as documented by Levinson and O'Brien (2019). We estimate the degree of non-homotheticity in preferences and the parameters of the income process using micro data from the Dutch Household Survey (LISS Panel), providing a disciplined empirical foundation for the calibration of our model. Our results confirm the presence of significant non-homotheticity in energy demand, highlighting its importance for assessing the distributional consequences of climate and energy policy. Our use and estimation of the Boppart (2014) utility function for energy and non-energy goods constitutes a significant contribution to the literature, as it not only aligns with the data, but also has crucial implications for the distribution of the costs associated with the green transition.

We then turn to assess the effects of the green transition in the EU from 2015 to 2030. Without any change in policy, we assume that green technology continues to grow linearly at the pace implied by the increase in renewable energy between 2005 and 2015. This progress drives an expansionary economic path, with output, wages, and capital increasing over time. Although energy prices decline along this trajectory, the share of renewable energy reaches only 30% by 2030, falling short of the EU's 42.5% target.

To address this shortfall, we introduce a gradually increasing carbon tax designed to meet the EU's renewable energy goal by 2030 and investigate how different revenue allocation schemes affect the economy at both the aggregate and individual level. Specifically, we examine three fiscal policy options for redistributing carbon revenue: (i) financing government consumption, (ii) providing uniform lump-sum transfers to households, and (iii) subsidizing green energy production. We then compare the aggregate, distributional, and welfare outcomes of these revenue recycling mechanisms with the no-policy baseline, where the transition relies solely on green technological progress, as described above.

The introduction of a carbon tax affects energy usage in both consumption and production. When revenues are used to finance government spending, the carbon tax significantly raises brown energy prices, leading to a sharp decrease in brown energy production. Green energy prices rise moderately, and total energy production declines compared to the baseline. Lump-sum transfers help cushion the impact of higher energy prices, resulting in a less substantial drop in energy consumption. Finally, green energy subsidies lead to the largest increase in green energy production and require a smaller carbon tax increase to meet the renewable energy target, resulting in a more moderate decline in total energy production

Next, we analyse the aggregate effects. Using the carbon tax to fund government spending leads to a significant economic contraction by increasing energy prices, which in turn reduces output, capital, and consumption. Transfers to households partially offset this contraction by increasing disposable income, which stimulates the consumption of non-energy goods. In this scenario, savings decrease, and physical capital accumulation lags behind that of other scenarios. Green energy subsidies result in the mildest output contraction, as the subsidies reduce energy costs and stimulate green energy production, thereby mitigating the negative effect on aggregate variables.

Finally, we study the distributional effects of the different policy scenarios. When revenues fund government spending, consumption inequality rises, as higher energy costs disproportionately impact poorer households, who have less flexibility to adjust their energy consumption compared to wealthier households. Uniform transfers reduce both consumption and income inequality by providing additional income to poorer households. However, wealth inequality rises, as the decline in precautionary savings leaves more households financially constrained. Green subsidies have a limited impact on redistribution, as both rich and poor households experience similar reductions in energy consumption.

All individuals experience a welfare loss during the green transition, regardless of the policy or their position in the wealth-income distribution.[2] However, the distribution of welfare costs differs significantly across scenarios. Uniform transfers primarily affect high-income individuals, independently of their wealth. This is because uniform transfers redistribute income from rich to poor households, mitigating the impact of higher energy prices. In contrast, green subsidies do not entail such redistribution, so households with both low income and low wealth suffer the most. Under this scenario, wealthy households experience the smallest welfare losses, regardless of their income. Moreover, we also show that non-homotheticity plays a crucial role in shaping both overall welfare effects and their distribution across households under different fiscal policies.

These findings highlight fundamental trade-offs between equity and efficiency, emphasizing the importance of accounting for both aggregate and distributional welfare effects in the design of climate policy. To quantify the cost of promoting equity, we trace the trade-off between aggregate output (and expenditure) and the concentration of expenditure, along the transition from the initial to the greener steady state. Quantitatively, the trade-off between equity and efficiency is significant. Over the long term, shifting from a full subsidy policy ($\omega_{sg} = 1$) to a full transfer policy ($\omega_{sg} = 0$) lowers the Gini coefficient of expenditure by roughly 7.66 percentage points, at the cost of reducing economic output by an additional 2.22 percentage points. Hence, this trade-off implies that a one percentage point drop in output leads to a 3.45 percentage point reduction in the Gini coefficient of expenditure relative to the baseline.

Policy recommendations thus depend on the goals of the policymaker. If the goal is to reduce consumption inequality and protect vulnerable households, lump-sum transfers would be the most effective policy. If the policymaker prioritizes aggregate economic stability, subsidizing

[2] In our analysis, we focus on the non-environmental welfare costs, measured in terms of expenditure equivalent variation, rather than consumption equivalent, given our utility function.

green energy production is the preferred approach, as this policy results in lower output overall costs, higher overall energy consumption, and a lower carbon tax.

The remainder of the paper is structured as follows. We first provide a brief overview of the related literature. Section 2 presents the model and defines the equilibrium. Section 3 describes the estimation of utility parameters, the calibration strategy, and the stationary distributions of income, wealth, and consumption. Section 4 examines transition dynamics under alternative fiscal policy scenarios. Section 5 analyses the distribution of welfare costs across income and wealth levels. Finally, Section 6 concludes.

1.1 Related Literature

The literature on the effects of the green transition within macroeconomic models is rapidly expanding. Studies such as Del Negro, di Giovanni and Dogra (2023) and Olovsson and Vestin (2023) examine the inflationary impact of climate policies in economies with nominal rigidities, while Ferrari and Nispi Landi (2022) explore the role of expectations in shaping inflationary dynamics. Airaudo, Pappa and Seoane (2023) focus on the green transition in a small open economy, and Fried (2018) analyses the effect of carbon taxation on green innovation.

However, these papers adopt a representative agent framework, abstracting from distributional aspects. Our model integrates, in a unified framework, key features that are critical for understanding the green transition: non-homothetic preferences, uninsurable income risks, and a disaggregated energy production sector. This allows us to provide a more comprehensive analysis of the aggregate and distributional effects. In particular, we build our preferences on the specification by Boppart (2014), who provides a non-Gorman specification of utility that matches the fact that the poor spend relatively more on energy goods than the rich. These preferences imply non-linear Engel curves over the different goods and hence also heterogeneous MPCs. In this case, indirect redistribution of income has aggregate consequences.

A closely related paper is Hochmuth, Krusell and Mitman (2025), who develop a two-agent general equilibrium model with non-homothetic preferences to examine the distributional effects of the EU's Fit-for-55 package.[3] Similar to our findings, they highlight that energy price increases place a disproportionate burden on poorer households due to Engel curve non-linearities. However, their framework features a stylized two-agent model with complete markets, whereas we adopt a fully fledged heterogeneous agents model that incorporates uninsurable income risk and endogenous wealth inequality. This richer structure enables us to study the interplay between carbon taxation, precautionary savings, borrowing constraints, and redistribution at a more granular level.

Coenen, Lozej and Priftis (2024), Fried, Novan and Peterman (2018), Boehl and Budianto (2024) and Fried, Novan and Peterman (2024) study alternative methods of recycling carbon tax revenues in heterogeneous agent economies and their implications for inequality. Coenen et al. (2024), similar to Känzig (2023), employ a two-agent New Keynesian framework. Like them, we compare the

[3] We became aware of their work only recently. Our analysis was developed independently and in parallel.

aggregate and distributional effects of uniform transfers and subsidies to green energy producers. Fried et al. (2018) and Fried et al. (2024) use lifecycle models with two goods and quasi-homothetic preferences to investigate the intergenerational redistribution effects associated with different uses of carbon tax revenues. Boehl and Budianto (2024) studies transfer vs. subsidies recycling schemes with endogenous innovation in a climate heterogeneous agents New Keynesian model, but does not model non-homothetic preferences.

On the normative side, Douenne, Hummel and Pedroni (2023), Belfiori, Carroll and Hur (2025), and Wöhrmüller (2025) analyse optimal climate policy in heterogeneous agent settings. The latter two are closest to our work, featuring two-good, incomplete-markets models with quasi-homothetic preferences and global climate damages. In contrast, we focus on the euro area, abstract from damages, and use non-homothetic preferences, which, in addition to declining energy expenditure shares, also generate a nonlinear relation between total and energy expenditure. Furthermore, while Wöhrmüller (2025) models energy production, he does not study firm-level subsidies.

Recent related work also shows that carbon taxes can serve non-climate policy goals. Bourany (2025) shows that global transfers between countries can support first-best carbon pricing, while in their absence, tax rates should account for equity-efficiency trade-offs. Wöhrmüller (2025) shows that carbon taxes with lump-sum transfers can raise welfare via redistribution and insurance, even without climate externalities. Similar mechanisms operate in our euro area setting.

A final contribution of our work is the use of Dutch and European data to parameterize the model. Specifically, we draw on Dutch microdata for households and the simplified Energy Balances from Eurostat for firms, a dataset also recently employed by Coenen et al. (2024).

2 Model

The economy consists of a household sector, the government and three production sectors. Two of these sectors produce energy, while the remaining sector produces a non-energy good. The two energy-producing sectors differ in their input requirements. Both use capital and labour, but one also utilizes a fossil natural resource. For this reason, we refer to the energy produced in the latter sector as brown energy, and that produced in the former as green energy.

Brown and green energy are then combined to produce an energy bundle, which is directly consumed by households and also used as an input in the production of the consumption good.

Households are heterogeneous in terms of income, wealth, and discount factors. The government levies a tax on the brown energy producer and can recycle the revenues in different ways. There is no aggregate uncertainty in the economy.

2.1 Households

The household sector is modelled as a continuum of households facing uninsurable income risk. At each point in time t, a household i is characterized by the idiosyncratic part of its labour income y_{it},[4] asset holdings a_{it}, and a household-specific discount factor β_{it}. Household income is subject to both persistent and transitory shocks, denoted by ε and ψ, respectively. The pair (ε, ψ) follows an exogenous Markov process with transition matrix Γ. In addition to income risk, households face idiosyncratic uncertainty in their discount factor. The discount factor β_{it} evolves according to a two-state exogenous Markov process with transition matrix Γ_β, where β^{low} represents currently impatient agents, and $\beta^{\text{high}} > \beta^{\text{low}}$ represents currently patient agents.

In each period, households derive utility from consuming a non-energy good, c_{it}, and an energy good, e^c_{it}. The former serves as the numeraire. As is standard, the household's problem can be solved in two stages. In the intertemporal dynamic stage, households allocate their resources between savings for future periods, a_{it+1}, and real total expenditure, x_{it}. In the intratemporal static stage, they decide how to split their total expenditure, given by $x_{it} = c_{it} + p^e_t e^c_{it}$ in real terms, between the non-energy and energy good, taking the relative price of energy, p^e_t, as given. Hence, households receive a utility flow $U\big(x_{it}, p^e_t\big)$, where $U(\cdot)$ represents the intratemporal indirect utility function.

Households can reallocate resources intertemporally by investing in physical capital a_t, which yields a net real return r_t, while being subject to a no-borrowing constraint. Household $i's$ budget constraint, in real terms, reads as

$$x_{it} + a_{it+1} \leq (1 + r_t)a_{it} + w_t y_{it} + T_t, \tag{1}$$

where y_{it} denotes household $i's$ labour endowment, w_t denotes the real wage, and T_t are uniform lump-sum transfers. Taking prices and transfers as given, each household solves the following dynamic programming problem

$$V_t(a_{it}, y_{it}, \beta_{it}) = \max_{x_{it}, a_{it+1}} U\left(x_{it}, p^e_t\right) + \beta_{it}\, \mathbb{E}_t\left[V_{t+1}\left(a_{it+1}, y_{it+1}, \beta_{it+1}\right)\right] \tag{2}$$

$$\text{s.t.} \quad x_{it} + a_{it+1} \leq (1 + r_t)a_{it} + w_t y_{it} + T_t \tag{3}$$

$$a_{it+1} \geq \underline{a}. \tag{4}$$

In the latter, the expectation $\mathbb{E}_t$ is taken over the realizations of idiosyncratic income and discount factor shocks.

Since we aim to capture non-homotheticity and the low substitutability between energy and non-energy consumption, we adopt the flexible specification of Boppart (2014).[5] We parameterize

[4] This is standard from Aiyagari (1994). The aggregate effective labour endowment is fixed and normalized to 1. Given inelastic unit labour supply by households, the stochastic idiosyncratic component of labour income $w_t y_{it}$ can be interpreted as idiosyncratic productivity.

[5] We adopt the Boppart (2014) PIGL demand system instead of a non-homothetic CES specification, for both empirical and computational reasons. Note, however, that under our assumption of $\gamma = \varepsilon$, the both systems imply constant substitution elasticities across expenditure levels. This assumption removes a core feature of the general PIGL system: that substitution elasticities vary with expenditure and converge to $1 - \gamma$ as expenditure rises (see Equation (19) in Boppart, 2014). While such dynamics may be desirable in growth contexts, they impose strong assumptions on how substitution patterns evolve over time. Our restriction avoids this, delivering constant substitution elasticities throughout the transition and in the steady state.

the indirect utility function as follows

$$U\left(x_{it}, p_t^e\right) = \frac{1}{\epsilon}\left(x_{it}\right)^{\epsilon} - \frac{\nu}{\gamma}\left(p_t^e\right)^{\gamma} - \frac{1}{\epsilon} + \frac{\nu}{\gamma}, \tag{5}$$

where $0 \leq \epsilon \leq \gamma < 1$ and $\nu > 0$. As we will clarify later, ϵ governs both the degree of non-homotheticity in the consumption bundle and the intertemporal elasticity of substitution. The parameter γ plays a key role in determining the intratemporal elasticity of substitution between energy and non-energy consumption, while ν controls the relative weight of the two sectors in the utility representation. By applying Roy's identity to the indirect utility function in Equation (5), we derive the Marshallian demand functions for expenditure on the non-energy and energy goods. Furthermore, the expenditure system implies the following expenditure shares

$$\eta_{it}^{e^c} = \nu\left(\frac{1}{x_{it}}\right)^{\epsilon}\left(p_t^e\right)^{\gamma} \quad \text{and} \quad \eta_{it}^{c} = 1 - \nu\left(\frac{1}{x_{it}}\right)^{\epsilon}\left(p_t^e\right)^{\gamma}. \tag{6}$$

Note that the expenditure shares are a function of both relative prices and total expenditure. If $\epsilon > 0$, expenditure shares are a non-linear function of total expenditure and preferences are non-homothetic. If $\epsilon = 0$, on the other hand, the expenditure shares only vary with relative prices, but are invariant to changes in total expenditure. Hence, expenditure expansion paths are linear and preferences are homothetic. Intertemporal optimization yields the following Euler Equation

$$\left(x_{it}\right)^{\epsilon-1} \geq \beta_{it}\mathbb{E}_t\left[\left(x_{it+1}\right)^{\epsilon-1}\left(1 + r_{t+1}\right)\right], \tag{7}$$

which clarifies that the elasticity of intertemporal substitution of expenditure is equal to $\frac{1}{1-\epsilon}$.

2.2 Production

Figure 2 provides an overview of the production side of the economy. At the base of the structure are the green and brown energy sectors. Moving upward, we find the energy bundler, which supplies energy to both production firms and households. At the top, final good producers complete the structure.[6] The figure also highlights the production inputs used at each stage. We describe the structure starting from the final goods sector.

Aside from this equivalence, the PIGL system offers several practical advantages. Like non-homothetic CES, but unlike Stone–Geary preferences, it allows for non-homotheticity at all income levels. Unlike CES, it yields closed-form expressions for Marshallian demands and budget shares (see Equation (6)), making the intratemporal allocation problem tractable and eliminating the need for a nonlinear root finder in our numerical solution. The structure also lends itself to straightforward empirical implementation: its log-linear Engel curves can be estimated via OLS or IV using household microdata. We exploit this to calibrate the degree of non-homotheticity in energy expenditure shares. This approach is simpler than that of Comin, Lashkari and Mestieri (2021), who estimate a system of log-linear equations via GMM under additional parametric restrictions.

[6] Recent work highlights how firm-level differences in emissions intensity affect optimal carbon taxation. Kim (2025) shows that more productive firms are also cleaner, suggesting carbon taxes can both cut emissions and improve efficiency by reallocating activity toward these firms. However, as cleaner firms expand, scale effects may dampen aggregate emissions reductions. These supply-side dynamics mirror the demand-side non-homotheticities we study in household behaviour and may affect the carbon price needed to meet climate goals. Accounting for such firm-level effects is a promising direction for future research.

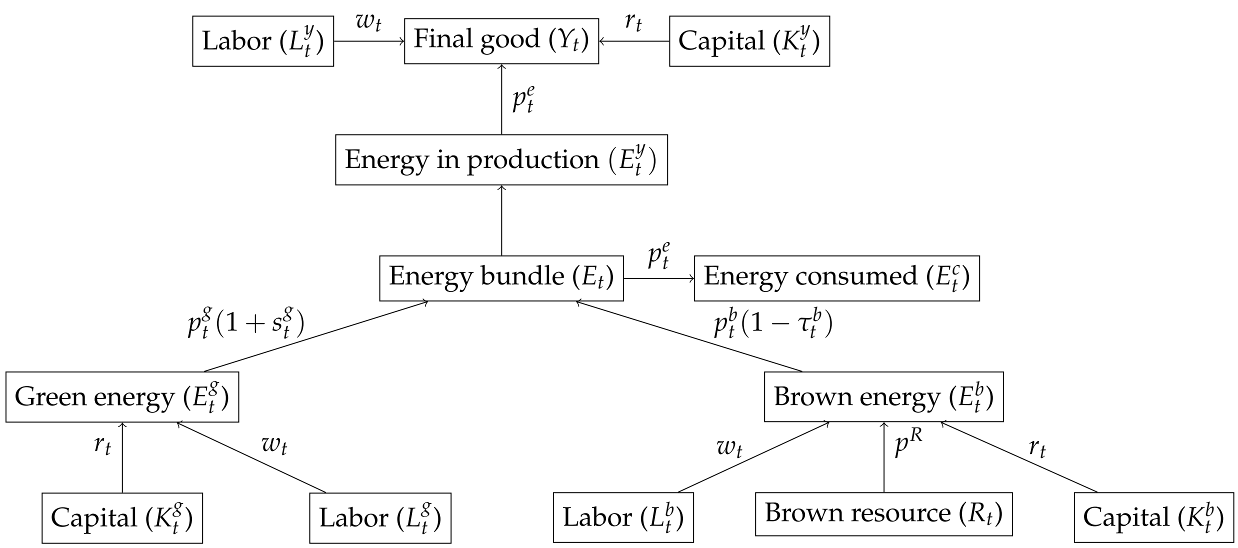


Figure 2: Overview of the production structure in the model

Final good sector The production of the final non-energy good requires two inputs. The first one is a Cobb-Douglas (CD) bundle between labour and capital, defined as $\mathcal{K}_t^y \equiv (K_t^y)^\alpha (L_t^y)^{1-\alpha}$, where α is a constant included between zero and one. The second input is energy, E_t^y. The two inputs are bundled with the Constant Elasticity of Substitution (CES) production function

$$Y_t = \left(\xi_y (\mathcal{K}_t^y)^{\frac{\rho_y - 1}{\rho_y}} + (1 - \xi_y)(E_t^y)^{\frac{\rho_y - 1}{\rho_y}} \right)^{\frac{\rho_y}{\rho_y - 1}}, \tag{8}$$

taking input prices r_t, w_t, and p_t^e as given.[7] The parameter ρ_y defines the elasticity of substitution between the two inputs of production.

The final good producers demand capital and labour to minimize the cost of producing $\mathcal{K}_t^y$. As a result of the CD structure characterizing $\mathcal{K}_t^y$, and perfect competition, the relative price of one unit of $\mathcal{K}_t^y$ is

$$p_t^{\mathcal{K}} = \left(\frac{w_t}{1-\alpha} \right)^{1-\alpha} \left(\frac{r_t + \delta}{\alpha} \right)^\alpha. \tag{9}$$

The demand for L_t^y is determined by

$$w_t = p_t^{\mathcal{K}} \, (1-\alpha) \, (L_t^y)^{-\alpha} (K_t^y)^\alpha, \tag{10}$$

while that for K_t^y reads as:

$$r_t + \delta = p_t^{\mathcal{K}} \alpha (L_t^y)^{1-\alpha} (K_t^y)^{\alpha - 1}. \tag{11}$$

[7] A CES production function provides greater flexibility in the substitutability between the composite input and energy, compared to the constraints imposed by a Cobb-Douglas production function. We will exploit this flexibility in our calibration strategy.

Recall that the price of the final good is the numeraire. Then, the demand for $\mathcal{K}_t^y$ is

$$\frac{\mathcal{K}_t^y}{Y_t} = \xi_y \left(p_t^{\mathcal{K}}\right)^{-\rho_y}, \tag{12}$$

while that for E_t^y reads as

$$\frac{E_t^y}{Y_t} = \left(1-\xi_y\right)\left(p_t^e\right)^{-\rho_y}. \tag{13}$$

Energy production Energy is produced in two sectors: the green energy sector and the brown energy sector. The green energy sector uses labour and capital to generate energy, while the brown energy sector additionally relies on fossil resources.

The representative firm in the green energy sector is described by the following production function

$$E_t^g = Z_t^g \left(K_t^g\right)^{\alpha_g} \left(L_t^g\right)^{1-\alpha_g}, \tag{14}$$

where Z_t^g denotes total factor productivity (TFP) in the green sector. The associated profit function is

$$\Pi_t^g = p_t^g(1+s_t^g)E_t^g - w_t L_t^g - r_t K_t^g, \tag{15}$$

where s_t^g denotes a green production subsidy (described in Section 2.3).

Brown energy firms produce energy using two inputs: the first one is a bundle between brown labour L_t^b and capital K_t^b as the one defined for the final good producers, denoted by $\mathcal{K}_t^b$, while the second one is a natural resource of fossil origin, denoted by R_t. Brown energy producers bundle these inputs via the following CES production function:

$$E_t^b = Z_t^b \left(\xi_b \left(\mathcal{K}_t^b\right)^{\frac{\rho_b-1}{\rho_b}} + (1-\xi_b) R_t^{\frac{\rho_b-1}{\rho_b}}\right)^{\frac{\rho_b}{\rho_b-1}}, \tag{16}$$

where Z_t^b denotes TFP in the brown energy sector. We normalize TFP in the brown sector to 1, allowing TFP in the green sector to be interpreted relative to that of the brown sector. Assuming that the government imposes a carbon tax τ_t^b on the revenues generated in the brown energy sector, the profit function of the representative firm reads as

$$\Pi_t^b = p_t^b(1-\tau_t^b)E_t^b - p_t^{\mathcal{K}}\mathcal{K}_t^b - p^R R_t \tag{17}$$

where p_t^b is the relative price of brown energy and p^R denotes the relative price of the fossil resource. Finally, green and brown energy are combined by a perfectly competitive energy provider using the following CES production function

$$E_t = \left(\xi (E_t^b)^{\frac{\rho_e-1}{\rho_e}} + (1-\xi)(E_t^g)^{\frac{\rho_e-1}{\rho_e}}\right)^{\frac{\rho_e}{\rho_e-1}}, \tag{18}$$

where E_t denotes the energy good demanded by both the final goods producer and the household sector. We assume that fossil energy R_t is supplied perfectly elastically, such that its price remains constant at its initial steady-state level, $p_t^R = p^R$.[8] This abstracts from resource scarcity, which is unlikely to be a binding constraint over our time horizon until 2030, during which the EU has set specific climate targets.[9] Another perspective on this assumption is to view the EU as a price taker in global fossil fuel markets, where prices, such as that of oil, are determined internationally. Hence, we treat fossil supply as perfectly elastic at an exogenous world price. Although upward-sloping supply curves can generate terms-of-trade effects, as in Conte, Desmet and Rossi-Hansberg (2025), our assumption implies that the full incidence of the carbon tax falls on domestic agents, with no offset from declining import prices. While this may overstate the cost of the policy, it provides a transparent benchmark for studying the domestic incidence of carbon taxation. Importantly, relative prices between green and fossil energy remain endogenous, allowing us to capture the key substitution mechanisms that shape the transition.

2.3 Government

The government runs a balanced budget. As mentioned above, it levies a carbon tax τ_t^b on the revenues of the brown energy producers. There are three possible ways the government can utilize the revenue from this carbon tax. First, the government can allocate the tax revenues for unproductive government spending, G_t. This recycling scheme will be employed for all tax revenues in the initial steady state. Second, the government can rebate the proceeds back to the green energy producer in the form of a production subsidy, s_t^g. Finally, it can distribute the tax revenues to households through uniform lump-sum transfers T_t. Taking these options into account, the government budget constraint reads as follows:

$$G_t + T_t + p_t^g s_t^g E_t^g = p_t^b \tau_t^b E_t^b. \tag{19}$$

2.4 Equilibrium

Definition 1. Given exogenous sequences for fiscal policy $\{\tau_t^b, G_t, s_t^g, T_t\}$ satisfying the government budget constraint (19), and a price sequence for the price of the fossil resource $\{p_t^R\}$, a competitive equilibrium is a set of prices

$$\{r_t, w_t, p_t^b, p_t^g, p_t^e\}$$

and quantities

$$\{Z_t^g, K_t^g, K_t^b, K_t^y, L_t^g, L_t^b, L_t^y, R_t, E_t^g, E_t^b, E_t^y, E_t, Y_t\},$$

firm policies, household policies, and distribution over their state variables $(a_{it}, y_{it}, \beta_{it})$ such that firms optimize, households optimize, the distribution evolves consistently with optimal policies

[8] R should be interpreted as a composite of coal, oil, and natural gas. While we do not explicitly model substitutability across these sources, we focus on the substitutability between renewables and non-renewables in energy production.

[9] Moreover, as noted by Fried (2018), prices of fossil resources have not followed the path implied by Hotelling's rule, further weakening the case for modelling scarcity.

and the following market clearing conditions hold:

1. The energy markets clear: $E_t = E_t^y + \int e_{it}^c d\Lambda_t(a_{it}, y_{it}, \beta_{it})$
2. The labour market clears: $\int y_{it} d\Lambda_t(a_{it}, y_{it}, \beta_{it}) = 1 = L_t^y + L_t^b + L_t^g$
3. The asset market clears: $\int a_{it+1} d\Lambda_t(a_{it}, y_{it}, \beta_{it}) = K_{t+1}^y + K_{t+1}^g + K_{t+1}^b$
4. The goods market clears by Walras' Law.

3 Parameterization

Since a closed-form solution to this model is not possible, we employ numerical methods to solve for the equilibrium. To ensure our approach is grounded in empirically plausible parameter values, we utilize both calibration and estimation techniques. We describe our parametrization approach for each sector of the economy. Parameterization is on an annual basis. Importantly, we use the Dutch Household Survey LISS Panel from 2009 to 2019 to estimate the preference parameters and income risk profile.[10]

Estimation of ϵ Two empirical regularities motivate our usage of non-homothetic preferences: (i) energy outlays increase with total expenditure but less than proportionally, and (ii) the energy budget share declines with income. Panel (a) of Figure 3 plots energy expenditure against total expenditure, while Panel (b) shows the energy share against income. Under homothetic preferences like Cobb–Douglas (when $\epsilon = 0$), expenditure shares are constant. The observed variation in energy shares with income indicates non-homothetic preferences, supporting the utility aggregator of Boppart (2014), which nests Cobb–Douglas preferences as a special case when $\epsilon = 0$.

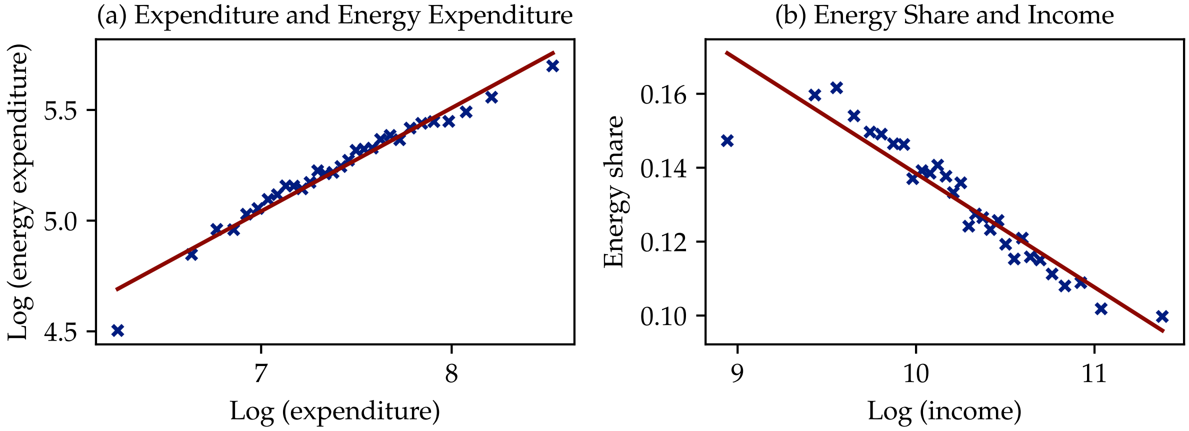
Our framework implies that a household's expenditure structure follows Equation (6). As shown by Boppart (2014), this leads to a log-linear relationship between a household's energy expenditure share and total expenditure. This log-linear form is a key implication of the PIGL demand system and facilitates empirical estimation. Specifically, the parameter ϵ can be identified as the slope coefficient in the following regression equation:

$$\log \eta_{it}^d = \eta_i - \epsilon \log x_{it} + \alpha_t + v_{it}, \tag{20}$$

where $\log \eta_{it}^d$ denotes the natural logarithm of the share of total expenditure that household i allocates to energy in year t. The term η_i captures household-specific fixed effects that account for time-invariant unobserved heterogeneity. The variable $\log x_{it}$ represents the natural logarithm of total equivalised expenditure for household i in year t, and the coefficient ϵ measures the elasticity of the energy expenditure share with respect to total expenditure. The term α_t includes time fixed effects that control for common shocks or trends affecting all households in year t, such as

[10] Further details on data usage and preparation are provided in Appendix A.

Figure 3: Comparison of Energy Expenditure and Energy Share



Note. This figure shows scatter plots of log(expenditure) vs. log(energy expenditure) in Panel (a), and energy expenditure share vs. log(income) in Panel (b), using 30 bins each. The red line illustrates the line of best fit.

energy price shocks. Finally, v_{it} is the error term capturing idiosyncratic factors affecting household i at time t. However, total expenditure x_{it} is potentially endogenous, as the error term may reflect unobserved household-specific factors and preferences that also influence how spending is allocated across goods. As Blundell, Pashardes and Weber (1993) and Blundell, Chen and Kristensen (2007) emphasize, treating total expenditure as exogenous in Equation (20) can induce a correlation between $\log x_{it}$ and the error term v_{it}, biasing the OLS estimate of ϵ.

To illustrate this, consider two households with similar observed income but different tastes for energy-intensive goods such as large homes or private vehicles. A household with stronger preferences for these goods is likely to have both higher total expenditure and a higher energy budget share. If these preferences vary over time and are not fully captured by fixed effects or other observables, they enter the residual v_{it} and become correlated with $\log x_{it}$ and $\log \eta^d_{it}$, violating the exogeneity condition for OLS.

To address this concern, we follow Blundell et al. (1993) and Boppart (2014) and instrument $\log x_{it}$ with log after-tax income, $\log y_{it}$, deflated and equivalised in the same way. After-tax income is a strong predictor of total expenditure, satisfying the relevance condition. Moreover, under the assumption that, conditional on household and time-fixed effects, after-tax income affects the energy budget share only through its effect on total expenditure, and not through direct changes in energy preferences or needs, it serves as a valid instrument. While this strategy does not eliminate time-varying unobserved heterogeneity per se, it allows us to isolate plausibly exogenous variation in total expenditure, thereby mitigating endogeneity concerns.

The IV estimates displayed in Table 1 are consistent across different fixed-effect specifications.[11] The null of homothetic preferences ($\epsilon = 0$) is rejected at the 1% significance level in all cases. Our preferred estimate, $\epsilon = 0.557$, comes from specification (3), which includes both

[11] The corresponding OLS estimates, reported in Appendix B (Table B.1), are of similar magnitude, suggesting limited bias, particularly when both individual and time-fixed effects are included.

Table 1: IV estimation results of ϵ

	(1)	(2)	(3)
Log Expenditure (IV)	-0.575***	-0.583***	-0.557***
	(0.034)	(0.037)	(0.124)
Observations	18608	18608	16242
R-squared	0.190	0.186	0.189
Fixed Effects	None	Time	ID + Time
Clustering	ID + Time	ID + Time	ID + Time

Note. Standard errors in parentheses. Significance levels: * p<0.1, ** p<0.05, *** p<0.01.

time and individual fixed effects, and we use this value in the model going forward.

Additional information related to data construction and OLS estimation are presented in Appendix B.

Income process We also use the Dutch Household Survey LISS Panel to estimate the stochastic income process. Following Floden and Lindé (2001) and Straub (2019), income has a persistent and a transitory component:

$$\log y_{it} = \kappa_{it} + \psi_{it}, \tag{21}$$

where κ_{it} follows an AR(1) process with persistence ρ and innovation variance σ_ε^2, and ψ_{it} is iid with variance σ_ψ^2.

The income process is estimated in two stages. First, we regress annualized log average monthly gross household income on education, occupation indicators, household size, and a polynomial function of age. In the second stage, we employ a Minimum Distance Estimator on the residuals from this regression to estimate the parameters $(\rho, \sigma_\psi^2, \sigma_\varepsilon^2)$ of the persistent-transitory income model.

The persistent component has an AR(1) coefficient of 0.9422 and an innovation variance of 0.0186, while the transitory shock variance is estimated at 0.0113. These estimates are consistent with those in related studies, such as Krueger, Mitman and Perri (2016) for the US. Further details on the estimation procedure are provided in Appendix C.

Other household parameters Following Auclert, Rognlie and Straub (2024), we assume that each household's discount factor, β_{it}, evolves according to a two-state Markov chain. Households with β^{low} are currently impatient, while those with $\beta^{\text{high}} > \beta^{\text{low}}$ are currently patient. Each period, an agent retains their existing discount factor with probability $1 - q$. With probability q, they receive a new independent draw, where β takes the value β^{low} with probability $\omega_{\beta^{\text{low}}}$ and β^{high} with probability $1 - \omega_{\beta^{\text{low}}}$. We calibrate $q = 0.04$, implying that households receive a new draw of β approximately once every 25 years. As suggested by Krusell and Smith, Jr (1998), we interpret this as capturing generational turnover. The value of β^{high} is chosen to ensure that the real interest rate in the initial steady state is 3%. Meanwhile, $\Delta\beta \equiv \beta^{\text{high}} - \beta^{\text{low}}$ and the transition probability

Table 2: Estimated and assigned parameters

	Description	Value	Target/source
	Households		
	Preferences		
ϵ	Degree of non-homotheticity	0.557	Estimated, LISS panel
γ	EoS factor	0.557	Literature
β^{high}	High discount factor	0.980	Asset market clearing with $r = 0.03$
	Income process		
ϱ	Income shock persistence	0.9422	Estimated, LISS panel
$\sigma^2_{\varepsilon^\kappa}$	Variance of innovations to persistent shock	0.0186	Estimated, LISS panel
σ^2_ψ	Variance of transitory shocks	0.0113	Estimated, LISS panel
	Production		
	Final goods production		
ρ_y	EoS between capital-labor and energy	0.04	Hassler et al. (2021)
α	Capital share	0.36	Literature
	Energy bundler		
ρ_e	EoS between brown and green energy	1.8	Papageorgiou et al. (2017)
	Brown energy production		
ρ_b	EoS between capital-labor and fossil resource	0.25	Bodenstein et al. (2011)
α_b	Capital share in the C-D bundle	0.597	Barrage (2020)
	Green energy production		
α_g	Capital share	0.597	Barrage (2020)
Z^g_0	TFP green energy	1.0	Normalization

Note. This table provides parameters that we estimated using the LISS data archive, and parameters sourced from the relevant literature. The first column shows the parameter symbols, the second the description, the third the value, and the fourth the sources or the target.

$\omega_{\beta^{\text{low}}}$ are set to jointly match both the wealth Gini coefficient and the average marginal propensity to consume (MPC) in the Euro Area. Specifically, we target a wealth Gini of 0.73 — the average of quarterly Gini coefficients for the Euro Area in 2015, as reported in the ECB's Distributional Wealth Accounts. To match the MPC, we draw on empirical estimates from European data. Based on the average of the findings in Jappelli and Pistaferri (2014), Crawley and Kuchler (2023), and Dimitris, Dimitris, Jappelli, Pistaferri and van Rooij (2019), we target an average MPC of 0.44. Finally, we need to set the second parameter in the non-homethetic formulation. We adopt $\gamma = \hat{\epsilon} = 0.557$ in the quantitative model, which implies an elasticity of substitution between energy and the non-energy composite of $1 - \gamma = 0.443$. This figure aligns with the 0.44 estimate for the United States in Balke and Brown (2018). We calibrate the preference parameter ν to match the average energy expenditure share.

Production of Final Goods The gross capital share α in the capital-labour bundle is set to a standard value of 0.36. The elasticity of substitution between the capital-labour bundle and energy is set to 0.04, following Hassler, Krusell and Olovsson (2022). This near-zero elasticity implies that the energy income share in final goods production closely tracks movements in the energy price. The share parameter ξ_y is set to one minus machine epsilon to get as close as possible to the observed energy income share of 0.072 (Coenen et al., 2024). Finally, the depreciation rate δ is calibrated to match a capital-to-output ratio of 3.197, as reported by Eurostat.

Energy production Turning to energy production, we aim to match two key relative magnitudes between brown and green energy. First, we target the relative price of green to brown energy, which was 1.8 in 2015, as documented by Jo (2024). The latter must be consistent with the initial quantity of fossil resources used in the production of brown energy, denoted as R_0. Second, we target the relative supply of brown and green energy. Using Eurostat's simplified energy balances, we calculate that the ratio of green to brown energy, both measured in tonnes of oil equivalent, was approximately $\frac{E^{g,\text{data}}}{E^{b,\text{data}}} = 0.1686$ in 2015.

In model units, this implies that $\frac{p^g E^g}{p^b E^b} = 0.1686$, which leads to $\frac{E^g}{E^b} = 0.0937$. We set the elasticity of substitution between brown and green energy, ρ_e, to 1.8, based on microeconometric evidence from Papageorgiou et al. (2017).

Finally, we calibrate the share parameter ξ of the energy bundle. The first-order condition for the energy bundler yields the following equation

$$\left(\frac{\xi}{1-\xi}\right)^{\frac{\rho_e - 1}{\rho_e}} \left(\frac{E^g}{E^b}\right)^{\frac{1}{\rho_e}} = \frac{p^b}{p^g}. \tag{22}$$

Using the target values for $\frac{E^g}{E^b}$ and $\frac{p^b}{p^g}$, we can solve for ξ analytically. This approach results in a value $\xi = 0.674$.

Brown energy is produced using a capital-labour bundle and a brown fossil resource. The capital-labour bundle follows a Cobb-Douglas specification with a capital share of 0.597, as in (Barrage, 2020). We set the elasticity of substitution between these inputs to 0.25, as in Coenen et al. (2024). Additionally, we calibrate the share parameter ξ_b numerically to match a labour share of 30%. Following Barrage (2020) and others, we assume that green energy production also follows a Cobb-Douglas function in capital and labour. Thus, we set $\alpha_g = 0.597$.

Government The only instrument available to the government for raising revenue is the carbon tax τ_t^b. Given the European context of our application, we calibrate the revenue share to match the European revenues from environmental taxes as a percentage of GDP in 2015. According to Eurostat, this amounted to 2.436% in 2015.

We summarize the model's parameterisation in two tables. Table 2 reports the estimated and assigned parameters. Table 3 presents the parameters used to target empirical moments, along with the target values, and corresponding model-implied moments. The model fits the data targets very well. Finally, Table 4 evaluates the model's performance in matching untargeted moments. Given the parameterisation described above, the model underestimates the Gini coefficient for income, arguably due to the absence of return heterogeneity in financial income. In contrast, the labour share in energy is overestimated relative to the data, while the empirical share in brown

Table 3: Numerically calibrated parameter values and moments

Parameter	Value	Moment		Model	Data
δ	0.0995	Capital-Output Ratio	$\frac{K}{Y}$	3.197	3.197
ξ_b	0.0601	Labor share in brown energy prod	$\frac{wL^b}{p^b E^b}$	0.300	0.300
ν	0.1571	Avg. exp. share in energy	$\int \frac{P_e e_i^c}{x_i} d\Lambda_i$	0.130	0.130
τ_d	0.1242	Carbon tax rev. to GDP	$\frac{\tau_d p^b E^b}{Y}$	0.0244	0.0244
$\Delta\beta$	0.0502	Gini wealth	$\text{Gini}(\Lambda_i)$	0.765	0.731
$1-\omega_{\beta^{\text{low}}}$	0.4597	Average MPC	$\int \frac{\partial x_i}{\partial y_i} d\Lambda_i$	0.460	0.440
$(1-\xi_y)$	2.22e-16	Energy income share	$\frac{p^e E}{Y}$	0.147	0.072
R_0	1.6822	Rel. price between brown and green energy	$\frac{p^g}{p^b}$	1.800	1.800

Note. This table provides the numerically calibrated parameters together with the corresponding moments of our benchmark calibration. We use the TikTak algorithm of Arnoud, Guvenen and Kleineberg (2019) to calibrate all parameters, except the last two, where ξ_y is set manually and R_0 is determined numerically by solving the firm's steady-state system of equations. The first column shows the parameter symbols, the second the value, the third the moment description, and the last two columns show the corresponding values in the model and the data.

energy is exactly matched. Overall, we consider the model successful in matching empirical moments, both targeted and untargeted.

3.1 Initial steady state

Before examining the transitional dynamics, we first discuss the characteristics of the initial steady-state household expenditure and the properties of the stationary distribution across different variables.

Household expenditure characteristics Panel (a) of Figure 4 illustrates households' energy expenditure as a function of total expenditure. The solid (blue) line represents the lowest income type, while the dashed (red) line corresponds to the highest.

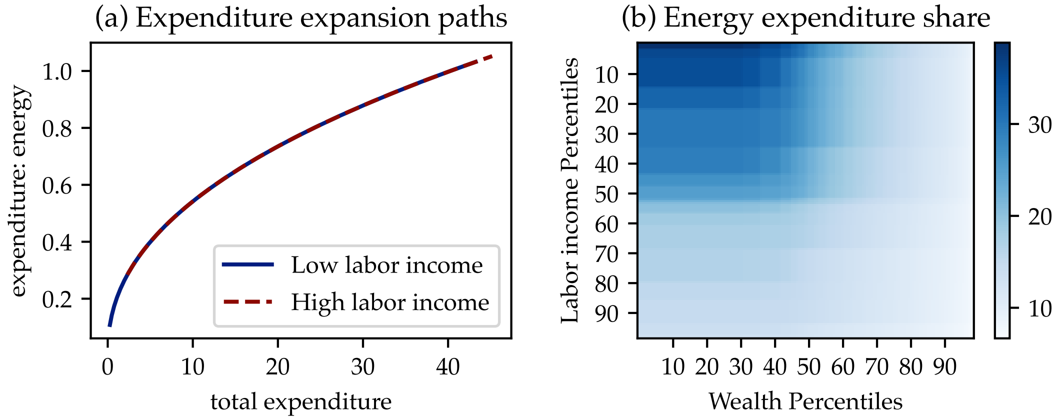
Two key observations emerge. First, for a given level of total expenditure, energy expenditure is identical across income types. This result arises because both income types face the same in-

Table 4: Untargeted moments at initial steady state

Moment Description	Formula	Model Moment	Data Moment	Data Source
Gini income	–	0.256	0.308	Eurostat
Brown energy share	$\frac{p_b E_b}{p_e E}$	0.856	0.856	Eurostat / Own calculations
Labor share in energy	$\frac{L_b+L_g}{L_y+L_b+L_g}$	0.117	0.024	Eurostat / EEA

Note. This table reports untargeted moments at the initial steady state together with its data counterparts. All data values are retrieved for the year 2015. We use the Gini coefficient of equivalised disposable income for the EU27 group, the simplified Energy Balances and share of energy from renewable source by Eurostat, and the employment in the EU's environmental goods and services sector by the European Environmental Agency (EEA) to retrieve the moments.

Figure 4: Expenditure expansion paths and energy expenditure shares across the distribution



tratemporal decision problem, where total expenditure is predetermined. Second, energy expenditure is *concave* in total expenditure. This follows directly from the non-homothetic preferences and the Marshallian demand system derived from Equation (5).

Panel (b) of Figure 4 illustrates the key implication of this concavity by displaying a heatmap of energy expenditure shares, plotted against the percentiles of income and wealth. The share of expenditure on energy decreases with both income and asset holdings, with a slightly stronger effect for asset holdings. The lowest expenditure share is observed among those with high asset wealth, regardless of their income level. Hence, what primarily matters for a household's expenditure share is cash-on-hand. Even if a household is at the borrowing constraint (i.e., holding the lowest asset position), a high income level significantly reduces its expenditure share. Similarly, low-income households with high asset holdings also have a lower expenditure share.

The use of the Boppart (2014) utility function is a distinctive feature of our model. First, the above patterns align with empirical evidence from microdata, as shown in Figure 3. Second, the fact that expenditure shares are unevenly distributed across households, and decrease with both income and wealth, has important implications for the distribution of the welfare costs of the green transition.

Initial Steady State Inequality Steady-state inequality metrics, summarized in Table 5, reveal notable patterns across household quantities. The Gini coefficient for energy consumption is 0.11, indicating a relatively homogeneous distribution of energy expenditure, in line with the specification of our preferences. This suggests a lower concentration of energy consumption compared to both income and wealth.

Additional measures of concentration commonly used in the literature further support this observation. The mean-to-median ratio and percentile ratios (99-50 and 90-50) for energy consumption are significantly lower than those for non-energy consumption and total expenditure, reinforcing the relatively equal distribution of energy consumption. In contrast, wealth concentration is substantially higher, with a 99-50 ratio of 99.91 and a 90-50 ratio of 37.73, highlighting

Table 5: Steady-State Inequality Metrics for various household quantities

Variable	Gini	Mean pctile	$\frac{\text{Mean}}{\text{Median}}$	$\frac{\text{99th}}{\text{50th}}$	$\frac{\text{90th}}{\text{50th}}$
Total Expenditure	0.27	63	1.15	3.75	1.85
Non-Energy Consumption	0.29	63	1.17	4.04	1.93
Energy Consumption	0.12	57	1.03	1.80	1.31
Wealth	0.76	72	12.78	110.57	41.22
Income	0.26	60	1.09	2.77	1.78

Note. This table provides the Gini coefficient, the location of the mean, the ratio of the mean to the median and the respective 99th-50th and 90th-50th percentile ratios across the distributions of total expenditure, non-energy consumption, energy consumption, wealth and total income.

the high concentration of assets among the top percentiles of the distribution.

4 Macroeconomic and Distributional Consequences of the Green Transition

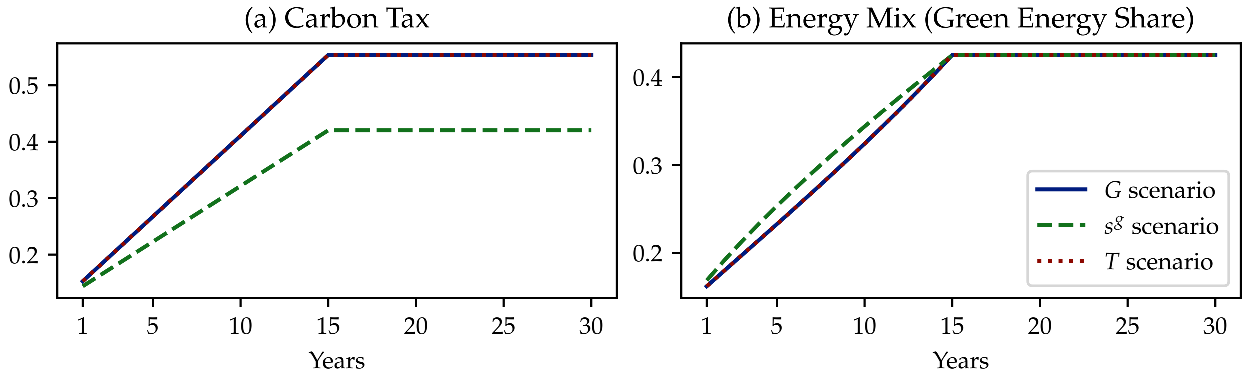
In this section, we explore the macroeconomic and distributional effects of the green transition under different policy scenarios. First, we present our baseline case of reference, and we precisely define our policy scenarios. Then, we will describe the consequences of each scenario in comparison with the baseline, first focusing on the aggregate effects and then on the distributional ones. Under each transition, the price of the fossil resource is exogenous and assumed to remain constant.

4.1 The green transition

We consider the initial steady state of our economy, just described above, as 2015, the year of the Paris Agreement. Recall that in this steady state, the government imposes a carbon tax equal to $\tau^b_{2015} = 0.12$ and uses the revenues to fund wasteful government consumption. Importantly, our model features technological progress in the production of green energy. In our baseline transition experiment green technology, Z_g, grows linearly from 2015 to 2030 at the same average rate as implied by the change in the share of green energy between 2005 and 2015 (see Figure 1). Appendix F presents the transition paths of key variables under this baseline scenario, which assumes no fiscal intervention beyond the automatic adjustment of government spending to maintain a balanced budget. Because of the technological growth in the green sector, the economy in this baseline transition is on an expansionary path where output, wages, and capital grow to the new long-run equilibrium. Energy prices decline along the transition path. However, by 2030, the share of renewable energy reaches only 30%.

To address this shortfall, we introduce a gradually and steadily increasing carbon tax, aiming to achieve the new EU target of renewable energy share of 42.5% by 2030. Starting from the initial steady state, the carbon tax, τ^b, rises steadily and linearly from $\tau^b_{2015} = 0.12$ to a level consistent with the 42.5% target. The carbon tax increase is modelled as a fully unanticipated policy. After

Figure 5: Carbon tax path and energy mix along the green transition.



Note. Panel (a) shows the different paths of the carbon tax τ_t^b over the transition. Panel (b) depicts the green energy share in total energy produced ($\frac{p_t^G E_t^G}{p_t^E E_t}$).

2030, both the carbon tax and green technology are assumed to remain constant.

A key contribution of our paper is the analysis of three alternative uses for the carbon tax revenue, each leading to a distinct transition path to 2030.

In the first scenario, all revenues are allocated to wasteful government consumption, aligning with the fiscal policy in our baseline transition scenario described above. Hence, this is a useful benchmark to present, where fiscal policy maintains its behaviour and does not target any specific use for the extra revenues generated by the increase in carbon taxation. We refer to this as scenario "G." In the second scenario, denoted as scenario "T", the revenues are distributed equally to households as lump-sum transfers, directly increasing disposable income and potentially mitigating the financial burden of higher carbon taxes, especially for poor households. This scenario mimics the government intervention in some euro area countries during the recent energy inflation surge. Finally, in the third scenario, labelled "s^g", the fiscal authority redirects the revenues to subsidize green energy production, encouraging the adoption of clean energy.[12]

The left Panel in Figure 5 shows the assumed path of the carbon tax over 30 periods, while the right Panel illustrates the dynamics of the green energy share over the three different scenarios. Solid (blue) lines refer to scenario G, dotted (red) lines to scenario T, and dashed (green) lines to scenario s^g. Green energy subsidies necessitate a smaller increase in the carbon tax to meet the 2030 green energy share target and imply a persistently higher share of green energy usage during the transition to 2030, in comparison with the other two policies.

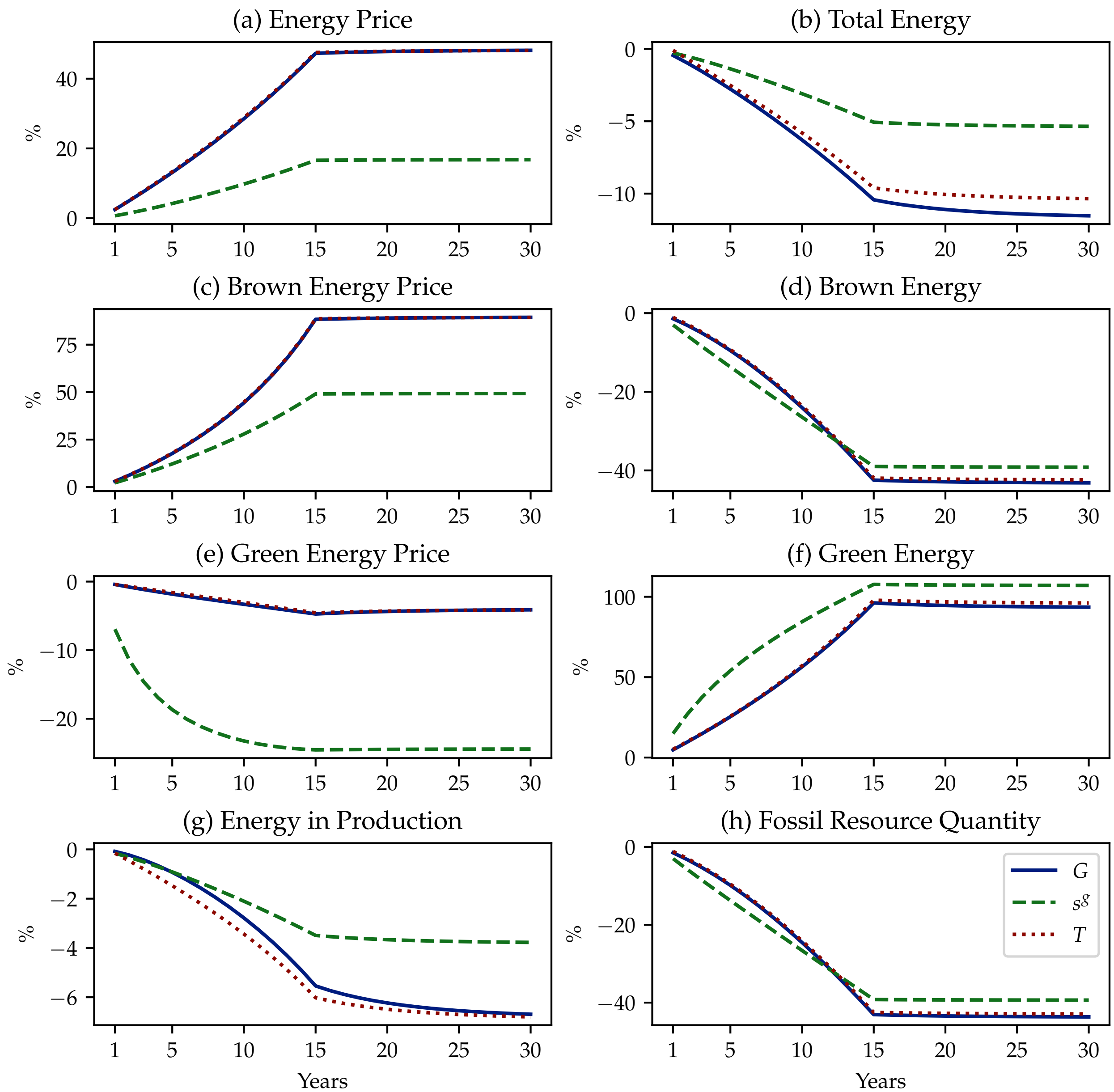
In the following, we assess the macroeconomic, distributional, and welfare effects of the green transition under these three fiscal policy scenarios. To disentangle the impact of fiscal policy from that of technological progress, we present the dynamics of key macroeconomic variables relative to their counterparts in the baseline transition experiment, where only technological progress is at play. Therefore, unless otherwise stated, in all the following figures the variables will be expressed

[12] In both the transfer and subsidy scenarios, government consumption is fixed at its initial steady-state level. Thus, revenue recycling occurs only as deviations from this baseline.

in percentage deviation from the baseline scenario. As in Figure 5, solid blue lines represent the G scenario, red dotted lines the T scenario, and dashed green lines the s^g scenario. For each, we compare both aggregate effects and distributional impacts.

4.2 Aggregate Effects

Figure 6: Dynamics of relative energy prices and energy quantities along the transition



Note. All paths are computed as percentage deviations relative to the transition with only green energy technology growth.

Energy market We first analyse the energy sector. Figure 6 presents energy market outcomes across all fiscal policy scenarios relative to the baseline scenario. It illustrates the relative price of energy (Panel (a)) and its equilibrium quantity (Panel (b)), along with the relative prices and the quantities of brown energy (Panels (c) and (d)) and green energy (Panels (e) and (f)). Additionally, it shows the amount of energy used in final goods production (Panel (g)) and the amount of fossil resources consumed in brown energy production (Panel (h)).

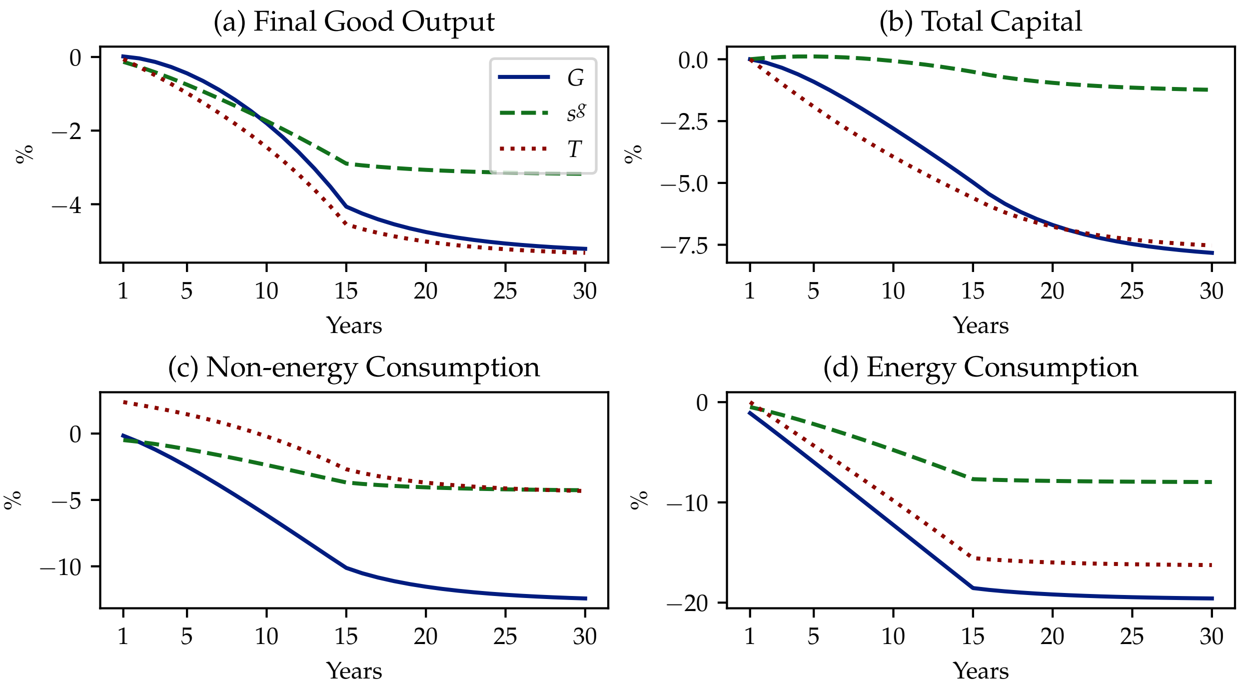
Let us focus on the blue lines, representing the G scenario. As expected, compared to the baseline scenario, the carbon tax increases the relative price of brown energy (Panel (c)), and reduces both the production of brown energy (Panel (d)) and fossil resource consumption (Panel (h)). In the literature (e.g., Fried, 2018), carbon emissions are typically modelled as a function of fossil resource consumption, assuming a constant conversion rate. For this reason, a reduction in the usage of R and in the production of brown energy can be interpreted as a reduction in emissions. This is the main and intended effect of the carbon tax. As a consequence, the price of energy (Panel (a)), which is produced using both brown and green energy, also rises with respect to the baseline.[13] The impact on energy usage in Figure 6 mirrors the price dynamics. Energy production (Panel (b)) declines as both households and firms cut their energy demand. As the price of brown energy increases, energy providers substitute brown with green energy. Total brown energy production declines sharply, exceeding a 40% reduction by the completion of the transition. The strong increase in green energy production (Panel (f)) only partially offsets the sharp reduction in the brown sector. Note that the price of green energy (Panel (e)) slightly falls, despite the strong increase in green energy usage in consumption and production. This general equilibrium effect is driven by the supply side of the model, as the carbon tax induces a strong increase in the production of green energy and a large reallocation of both labour and capital from the brown to the green sector (see Figure E.1 in Appendix E).[14] Moreover, the cost of producing green energy tends to decrease because of the general equilibrium effects induced by the contraction of factor prices (see below).

The red-dotted lines in Figure 6 visualize the T scenario and show that the paths of the variables in all the panels are very close to those in the G scenario. Notable differences emerge, however, in energy production and usage: as shown in Panel (b), energy production declines less under the T scenario, while energy use in final goods production (Panel (g)) falls more sharply. This occurs because the additional carbon tax revenue is rebated to households rather than spent on final output. Uniform transfers directly ease households' budget constraints, and proportionally more so for poor households with a high marginal propensity to consume (MPC). Households

[13] As said above, unless otherwise stated, in all the following figures the variables will be expressed in percentage deviation from the baseline scenario, where the economy is growing because of technological progress in the production of green energy. So we will not any more state 'relative to the baseline' in what follows. Appendix E presents the corresponding figures from this subsection expressed as deviations from the initial steady state, highlighting the dynamics of variable levels.

[14] Our model does not feature any factor reallocation costs across brown and green energy sectors. While it would be easy to introduce reallocation costs, it is also clear what the effect would be, i.e., they would make the transition even more inflationary in terms of energy prices.

Figure 7: Dynamics of output, capital, non-energy and energy consumption along the transition.



Note. All paths are computed as percentage deviations relative to the transition with only green energy technology growth.

will have more resources available for consumption, and they will spend it partly on energy and partly on the non-energy good. Hence, with respect to the previous scenario, T diverts resources from final good producers to energy producers. Brown energy production evolves identically in both scenarios, as confirmed by the nearly identical paths of R across policies. This indicates that the environmental impact of the two policies is essentially the same. In contrast, the effects in the s^g scenario – green dashed lines – differ significantly from those observed in the previous scenarios. The s^g scenario stands out because the primary role of the subsidy is to further stimulate production in the green energy sector. Indeed, the subsidy drives a sharp decline in the price of green energy – beyond what technological progress alone would achieve – and leads to a strong expansion in green energy production, facilitating the achievement of the green share target. As a result, a smaller increase in the carbon tax is needed in the s^g scenario, compared to the other scenarios, as shown in Figure 5. The lower carbon tax in the s^g scenario leads to a milder increase in both brown energy prices and the aggregate energy price. As a result, the decline in total energy production and energy used in final goods production is much smaller than under the other two policy scenarios. While green energy output rises substantially, brown energy use falls more sharply at the start of the transition but declines less in the new steady state. Fossil fuel usage R follows a similar pattern, implying that the s^g policy results in lower emissions early in the transition but higher emissions in the long run.

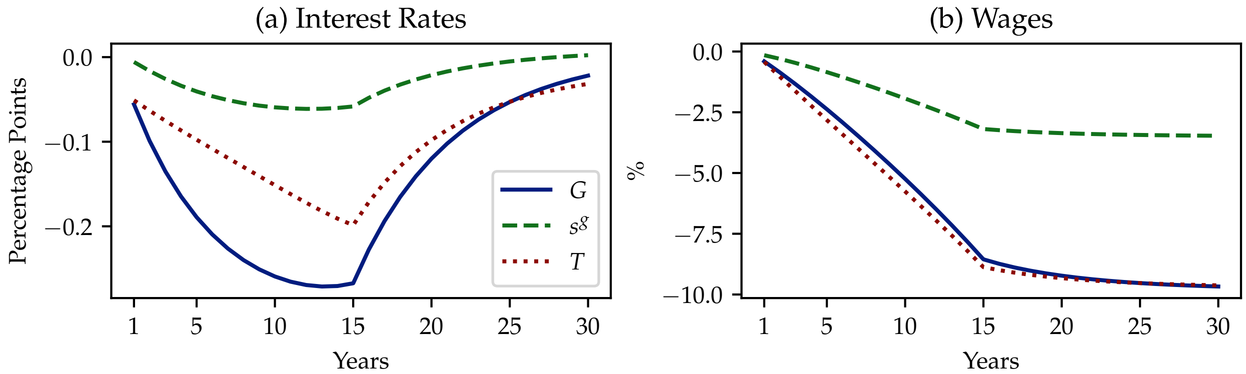
Output, capital, and consumption Figure 7 illustrates the dynamics of aggregate output (Panel (a)), total capital (Panel (b)) and both non-energy (Panel(c)) and energy consumption (Panel (d)). The G scenario features a strong contractionary effect on output, capital, and consumption, which all grow more slowly than in the baseline following the increase in the carbon tax. Consumption, both of energy and non-energy goods, declines significantly due to the negative wealth effects from higher taxes, as in a standard real business cycle model. Energy consumption falls more sharply than non-energy consumption, reflecting a substitution effect away from the now more expensive energy good. While output of the final good decreases because of lower consumption, government spending increases by design, making the net effect on output ex ante ambiguous. Note that this can be seen as an example of a negative fiscal multiplier, given that this scenario could be interpreted as an increase in government spending financed by an increase in the carbon tax. Two main factors dampen the expansionary effect typically associated with government spending in standard real business cycle (RBC) models. First, labour supply is fixed in our model, eliminating the wealth effect on labour supply that drives output expansion in standard RBC frameworks when spending is financed through lump-sum taxes. Second, and most importantly, our model is multi-sectoral and the carbon tax is a distortionary tax on a production input. By raising the cost of brown energy, the tax acts like a negative productivity shock. Since output relies on energy, capital, and labour, firms respond by cutting back not only on energy use but also on capital and labour inputs. As a result, aggregate capital declines significantly.

Not surprisingly, both non-energy and energy consumption are higher in the T scenario, since the revenues from the increase in the carbon tax are rebated to households in this case. Of course, given the increase in the price of energy, households substitute away energy with non-energy consumption, such that the impact on non-energy consumption in the T scenario is initially positive. In contrast, final output contracts more than in the G scenario, where all the receipts from the extra carbon tax are spent on the final good. Hence, relative to the G scenario, the T scenario diverts energy usage from final good production to consumption. The reallocation of resources away from final good production is also evident in the allocation of capital and labour across sectors (see Figure E.1 in Appendix E).

The boost in green energy production in the s^g scenario has a significant impact on the dynamics of aggregate variables. Subsidies for green energy help mitigate the contractionary effects of the green transition, resulting in a smaller decline in output and capital compared to other scenarios. The reallocation of labour from final goods and brown energy production to green energy production, a trend observed across all scenarios, is quantitatively more pronounced in the s^g case (see Figure E.1 in Appendix E).

Factor prices The contractionary effects of higher carbon taxation affect the dynamics of factor prices throughout the green transition, as shown in Figure 8. Reflecting the differing aggregate responses across the three scenarios, both the return on capital and wages decline more in the G and T scenarios compared to the s^g scenario. By mitigating the impact of carbon taxation on

Figure 8: Dynamics of wages and returns to capital along the transition.



Note. The interest rate path is computed as the percentage point differences whereas the wage path is computed as percentage deviations relative to the transition with only green energy technology growth.

energy production, the s^g policy has important supply-side effects. In particular, the final goods sector relies on energy as a production input with a very low elasticity of substitution. The higher energy production under the s^g scenario supports the productivity of labour and capital in the final good sector, in contrast with the strong reduction in energy production induced by the G and T polices. These dynamics of the marginal productivities of factors, and hence in factor demands, shape factor prices throughout the transition.[15] In all scenarios, total capital is reallocated from the brown sector to the green sector, but in the case of s^g capital is partly reallocated to the final good sector too, leading to an increase in total capital (see Figure E.3), exactly because the total production of energy – and of energy used in production – increases, supporting the production of final good.

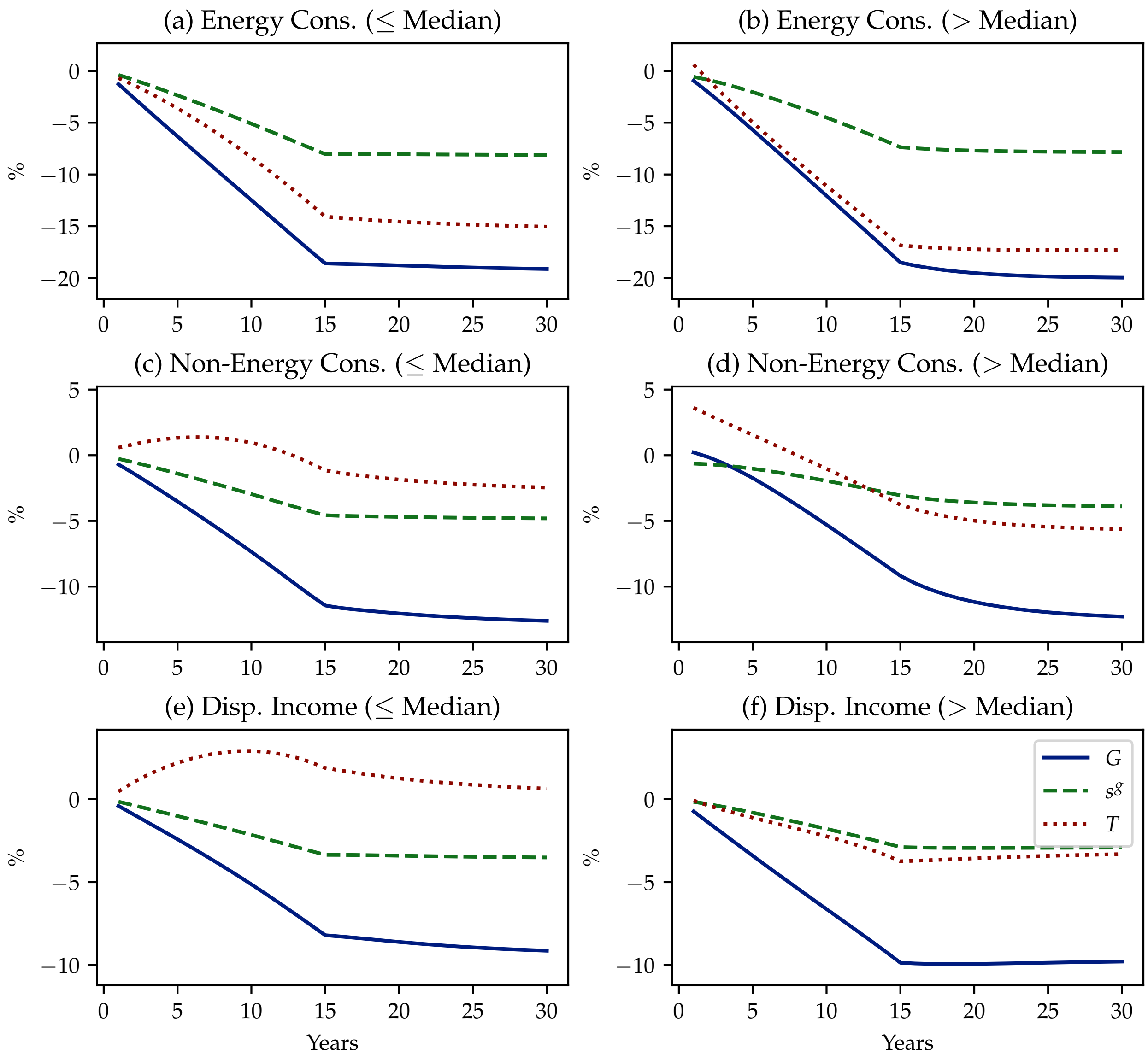
Note, however, that the interest rate declines much less than the wage in all scenarios and follows a different path, as it begins to rise after about fifteen years, when the carbon tax stays constant and the economy moves to reach the new steady state. To understand this difference, it is essential to consider factor supplies too. Aggregate effective labour supply is exogenously fixed and inelastic, so wage dynamics reflect changes in the marginal productivity of labour. This productivity falls under the G and T scenarios due to sharp declines in both energy and capital all along the transition. In contrast, wages rise under the s^g scenario, where both energy and capital increase – relative to the initial steady state (see Figures E.2–E.4) – though by less than in the benchmark scenario without policy intervention, as shown in Figure 8. The capital market behaves quite differently, as the supply of savings is endogenous in our heterogeneous agent model. The interest rate is determined by the interaction of capital demand and supply. To convey the intuition, Figure E.5 presents standard Aiyagari-type diagrams showing how the supply and demand schedules of capital shift from the initial steady state, to year 15, when thereafter the policies remain constant, to a long enough period in the future, that approximate the final steady state in all the scenarios, including the benchmark one with no policy intervention. The figure shows that,

[15] Indeed, Figure E.4 shows that both interest rate and wages increase relative to the initial steady state values under s^g, while they strongly decrease under G and T.

as expected from the above discussion, the demand for capital schedule: (i) is price insensitive, given the low elasticity of substitution of energy in production; (ii) decreases – it shifts to the left – under the G and T scenarios, and increases – it shifts to the right – under the benchmark and the s^g scenarios. The capital supply curve (i.e., the savings schedule), instead, is more elastic and it initially increases – shifts to the right – under the G and T scenarios, and it decreases – it shifts to the left – under the benchmark and the s^g scenarios. Under the benchmark scenario the economy is growing and agents would like to save less, other things equal, to smooth consumption, especially so up to years 15, when the technology in the green sector stops growing and the pure transitional dynamics to the new steady state kick in. This shift in the savings schedule, combined with the increase in capital demand, causes the interest rate to rise unambiguously in the short run. The same mechanism works under the s^g scenario, even if to a lower degree because of the additional carbon tax. However, as discussed, the green sector subsidy offsets much of the aggregate impact, making this policy the closest to the benchmark case without intervention. In contrast, the opposite occurs under the G scenario: capital demand falls while capital supply rises. Agents anticipate the negative aggregate effects of the policy and a lower level of output and consumption in the future. Thus, they increase savings, other things equal, for the coming rainy days. The combination of these two shifts in the demand and supply schedule unambiguously reduces the interest rate. While this negative wealth effect is particularly strong for the G scenario, rebating the increased carbon tax revenues to households in the T scenario partially offsets it. As a result, consumption – especially of non-energy goods – is higher in the T scenario and savings are lower, accelerating the depletion of the capital stock in the T scenario relative to the G one. Figure E.5 shows that the T policy mitigates the negative wealth effect on households – inducing a smaller rightward shift of the saving schedule, so that the interest rate falls less in this scenario relative to G. Additionally, due to transfer income, households' need for precautionary savings diminishes, contributing further to a reduction in their savings relative to the G scenario. Overall, the behaviour of savings shapes the path of the interest rate in all the scenarios considered.

To sum up, the analysis of the aggregate dynamics suggests that subsidizing green energy production achieves the policy objective while imposing a lower overall cost on the economy. This is the scenario where energy consumption falls the least. Non-energy consumption falls slightly, but not as much as in the G scenario. If the fiscal policymaker aims to increase energy consumption, subsidies to firms, rather than households, prove more effective. However, in our model economy – characterized by household heterogeneity, incomplete markets, and non-homothetic preferences – these costs may be distributed more unevenly across households compared to the previous T scenario. Hence, we turn to analyse the distributional effects of the green transition across the different scenarios.

Figure 9: Dynamics of energy consumption, non-energy consumption and disposable income above and below the median of the wealth distribution along the transition.



Note. All paths are computed as percentage deviations relative to the transition with only green energy technology growth.

4.3 Distributional Effects

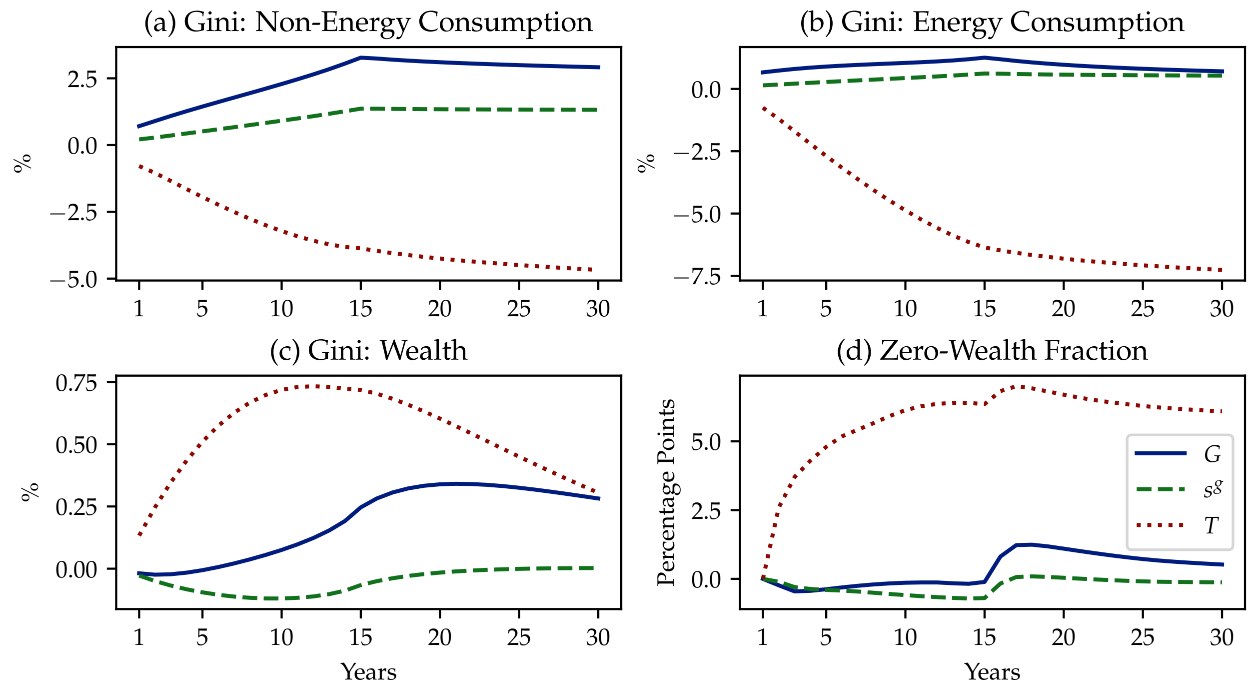
Figure 9 displays the dynamics of consumption of the two goods, as well as disposable income, distinguishing between agents with wealth above and below the median.[16] The behaviour of consumption is similar across the wealth distribution (Panels (a)-(d)) in the G scenario. Both asset-rich and asset-poor agents significantly reduce their consumption of both the non-energy good and of energy, not surprising the latter relatively more than the former. Note that asset-rich households

[16] We consider the wealth distribution at the initial steady state to determine the split. So, the figure tracks the variables of interest conditional on initial wealth below or above the median of the initial wealth distribution.

can more easily shift their consumption from energy to non-energy goods during the transition. In the T scenario, both asset-poor and asset-rich agents use the transfers to reduce energy consumption less (Panels (a) and (b)) relative to the G scenario. Moreover, they actually increase their final good consumption relative to the baseline (Panels (c) and (d)). However, they do that to a different degree. While rich households mainly use the transfer to increase their non-energy consumption, poor households use the transfer to limit their reduction in energy consumption. This outcome aligns with the transfer's primary goal: to support the income of poor households and shield them from the increase in energy prices. Indeed, the significant redistributive effects of this transfer policy are evident in Panels (e) and (f), which show that disposable income increases for poor households, while it decreases for rich households. However, this decline is much smaller than in the G scenario, as they also receive the transfer. The amount of transfer is sizeable. As a percentage of disposable income, it increases progressively up to around 8% in the new steady state. Being equally distributed across households, it then has a large impact on the disposable income of poor households. The lower aggregate costs associated with the s^g policy translate into milder distributional effects. The decrease in both non-energy and energy consumption and in disposable income is similar across the wealth distribution, with a lower decrease in non-energy consumption and disposable income for rich households. Note that in terms of deviation from initial steady state, while disposable income decreases sharply for all households across the wealth distribution in scenario G, it increases in the other two scenarios (see Figure E.6). The difference between these two scenarios is in the implied redistribution: while in the s^g scenario the increase in disposable income is small and similar across the income distribution, in the T scenario the increase in disposable income is sizeable and concentrated among the poor household. The milder aggregate impact under s^g and the strong redistributive effects of the T policy reveal a classic efficiency-equity trade-off, as we show next.

Gini coefficients and constrained agents Figure 10 displays the dynamics of the Gini coefficient of concentration in non-energy consumption (Panel (a)), energy consumption (Panel (b)), wealth (Panel (c)) and the fraction of households at the borrowing constraint (Panel (d)) across the three scenarios. In the G scenario, asset-poor agents experience initially a sharper contraction in consumption than wealthier agents, leading to the increase in the Gini coefficients for both non-energy and energy consumption. Richer households' greater ability to substitute away from energy causes the Gini coefficient for non-energy consumption to increase more than that for energy consumption. Panel (c) shows that wealth is becoming slightly more concentrated, while Panel (d) shows that the fraction of households at the borrowing constraint remains largely unchanged. In contrast, the T scenario yields lower consumption inequality in both goods. The Gini coefficients for both energy consumption and non-energy consumption decrease substantially, despite the rise in energy prices. This reflects a classic efficiency-equity trade-off. The carbon tax reduces production of both energy and non-energy goods, causing significant distortions in resource allocation. However, the transfers under scenario T reduce consumption inequality. On the flip side,

Figure 10: Dynamics of the Gini coefficients for non-energy consumption, energy consumption, wealth, and the fraction of financially constrained households



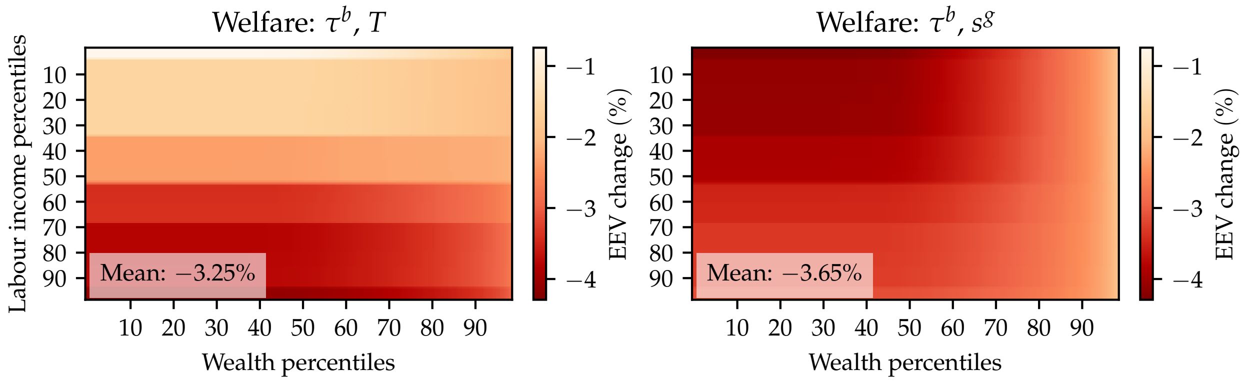
Note. The fraction of zero-wealth households is computed as percentage point deviations whereas all other paths are computed as percentage deviations relative to the transition with only green energy technology growth.

wealth inequality has risen considerably (Panel (c)), as wealth becomes more concentrated due to the decreased need for precautionary savings. Since transfers are identical across households, poorer individuals receive a larger transfer, relative to their income, than wealthier individuals. This leads to lower savings compared to the baseline, which pushes a much larger fraction of agents towards their financial constraint (see Panel (d)), resulting in a substantial increase in the fraction of agents with no wealth. This, in turn, causes a significant rise in the Gini coefficient of wealth concentration. The distinguishing feature of the T scenario is its redistributive nature, which leads to a less dispersed disposable income, a decrease in the Gini coefficients for (both energy and non-energy) consumption, and a rise in the fraction of agents at zero wealth, in contrast with the other alternative scenarios. Indeed, under the s^g scenario, the Gini coefficients for both non-energy and energy consumption mildly increase, while the Gini coefficient for wealth slightly decreases. Overall, concentration coefficients are less affected under this efficiency-focused policy compared to the other fiscal strategies. Its primary role is to mitigate negative aggregate effects, with only a limited impact on redistribution.

These results suggest that uniform transfers to households are more effective in reducing consumption inequality than subsidies to green firms. However, the opposite holds for wealth distribution. The optimal policy choice thus depends on the underlying objective, reflecting the equity-efficiency trade-off.

If the goal is to support low-income households and reduce inequality in the face of the green

Figure 11: Heat map of EEVs



Note. Lower values are red whilst higher values are orange / white.

transition, transfers are the more appropriate instrument. Conversely, if the aim is to sustain aggregate output and limit the decline in energy use—both in production and consumption—while accepting a moderate increase in consumption inequality, subsidies are preferable.

5 Welfare Analysis

This section presents the welfare implications of the green transition. Since the reductions in brown energy use and fossil resource consumption are comparable across scenarios, we expect that accounting for the welfare impact of environmental quality changes would not alter the policy ranking or, more importantly for our research question, the distribution of welfare costs among households. Hence, here we examine the non-environmental welfare effects of the alternative carbon revenue recycling schemes presented in the previous section.

Specifically, we focus on the T and s^g scenarios, and we provide an evaluation of the distributional impact of these two scenarios across the distributions of households' income and wealth. To do so, we compute individual expenditure-equivalent variations (EEV) – see Appendix D for details – and their distribution across the population, for all policy experiments. We also provide the average, population-weighted, welfare cost experienced by society during the transition to 2030.

Figure 11 presents a heat map illustrating the distribution of EEVs across wealth and income percentiles under scenarios T and s^g. The horizontal axis represents wealth percentiles, while the vertical axis shows income percentiles. Each point on the map corresponds to the EEV of a household with a given combination of wealth and income.

In both scenarios, all individuals experience a welfare loss, regardless of their position in the wealth-income distribution. However, the magnitude and distribution of these losses differ. Under the lump-sum transfer scenario T, losses are concentrated at the bottom of the figure, suggesting that high-income households bear the greatest burden under this fiscal policy. On the contrary, under scenario s^g, the largest welfare losses are concentrated in the top left corner of the map, indicating that households with both low income and low wealth suffer the most during the transition. This pattern arises because uniform transfers redistribute income toward poorer households, helping to offset the impact of higher energy prices, whereas green subsidies do not involve any redistribution.

Finally, note another important difference between the two scenarios. Under T, the welfare effects differ across income percentiles, for a given wealth, while they do not change much across the wealth distribution, for a given income – the color in the heatmap is distributed along horizontal bars. In this case, therefore, it is the income distribution, not the wealth distribution, that matters for the distribution of welfare costs. Again, this is intuitive because uniform transfers redistribute *income* from high income to low income households. Under s^g, instead, the richest households suffer the least, no matter what their income is. Hence, both the income and wealth distributions play a crucial role in determining the distribution of welfare costs across households in the s^g scenario.

This analysis underscores the importance of considering both the aggregate and distributional welfare impacts when evaluating policy trade-offs during the green transition.

The equity-efficiency trade-off Our analysis highlights a trade-off between equity and efficiency across the two scenarios, T and s^g. The former is more effective at reducing consumption inequality than the latter, but it comes at the cost of a larger output reduction. To quantify this equity-efficiency trade-off more thoroughly, we consider hybrid policies in which a fraction ω_{s^g} of the revenues raised through carbon taxation is allocated to subsidize green energy, while the remaining revenues are used for uniform lump-sum transfers.[17]

Panel (a) of Figure 12 illustrates this trade-off between output and the Gini coefficient of expenditure under different hybrid policies during the entire transition from the initial to the final steady state. The x-axis measures the percentage deviation of aggregate output relative to the baseline, with no policy interventions as in the previous section, while the y-axis is reversed and measures the percentage change in the Gini coefficient of expenditure relative to the baseline.[18] Panel (b) depicts the trade-off between the Gini coefficient of expenditure and aggregate expenditure. The latter is again measured in percentage deviations from the baseline transition without any change in fiscal policy.

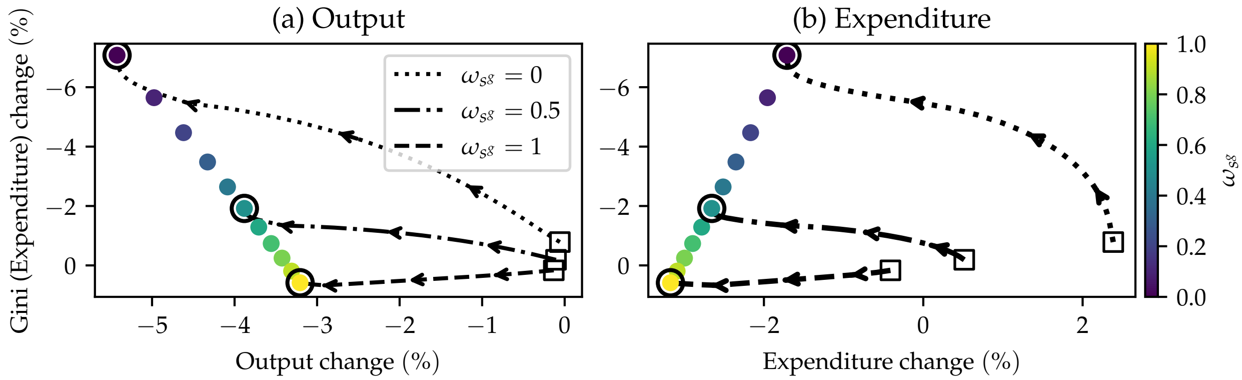
The colored circles indicate the final steady states for eleven values of ω_{s^g}, ranging from 0 to 1 in increments of 0.1. We also plot the equity-efficiency path over the full transition for three selected values of ω_{s^g}: 0, 0.5, and 1.

The case $\omega_{s^g} = 1$, corresponding to policy s^g, is shown by the dashed line; $\omega_{s^g} = 0$, corresponding to policy T, is represented by the dotted line; and $\omega_{s^g} = 0.5$, shown by the dash-dotted line, reflects a hybrid policy that allocates carbon tax revenues equally between household transfers

[17] We thank the referee of the paper for suggesting this experiment.

[18] We consider total expenditure as a synthetic measure of consumption possibilities across both goods. This is also consistent with our welfare analysis, which expresses welfare costs in terms of expenditure-equivalent units.

Figure 12: Equity efficiency trade-off



*Note.*The x-axis reports the percentage change relative to the baseline in aggregate output (Panel (a)) and aggregate expenditure (Panel (b)), while the y-axis shows the corresponding percentage change in the Gini coefficient of expenditure. The baseline transition and final steady state correspond to the scenario with technological change in the green sector only. Hollow squares indicate the impact effects of the policies. The dashed, dash-dotted, and dotted lines trace the transition paths for $\omega_{sg} = 1$, 0.5, and 0, respectively, while the circles denote the final steady states.

and green energy subsidies.[19] Hollow squares denote the impact effects of these three policies, while hollow circles mark their final steady states.

Focusing first on the trade-off between inequality and output in Panel (a), values of ω_{sg} close to 1 lead to small increases in inequality during the transition, accompanied by moderate output losses. As ω_{sg} decreases, the transition entails a more pronounced reduction in inequality but also noticeably larger output losses.

In the long run, this trade-off becomes more pronounced. Under a pure subsidy policy ($\omega_{sg} = 1$), output declines by about 3.20%, while inequality slightly increases. Under policy T, by contrast, output falls by around 5.42%, but the Gini coefficient of expenditure concentration drops by roughly 7.08%. So, although policy T entails a larger long-run output cost, it achieves significantly larger distributional gains. From a welfare perspective, the output loss is offset by the policy's ability to protect vulnerable households, both during the transition and in the new steady state, as highlighted earlier.

Turning to Panel (b), which depicts the trade-off between expenditure concentration and total expenditure, policy T clearly dominates policy s^g. The two policies differ markedly in their transition dynamics: policy s^g reduces aggregate spending on impact, primarily due to lower disposable income for agents below the median. Policy T, in contrast, leads to an increase in spending on impact, which remains elevated throughout much of the transition, and implies a smaller reduction in long-run expenditure. So, while policy s^g is associated with a gradual decline in expenditure and a mild increase in concentration, policy T achieves a more favourable distributional path with only a modest contraction in overall spending towards the end of the transition.

Quantitatively, the trade-off between equity and efficiency is non-trivial. In the long run, moving from a pure subsidy policy ($\omega_{sg} = 1$) to a pure transfer policy ($\omega_{sg} = 0$) reduces the Gini

[19] The carbon tax is endogenously determined, as in the baseline transitions for each scenario.

coefficient of expenditure by approximately 7.66 percentage points, but comes at an additional output cost of around 2.22 percentage points (from a 3.20% to a 5.42% decline in output). This implies that one needs to sacrifice one percentage point in output in order to decrease Gini expenditure by 3.45 percentage points relative to the baseline.

Learning-by-doing in the green sector While the baseline model assumes constant returns in green energy production, we extend the framework to include learning-by-doing (LBD) as a form of scale economy. We incorporate scale economies by endogenizing green TFP assuming $Z_g = \tilde{Z}_g E_g^{\lambda}$, so that the unit cost of green energy falls with cumulative output, $c = aE_g^{-\lambda}$. This captures a standard one-factor learning curve, with λ mapping to the learning rate – defined as the fractional reduction in cost associated with a doubling of the stock of experience (i.e., E_g in our case) – via $\mathrm{LR} = 1 - 2^{-\lambda}$. We assume a learning rate of 0.153 which implies $\lambda \approx 0.24$ based on empirical estimates from Rubin, Azevedo, Jaramillo and Yeh (2015), which lie near the midpoint of the range reported by Arkolakis and Walsh (2023). See Appendix H for details.

We then explore how introducing LBD affects the equity-efficiency frontier. Panel (a) in Figure H.1 in Appendix H compares the equity-efficiency frontier for the benchmark case of no learning-by-doing – i.e., the one in Panel (a) in Figure 12 – with the one implied by a learning rate of 0.153. Our results show that the frontier shifts inward, implying lower output losses for any given reduction in inequality. Moreover, the frontier also flattens marginally, indicating a smaller price of additional output in terms of inequality (see Panel (b) in Figure H.1 showing the slope as a function of the learning rate). From a policy perspective, learning-by-doing would thus strengthen the case for subsidizing green investment via carbon tax revenues, rather than rebating them.

The role of non-homothetic preferences for welfare We conclude this section by discussing the role of the preference parameter ϵ for our welfare analysis. To do so, we set ϵ to zero, making preferences homothetic. We keep the other parameters fixed at the value of our benchmark calibration, and repeat the main scenarios. Figure G.1 in Appendix G displays the heat maps illustrating the distribution of EEVs across wealth and income percentiles under this preference specification.

The distribution of welfare costs displays important differences in the homothetic case compared to the benchmark one. With homothetic preferences, energy expenditure depends only on relative prices, so expenditure shares are independent of total expenditure, that is, from income and wealth.[20] In this case, income-poor households allocate a smaller portion of their income to energy compared to the baseline. Hence, the carbon tax is less regressive, as the increase in energy prices during the green transition hurts all households proportionally.

Under the T scenario, thus, income-poor households gain from the policy having slightly positive EEVs. This is because they are hit less by the energy price increase relative to the non-homothetic case, but they still gain from the income redistribution due to the transfer. Moreover,

[20] In other words, Panel (b) in Figure 4 will have just one color.

for the same reason, wealthy households suffer (slightly) more under homothetic preferences, especially the high-income ones. Second, under the s^g scenario, as the negative welfare impacts of higher energy prices are distributed proportionally across households, welfare losses are much more compressed across the income and wealth distribution than in our baseline case. Thus, again, relative to our baseline scenario, low-income and asset-poor agents suffer less, while asset-rich households are impacted more. Furthermore, while both income and wealth matter for welfare costs in the baseline case, wealth becomes the more relevant factor when preferences are homothetic.

Overall, this sensitivity analysis underscores the relevance of non-homothetic preferences in our analysis. Non-homotheticity not only aligns households' expenditure shares with empirical data, but also influences both overall welfare effects and their distribution across households under different fiscal policies.

6 Conclusion

This paper explores the aggregate and distributional consequences of the European Union's green transition. Using a heterogeneous-agent general equilibrium model with non-homothetic preferences and a disaggregated energy sector, we assess the impact of increasing carbon taxation under different revenue-recycling scenarios.

A key feature of our model is the use of non-homothetic preferences, which generate energy expenditure shares that decline with both income and wealth. This assumption is supported by empirical evidence from microdata and has important implications for the distributional impact of the green transition. In particular, the heterogeneity in expenditure shares across households shapes how the costs of the transition are distributed.

Our findings reveal important trade-offs between equity and efficiency in the design of climate policy. Using carbon tax revenues for lump-sum transfers supports lower-income households during the green transition, thereby reducing consumption and disposable income inequality. Alternatively, directing revenues into subsidies for green energy firms boosts renewable energy production, mitigates aggregate output losses, and allows the EU to meet its 2030 target of a 42.5% renewable energy share with a lower carbon tax rate. However, unlike lump-sum transfers, this policy slightly increases both consumption and disposable income inequality. Under this approach, low-income and asset-poor households bear the highest welfare costs, making it less effective at addressing the distributional consequences of the green transition.

That said, our model highlights a non-negligible cost of prioritizing redistribution: in the long run, moving from a pure transfer to a pure subsidy policy reduces the severity of the output decline, but at the cost of a roughly 3.45 percent increase in the Gini of expenditure concentration for every percentage point of output preserved.

These findings underscore the importance of accounting for distributional impacts when designing policies for the green transition. Policymakers must weigh the equity gains from reducing consumption inequality against potential efficiency losses and decarbonization goals. The optimal policy mix will ultimately depend on societal preferences over these competing objectives.

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Appendix

A LISS panel and cleaning

The LISS (Longitudinal Internet Studies for the Social Sciences) panel, operated by CentERdata at Tilburg University, is a representative online survey of Dutch households. Established in 2007, the panel comprises approximately 5,000 households and reflects the demographics of the Dutch population. Members of the panel participate in surveys on diverse topics, including health, employment, education, and social values. For this study, we utilize two components of the dataset: the Background Variables (BV) module and the Time Use and Consumption (TUC) module. We can use the 2009, 2010, 2012, 2015, 2017, 2019, 2020 and 2021 waves for our analysis.

Background Variables The BV module provides longitudinal data on demographics and socioeconomic characteristics such as age, gender, education, and household income. We focus on household heads aged 20 to 64, representing individuals with active labour market participation. Observations are excluded if gross household income is below half the annual minimum wage or above €500,000, or if year-on-year income changes exceed a 500% increase or fall below an 80% decrease. Observations with fewer than nine months of data in a given year are excluded to ensure data completeness. Income values are deflated to 2015 Euros using the Dutch Consumer Price Index (CPI) to account for inflation.

Time Use and Consumption We use the Time Use and Consumption (TUC) module of the LISS panel to analyse household time use and expenditures, including energy-related spending. To construct total household expenditure, we sum several expenditure categories such as mortgage or rent payments, utility bills, transportation, insurance, childcare, and food. In years where variables differ by household composition (e.g., singles vs. families), we adjust the calculations to ensure consistency and comparability across households. For energy expenditures, we focus on gas and electricity costs, which we extract from the utility-related variables in the dataset.

We identify and exclude outliers using distributional thresholds for total household expenditure and energy expenditure. Specifically, we remove observations with expenditures that significantly exceed realistic bounds or exhibit implausible year-on-year changes. We also drop observations with missing or inconsistent household identifiers to maintain the longitudinal integrity of the data. Additionally, we construct household size and composition variables, such as the number of adults and children, to normalize expenditures and enable meaningful comparisons across households. After cleaning the TUC module, we merge it with the Background Variables (BV) module using unique household identifiers.

B Estimation of ϵ: further details

Using the cleaned and merged TUC and BV dataset, we normalize expenditures and income for household composition using a modified OECD equivalence scale

$$\text{scale} = 1 + 0.5 \times (\text{adults} - 1) + 0.3 \times \text{children}, \tag{B.1}$$

where *adults* is household size minus children younger than 14. This scale adjusts household expenditures and income to account for differing household structures.

The key variables used in the estimation are as follows:

- *Total expenditure (x)*: Total household expenditure, adjusted for the equivalence scale.
- *Expenditure share on energy (η^d)*: The proportion of total household expenditure allocated to energy-related expenses, such as gas and electricity costs.
- *Income in service prices*: The logarithm of household income adjusted for equivalence scale and service price changes, $\log(\text{income after taxes and transfers}/(\text{scale} \cdot p_{\text{services}}))$.

In the main text, we instrument total expenditure in service prices with total household income in service prices. This instrumentation addresses potential measurement errors and the endogeneity of expenditure data. For comparison purposes, we provide below also the estimation results *without* using instrumental variables, i.e. with using log(Expenditure) on the RHS. The results for estimations with different fixed effects are presented in Table B.1. All specifications suggest again that there is a significant degree of non-homotheticity between non-energy and energy goods. The coefficients are quite close to the IV coefficients, especially when we control for the ID and time fixed effects. This suggests that, for our most stringent estimation specification, the magnitude of the bias is relatively small.

Table B.1: Least squares estimation results for ϵ

	(1)	(2)	(3)
Log Expenditure	-0.509***	-0.504***	-0.566***
	(0.018)	(0.018)	(0.018)
Observations	18794	18794	16410
R-squared	0.187	0.198	0.685
Fixed Effects	None	Time	ID + Time
Clustering	ID + Time	ID + Time	ID + Time

Note. Standard errors in parentheses. Significance levels: * p<0.1, ** p<0.05, *** p<0.01.

C Estimation of income process

Using the cleaned and processed BV dataset, we estimate the income process by regressing the logarithm of gross household income on the constructed variables. The model takes the form:

$$\begin{aligned}\log(y_{it}) =& \alpha + \alpha_t + \gamma_1 \text{ age}_{it} + \gamma_2 \text{ age}_{it}^2 + \gamma_3 \text{ age}_{it}^3 + \\ & \iota \text{ educ}_{it} + \rho \text{ occupation}_{it} + \theta \text{ gender}_{it} + \sigma \text{ size}_{it} + u_{it}.\end{aligned} \tag{C.2}$$

Using the residuals (u_{it}) obtained from the income regression described above, we estimate a persistent-transitory income process. This model decomposes observed income into two components: a persistent AR(1) process and a transitory shock. The specification is as follows:

$$u_{it} = \kappa_{it} + \psi_{it} + \xi_{it} \tag{C.3}$$

$$\kappa_{it} = \rho\kappa_{it-1} + \varepsilon_{it} \tag{C.4}$$

where κ_{it} is the persistent component, ψ_{it} is the transitory shock, and ξ_{it} denotes measurement error with variance σ_ξ^2. The persistent component evolves according to an AR(1) process with persistence ρ and innovation ε_{it}.

We estimate the parameters ρ, σ_ε^2 (variance of persistent shocks), and σ_ψ^2 (variance of transitory shocks) using Minimum Distance Estimator (MDE). Following the literature, the variance of measurement error (σ_ξ^2) is fixed at 0.02, based on estimates from French (2004) and Heathcote, Storesletten and Violante (2010), albeit using data from the Panel Study of Income Dynamics of US households. This approach reflects the inability to separately identify the variance of transitory shocks and measurement error in our data.

The estimation uses moments derived from the theoretical properties of the model. Variances and covariances of income across time periods form the basis of the moment conditions:

$$\mathbb{E}[u_{it}^2] = \frac{\sigma_\varepsilon^2}{1-\rho^2} + \sigma_\psi^2 + \sigma_\xi^2, \tag{C.5}$$

$$\mathbb{E}[u_{it}u_{i,t-s}] = \rho^s \frac{\sigma_\varepsilon^2}{1-\rho^2}, \quad \text{for } s > 0. \tag{C.6}$$

The MDE procedure minimizes the distance between the model-implied moments and their empirical counterparts using an identity weighting matrix. Variances capture the contributions of persistent and transitory components, while covariances identify the degree of persistence in income dynamics.

The results of the estimation are as follows:

$$\rho = 0.9422\,(\pm 0.0273), \tag{C.7}$$

$$\sigma_\varepsilon^2 = 0.0186\,(\pm 0.0095), \tag{C.8}$$

$$\sigma_\psi^2 = 0.0113\,(\pm 0.0098), \tag{C.9}$$

where values in parentheses represent bootstrapped standard errors. These estimates are in line with findings from prior studies such as Floden and Lindé (2001) and Krueger et al. (2016) for US data. The estimated persistence parameter (ρ) indicates that income shocks are highly persistent, with the AR(1) process accounting for most of the observed income variation over time.

D Welfare computation

In order to calculate expenditure equivalent welfare we compare value functions in the initial steady state with the value when the policy was announced, following many papers such as Ascari and Ropele (2012) and Bakış, Kaymak and Poschke (2015). Below is a step by step description of our approach. To evaluate welfare, we calculate an expenditure equivalent measure (Δ) for each state of the household:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) U((1+\Delta_i)x_i^*, p^e) = \mathbb{E}_0 \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) U\big(x_{it}, p_t^e\big), \tag{D.1}$$

where $\beta(j)$ is the discount factor between $j-1$ and j, with $\beta(0) = 1$. This measure represents the percentage change in expenditure required in the initial steady state to make a household indifferent between remaining in the initial steady state and transitioning to the new steady state or policy scenario.

Recall that expectations are taken over idiosyncratic shocks to income and discount factors. The indirect utility function is:

$$U\big(x_{it}, p_t^e\big) = \frac{1}{\epsilon}\left(x_{it}\right)^{\epsilon} - \frac{\nu}{\gamma}\left(p_t^e\right)^{\gamma} - \frac{1}{\epsilon} + \frac{\nu}{\gamma}, \tag{D.2}$$

Defining $\kappa \equiv \frac{\nu}{\gamma}\left(p^e\right)^{\gamma} + \frac{1}{\epsilon} - \frac{\nu}{\gamma}$ one can rewrite the left-hand side of Equation (D.1) as

$$\begin{aligned}
&\mathbb{E}_0 \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) U((1+\Delta_i)x_i^*, p^e) = \\
&\qquad (1+\Delta_i)^{\epsilon}\mathbb{E}_0 \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \frac{1}{\epsilon}(x_i^*)^{\epsilon} - \mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \kappa \\
&\qquad + (1+\Delta_i)^{\epsilon}\mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \kappa \\
&\qquad - (1+\Delta_i)^{\epsilon}\mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \kappa \\
&\qquad = (1+\Delta_i)^{\epsilon} \underbrace{\mathbb{E}_0 \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \left(\frac{1}{\epsilon}(x_i^*)^{\epsilon} - \kappa \right)}_{V_{ss}^*} \\
&\qquad - \mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \kappa + (1+\Delta_i)^{\epsilon}\mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \kappa \\
&\qquad = (1+\Delta_i)^{\epsilon} \left(V_{ss}^* + \mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \kappa \right) - \mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \kappa
\end{aligned}$$

The expectation operator $\mathbb{E}_0^b$ only takes into account uncertainty with respect to the discount factor.

To compute the steady-state value function V_{ss}^*, we use iterative policy function updates:

$$V_{ss}^*(a_i, y_i, \beta_i) = U(x_i^*, p^c, p^e) + \beta_i \mathbb{E}_t \left[V_{ss}^*(a_i^*, y_i', \beta_i') \right],$$

where x_i^* and a_i^* are the optimal expenditure and asset decisions from the policy functions.

To compute the right-hand side of Equation (D.1), we first then compute the sequence of value functions V_t using backward induction, starting from the terminal steady state. At each step:

$$V_t^*(a_{it}, y_{it}, \beta_{it}) = U(x_{it}^*, p_t^c, p_t^e) + \beta_{it} \mathbb{E}_t \left[V_{t+1}(a_{it+1}^*, y_{it+1}, \beta_{it+1}) \right].$$

where variables with stars are again the optimal policies along the transition. Since $V_1^*(a_{it}, y_{it}, \beta_{it})$ summarizes the infinite sequence on the right-hand side of Equation (D.1), we can rewrite it as

$$(1+\Delta_i)^\epsilon \left(V_{ss}^* + \mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \kappa \right) - \mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \kappa = V_1^*$$

and solve for Δ_i to get

$$\Delta_i = \left(\frac{V_1^* + \mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \kappa}{V_{ss}^* + \mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right) \kappa} \right)^{\frac{1}{\epsilon}} - 1. \tag{D.3}$$

Finally, we follow Krusell, Mukoyama, Şahin and Smith Jr (2009) to rewrite the infinite sum over the discount factors. Define $d \equiv \mathbb{E}_0^b \sum_{t=0}^{\infty} \left(\prod_{j=0}^{t} \beta(j) \right)$ and let $\bar{d}_i$ be the value of d when $\beta(1) = \beta_i$ with $i = \{\text{low}, \text{high}\}$. The column vector $D = \begin{pmatrix} \bar{d}_{\text{low}} \\ \bar{d}_{\text{high}} \end{pmatrix}$ then solves

$$D = \mathcal{I} + B\Gamma_\beta D$$

where $\mathcal{I} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$ and $B = \begin{bmatrix} \beta_{\text{low}} & 0 \\ 0 & \beta_{high} \end{bmatrix}$. Solving yields $D = (I - B\Gamma_\beta)^{-1}\mathcal{I}$ such that Equation (D.3) becomes

$$\Delta_i = \left(\frac{V_1^* + \bar{d}_i \kappa}{V_{ss}^* + \bar{d}_i \kappa} \right)^{\frac{1}{\epsilon}} - 1. \tag{D.4}$$

E Green Transition: Other figures

Figure E.1 shows the dynamics of capital and labour along the transition, all relative to the baseline transition, as in the main text. Figures E.2-E.4 show the same figures as in the subsection 4.2 in the main text but with the variables expressed in deviations from the initial steady state, to highlight the dynamics of the levels of the variables.

Figure E.1: Dynamics of capital and labour across sectors along the transition.

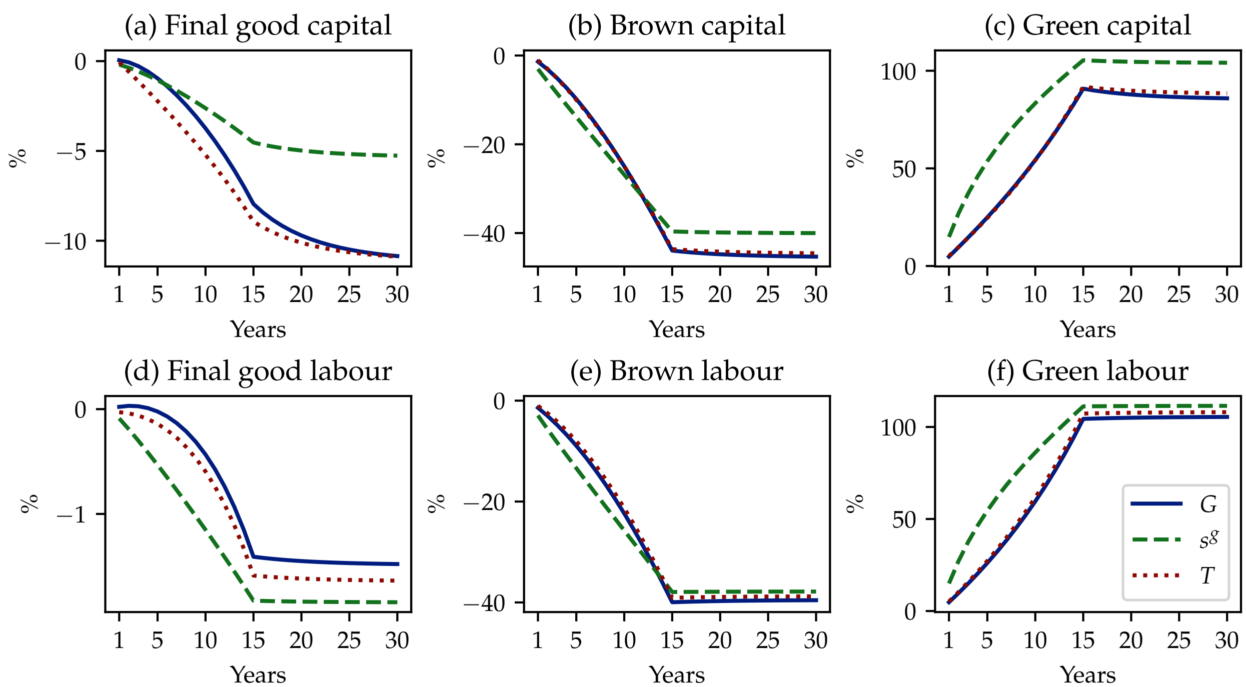


Figure E.2: Dynamics of relative energy prices and energy quantities for the three policies in terms of *deviations from the initial steady state*.

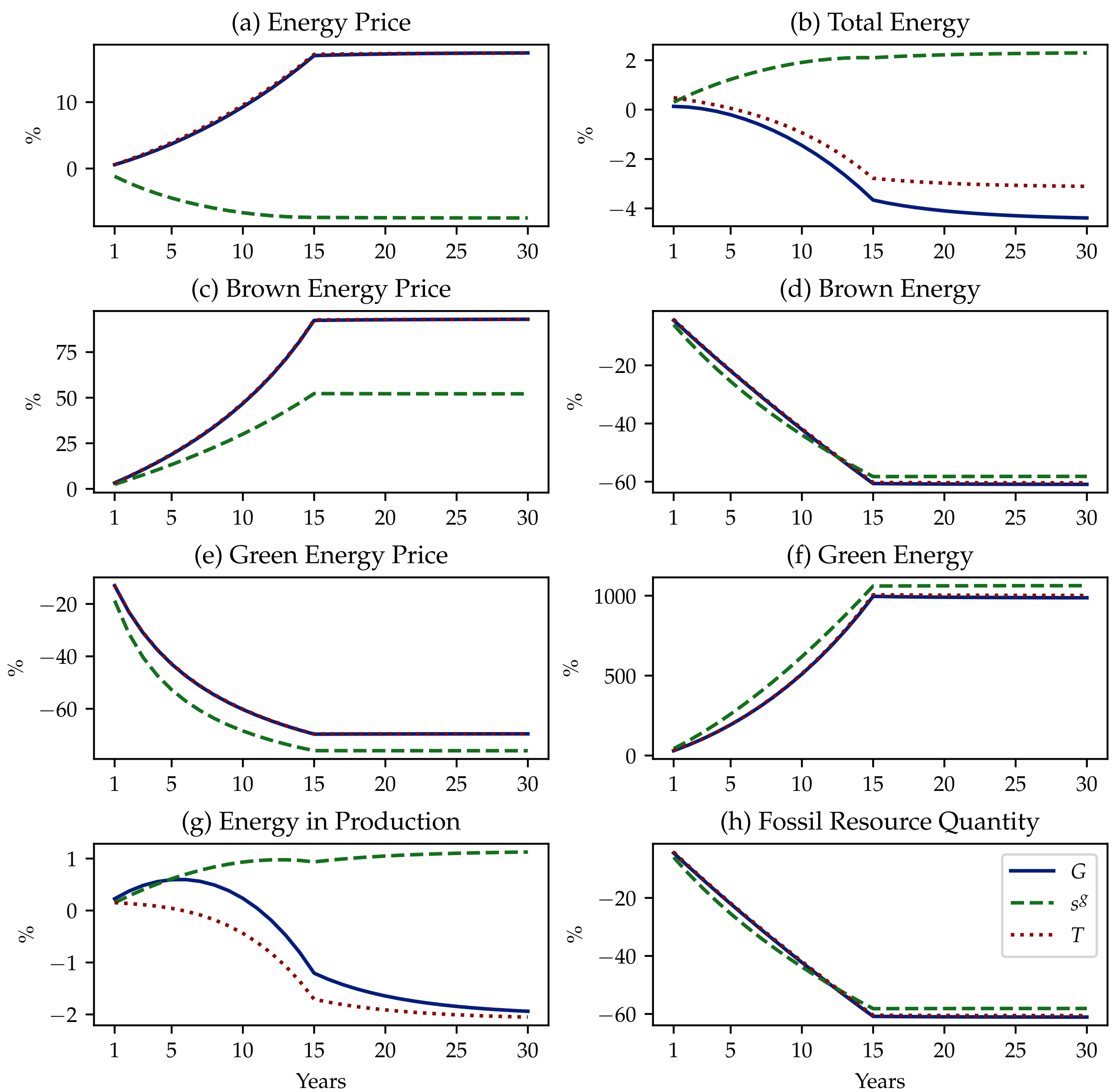


Figure E.3: Responses of output, capital, non-energy consumption and energy consumption for the three policies in terms of *deviations from the initial steady state*.

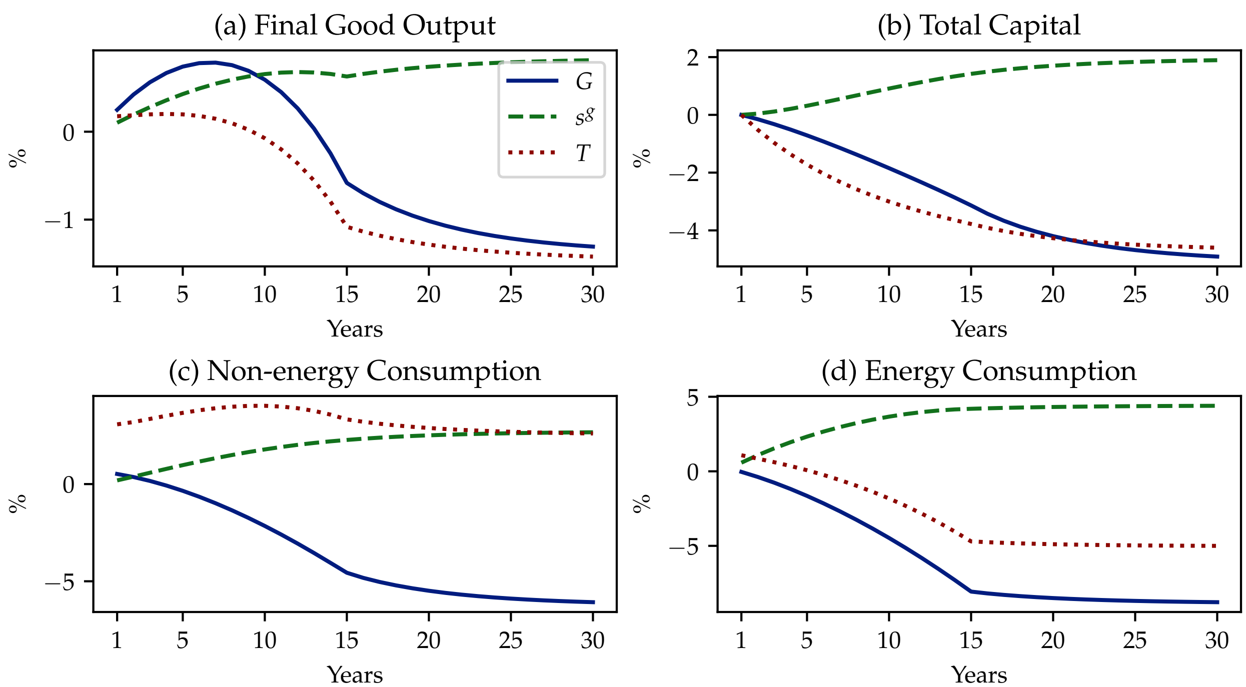


Figure E.4: Dynamics of wages and returns to capital for the three policies in terms of *deviations from the initial steady state*.

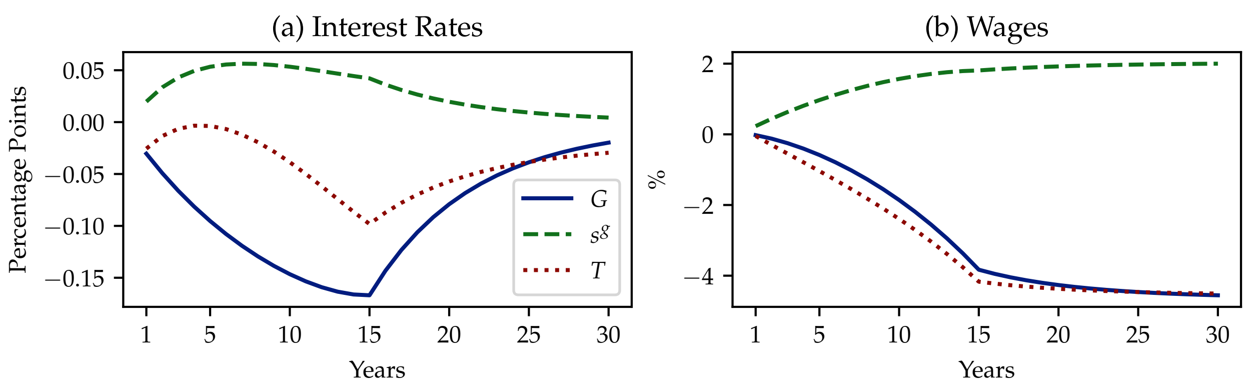


Figure E.5 plots the asset market equilibrium along the transition, resembling the famous Figure IIb in Aiyagari (1994). The figure in Aiyagari (1994) describes steady state determination, where agents face a constant, steady state interest rate. In our case, however, we construct the asset market equilibrium repeatedly along the perfect foresight transition, so we cannot rely on solving the household problem for different steady state interest rates. This is because along the transition, agents observe the entire paths of interest rates. Note that the issue above does not hold for the firm, since these solve a static problem. We then construct the figure as follows:

1. Construct the capital supply schedule of households in the initial steady state.

2. Choose a point in time, t, along the transition.

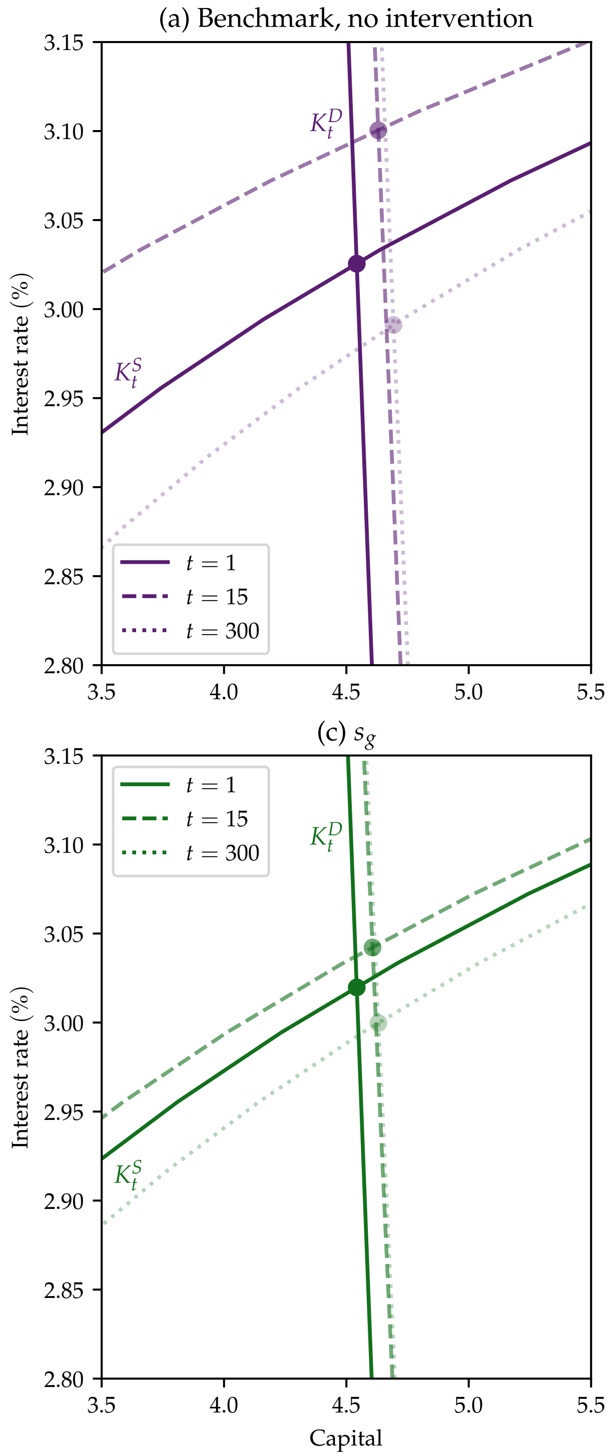
3. Create the capital demand schedule as a function of different interest rates at time t. In particular, for a grid of interest rates, solve for the total capital stock demanded by all firms in the model, using their first-order conditions with respect to capital. All other quantities and prices are fixed to their equilibrium value at time t.

4. Shift the capital supply schedule created in Step 1 to the equilibrium interest rate and capital stock observed at time t.

The key idea is that, since we can easily construct the capital demand curve from the static firm problem and we know the equilibrium interest rate and capital stock from the GE transition, we know where the supply curve has to cross the demand curve at that particular point in time. By shifting the initial steady state capital supply curve, the implicit assumption we make is that its shape does not change along the transition.

Figure E.5 shows the result of this procedure for $t = \{1, 15, 300\}$. The top left Panel shows the case when only green technology is growing exogenously. The other three Panels show the results for our different revenue recycling strategies, when carbon taxes get adjusted as well. To compare this figure to the transitional dynamics in the main text, recall that the figures in the main text show deviations from the baseline case in which the green technology is growing exogenously. Here instead, we show the absolute values.

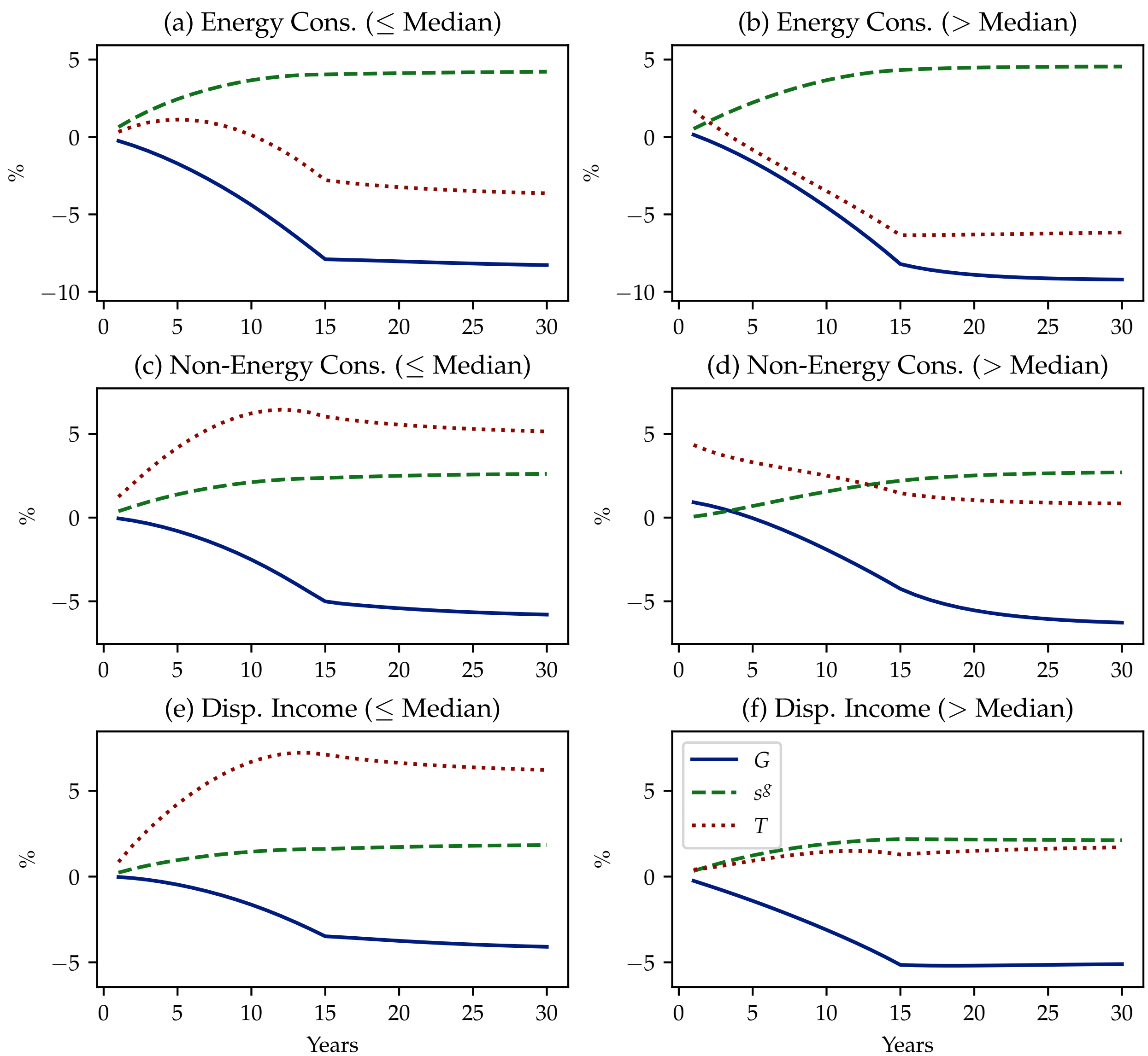
Figure E.5: The asset market: demand and supply of capital along the transition



Note. This figure shows the asset market equilibrium for different points along the transition. To construct it, we first trace out the capital demand function from the static profit maximization problem of the firm. We then shift the capital supply schedule of households in the initial steady state to the equilibrium interest rate and capital stock that we observe along the transition at that point in time. The top left Panel shows the transition due to the exogenous increase in the green technology. The other three Panels show the results for our different revenue recycling strategies, when carbon taxes get adjusted as well.

Figure E.6 corresponds to Figure 9 in the subsection 4.3 in the main text but with the variables expressed in deviations from the initial steady state, to highlight the dynamics of the levels of the variables.

Figure E.6: Dynamics of energy consumption, non-energy consumption and disposable income above and below the median of the wealth distribution for the three policies in terms of *deviations from the initial steady state*.



F Green transition with no policy intervention

Figure F.1: Energy Prices and Quantities with no policy intervention

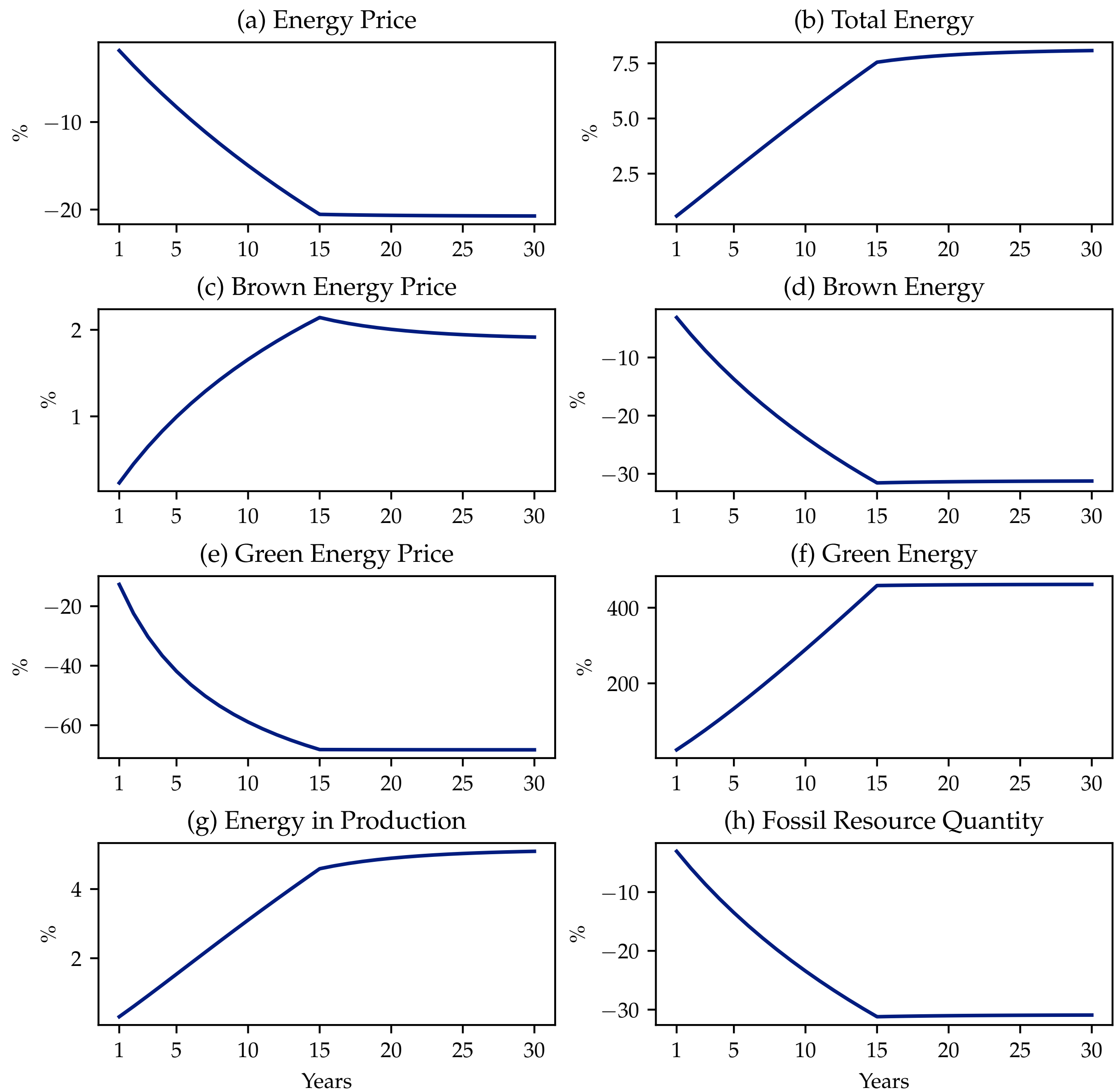


Figure F.2: Output, Capital, and Consumption with no policy intervention

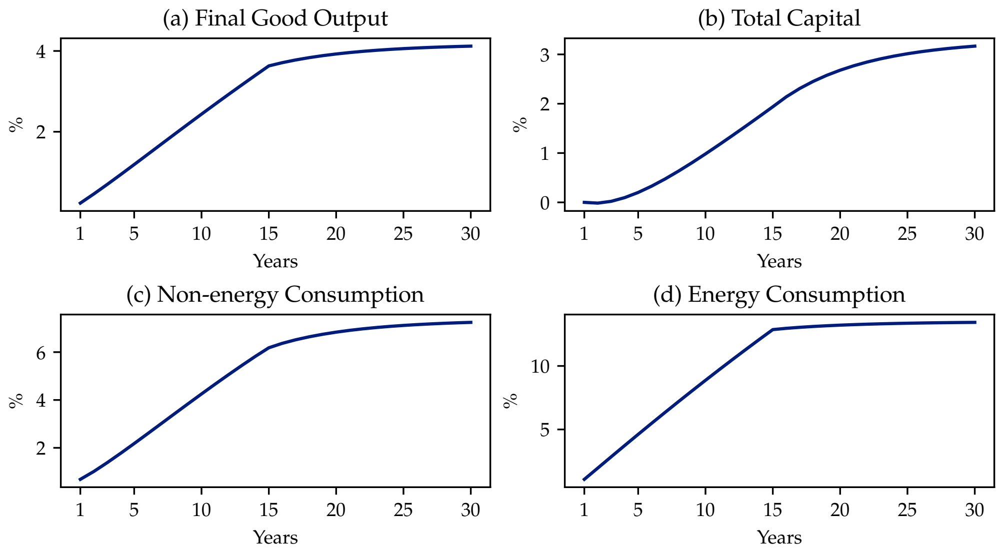


Figure F.3: Factor Prices with no policy intervention

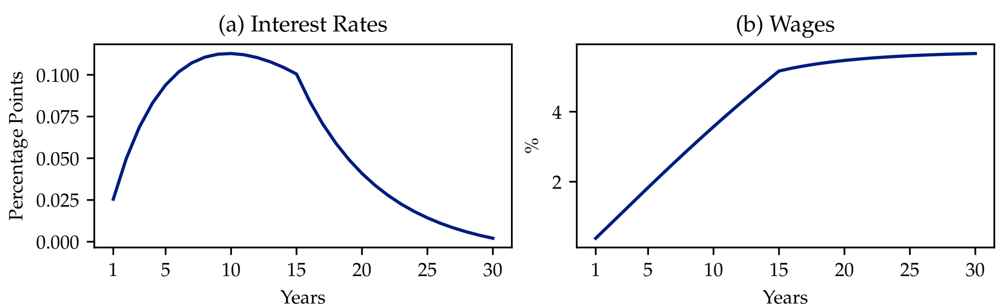
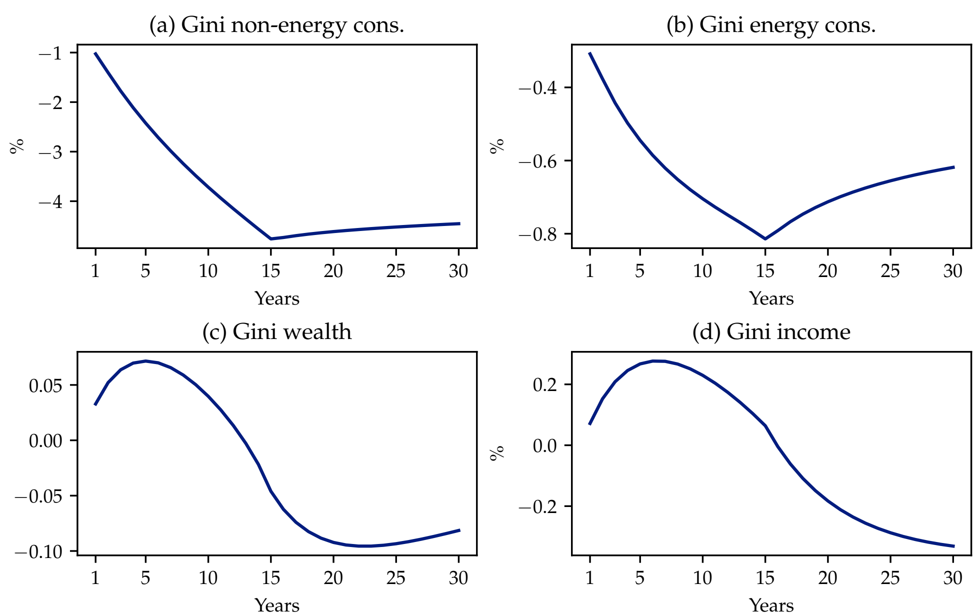


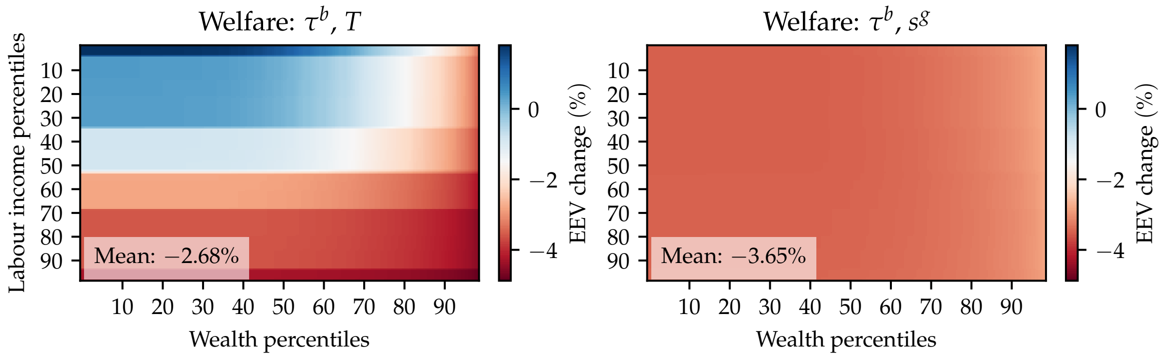
Figure F.4: Gini with no policy intervention



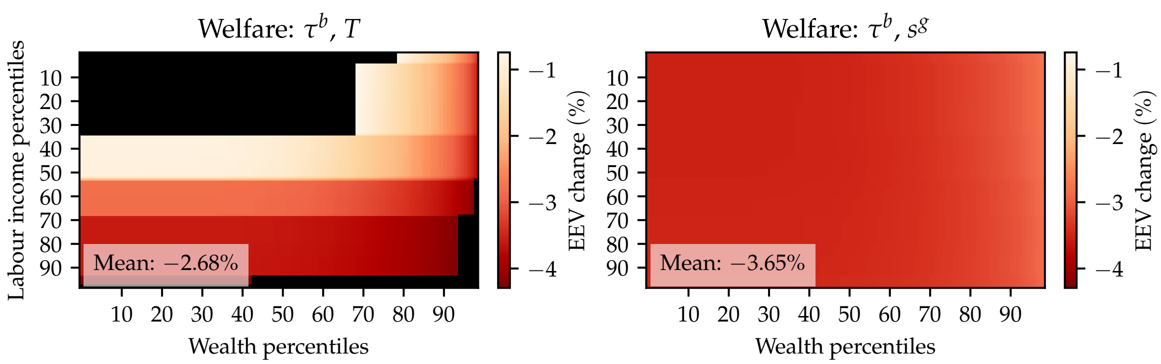
G Welfare heatmaps for homothetic preferences

Figure G.1: Welfare heatmaps for homothetic preferences

(a) Heat map of EEVs for ϵ=0



(b) Heat map of EEVs for ϵ=0 with the same limits as Figure 11



Note. The black areas in the bottom left Panel represent values outside of the specified range. The black area in the top left represents values larger than -0.7, whereas the black are in the bottom right represents values smaller than -4.3

In this section, we show the welfare consequences under homothetic preferences, that is, when we set $\epsilon = 0$. For this purpose, Panel (a) of Figure G.1 plots again the heat maps illustrating the distribution of EEVs across wealth and income percentiles under scenarios T and s_g. Since now expenditure shares are constant along the income and wealth distribution, households face the same burden from rising relative energy prices. This can be seen from the fact that the variance of the welfare distribution in the subsidy scenario s_g is lower in the homothetic case than under the non-homothetic case. Vice versa, poorer households, in the homothetic case, spend a lower fraction of their expenditure on energy, such that the net budget gain from uniform lump-sum transfers is higher. As a result, the variance of the welfare distribution is higher and some households even gain in the transfer scenario.

This welfare gain is clearly visible in Panel (b) of Figure G.1. In this figure, we apply the same range over which EEVs are coloured as Figure 11 in the main text. We see that especially the top left and the bottom right corner are now black. This implies that the EEVs in the homothetic case are, respectively, larger and smaller than under the non-homothetic benchmark. In other words, in the top left, poorer households have a larger welfare gain (a smaller welfare loss) under $\epsilon = 0$. Vice versa for rich households in the bottom right. Moreover, the right figure of Panel (b), depicting the subsidy scenario s_g, is now almost one colour, reflecting the identical expenditure shares between households.

H Learning-by-doing

The baseline version of the model does not consider induced innovation and there is no interaction between the carbon tax and the growth rate of the clean technology parameter Z_g. In order to understand to what extent this channel could influence the equity-efficiency trade-off in the model, we introduce learning-by-doing in the green energy sector in a reduced and simple form.

In particular, for this exercise we specify green technology as

$$Z_g = \tilde{Z}_g E_g^{\lambda}.$$

The functional form is taken from Krueger et al. (2016), who model a pure demand externality between consumption and total output. Under this specification, Z_g is a function of a base technology parameter $\tilde{Z}_g$ and green energy production E_g. The parameter $\lambda > 0$ is related to the learning rate in the economy as will become clear below.

In the spirit of an externality, energy producers do not take this channel into account when choosing their inputs. When we now solve for the solution to the firm maximization problem, energy production reads $E_g = \left(\tilde{Z}_g K_g^{\alpha_g} L_g^{1-\alpha_g}\right)^{\frac{1}{1-\lambda}}$.

Learning rates of technologies In the following, we attempt to relate our simple setup to green learning rates in the literature.

The cost-minimization of the green energy Cobb-Douglas production function yields

$$c(r+\delta, w, E_g) = \frac{1}{Z_g}\left[\left[\left(\frac{\alpha_g}{1-\alpha_g}\right)^{1-\alpha_g} + \left(\frac{\alpha_g}{1-\alpha_g}\right)^{-\alpha_g}\right](r+\delta)^{\alpha_g}(w)^{1-\alpha_g} E_g\right]$$

Denote the cost of one unit of energy by $c(r+\delta, w, 1)$, which equals

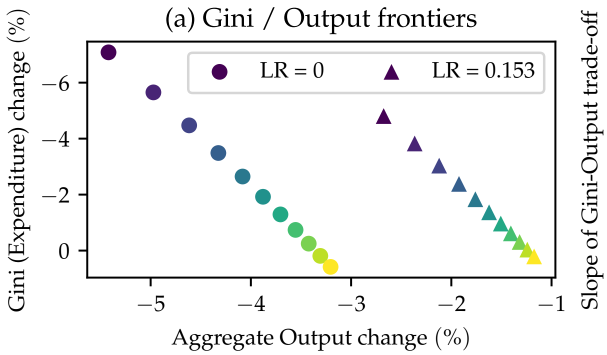
$$\frac{1}{Z_g}\left[\left[\left(\frac{\alpha_g}{1-\alpha_g}\right)^{1-\alpha_g} + \left(\frac{\alpha_g}{1-\alpha_g}\right)^{-\alpha_g}\right](r+\delta)^{\alpha_g}(w)^{1-\alpha_g}\right].$$

Using our formulation for the learning-by-doing technological progress implies

$$c(r+\delta, w, 1) = \frac{1}{\tilde{Z}_g E_g^{\lambda}}\left[\left[\left(\frac{\alpha_g}{1-\alpha_g}\right)^{1-\alpha_g} + \left(\frac{\alpha_g}{1-\alpha_g}\right)^{-\alpha_g}\right](r+\delta)^{\alpha_g}(w)^{1-\alpha_g}\right].$$

Importantly, we distinguish the level of energy currently produced, which matters for the level of the green technology parameter, and the unit of energy which is bought at cost $c(r+\delta, w, 1)$,

Figure H.1: Equity-efficiency frontiers and slope of trade-off



Note. Panel (a) depicts the equity-efficiency frontier for both the case without learning-by-doing (dots) and the one with a learning rate of 0.153 (triangles) at the final steady state. The numbers are relative to the respective terminal steady states without any policy intervention at which a share of green energy of 30% is attained. The figure in Panel (b) depicts the slope of the equity-efficiency trade-off as a function of the learning rate. A lower number implies a larger increase in inequality for any gain in output.

which is set to unity. Define $a \equiv \frac{1}{\bar{Z}_g}\left[\left[\left(\frac{\alpha_g}{1-\alpha_g}\right)^{1-\alpha_g} + \left(\frac{\alpha_g}{1-\alpha_g}\right)^{-\alpha_g}\right](r+\delta)^{\alpha_g}(w)^{1-\alpha_g}\right]$, such that we can write

$$c(r+\delta, w, 1) = aE_g^{-\lambda}. \tag{H.1}$$

We interpret this very simplified setup as an instance of the "one-factor learning curve", as described in Rubin et al. (2015), where the unity cost of the technology and its cumulative output form a log-linear relationship. One can then relate λ to the learning rate (LR) as $LR = 1 - 2^{-\lambda}$.

Calibration of λ We rely on estimates of learning rates in Rubin et al. (2015) and Arkolakis and Walsh (2023) to calibrate λ. Rubin et al. (2015) document one-factor learning rates of 12%, 23%, and 11% for wind, solar, and biomass power generation, respectively. Averaging these values yields a learning rate of 15.3%, which corresponds to a λ of approximately 0.24.

This value aligns well with the estimates of Arkolakis and Walsh (2023), who regress total cost on cumulative installed capacity using data from the International Renewable Energy Agency. Their preferred coefficients imply values of $\lambda = 0.2$ for wind and $\lambda = 0.35$ for solar, placing our benchmark value of $\lambda = 0.24$ squarely within their empirical range.

The equity-efficiency trade-off under learning-by-doing We illustrate the changes to the equity-efficiency trade-off in Figure H.1. In Panel (a) it depicts the two equity-efficiency frontiers for a case of no learning-by-doing and one with a learning rate of 0.153. Clearly, the line shifts in, indicated a lower overall cost of the green transition, as expected. However, the slope of the curve changes only very slightly. To further illustrate the changes of the slope as a function of learning-by-doing, Panel (b) depicts the slope as a function of the learning rate. As can be seen, a higher learning rate flattens the slope, indicating that the inequality cost of mitigating one percentage point of output loss becomes smaller. From a policy perspective, learning-by-doing would thus strengthen the case for subsidizing green investment via carbon tax revenues, rather than rebating them.