Distributional Consequences of Becoming Climate-Neutral*

Philipp Hochmuth, Per Krusell, Kurt Mitman

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Abstract

The EU has embarked on an ambitious path toward climate neutrality. How difficult will this transition be for the population as a whole and different subsets of consumers? This paper investigates this question using a dynamic general equilibrium model that captures a key feature of energy consumption: the relative energy content in one's consumption basket falls significantly as a function of one's relative income. Thus, low-income consumers are expected to be hit harder by the higher energy prices that we anticipate over the next few decades. In the model, energy—a complementary input to capital and labor—can be produced either using fossil fuel or a "green" technology. We represent the EU policy in terms of a tax on fossil fuel and show that the European Commission's Fit-for-55 package implies a 106.5% tax on the fossil-based technology. The output losses from this tax are substantial, and GDP is 6.2% lower in the new steady state. The burden falls primarily on the lowest-income agent who represents the first income quintile and is 48% more worse off than the highest-income agent representing the fifth quintile. The output losses can almost be cut in half if the economy achieves a simultaneous increase in energy efficiency as outlined in the Fit-for-55 package.

*The views in this paper are solely those of the authors and should not be interpreted as reflecting the views of the Oesterreichische Nationalbank or the Eurosystem.

1 Introduction

Europe's push toward climate neutrality promises to transform the economy, but at what cost, and to whom? The EU's legally binding Fit-for-55 framework aims to cut net greenhouse gas (GHG) emissions by 55% by 2030 and achieve climate neutrality by 2050. Policies such as the Emissions Trading System (ETS) and accompanying fiscal measures are designed to phase out carbon-intensive technologies while fostering investment in cleaner alternatives. While the macroeconomic implications of decarbonization policies have been widely studied, their distributional consequences remain poorly understood. Because low-income households spend a larger share on energy, the green transition risks amplifying inequality.

This paper studies both the aggregate and distributional costs of moving toward climate neutrality. We develop a parsimonious dynamic general-equilibrium model with five income-group agents and non-homothetic preferences calibrated to euro-area data. We use the framework to quantify both aggregate and distributional costs of the EU's green transition under the Fit-for-55 plan. A particularly novel feature of our paper is the use of non-homothetic preferences, where we use the same class of preferences as in Boppart (2014). This yields nonlinear Engel curves, such that the lower-income agents have a higher energy expenditure share than the higher-income agents. The parameter in the model controlling the degree of non-homotheticity can then easily be calibrated with empirical observations on household expenditure shares. Energy is also used on the production side as a complementary input, together with capital and labor. Energy services are produced using two technologies. The brown technology takes units of the final output good to convert them into energy services using an emission-intensive technology, while the green technology is emission-free. Our framework incorporates a lower short-run and a higher long-run elasticity of substitution between the brown and green energy by allowing firms to choose the relative technology terms between brown and green energy sources subject to adjustment costs.

We calibrate the model to the euro area and use it to simulate perfect foresight transitions to a climate-neutral environment. In the model, this is achieved by a government that gradually introduces a tax on the brown technology and redistributes the revenue as a subsidy to the green technology. Since these two technologies are not perfect substitutes, this consequently raises the price of energy services, despite the subsidy for the green technology. The distribution of wealth between the agents in the initial steady state is set exogenously according to observed data. Importantly, the final steady state including the wealth distribution in the model depends on the exact transition path. This allows us to analyze the welfare and distributional effects of different policies along the transition and in the final steady state.

We find that achieving the Fit-for-55 targets entails sizable aggregate costs and sharply unequal welfare effects. GDP falls by about 6%, and the poorest income quintile experiences welfare losses nearly 50% larger than the richest. Improvements in energy efficiency—consistent with the EU's plans—cut these costs roughly in half. Reducing emissions to the target outlined in the Fit-for-55 package with a tax on the brown technology requires a tax rate of 106.5% that is gradually introduced following a linear path over the next 25 years. Under the assumed short-run and long-run elasticity of substitution between the brown and green technology for producing energy services, this leads to a 29.1% increase in the price of energy. This increase has substantial implications for aggregate consumption and output. GDP is 6.2% lower in the new steady state and compared to the highest-income agent the lowest-income agent suffers about 48% more in terms of expenditure equivalent losses. The results turn out to be quite sensitive to the long-run elasticity of substitution between the brown and green technology, and using alternative values of 3 or 8 instead of 5 can almost double or halve the aggregate effects. Furthermore, a comparison with homothetic preferences yields that the aggregate effects are 18% smaller. This indicates that non-homothetic preferences are particularly important to consider.

The government can alleviate all changes in inequality by appropriately redistributing the tax revenues from the brown technology as lump-sum transfers to the households instead of a subsidy on the green technology. However, this comes at an additional cost in terms of aggregate output losses. In such a scenario GDP losses would be 7.7%, which is 24% more than in the baseline.

The model also highlights the importance of transition timing. Because energy technologies adjust gradually, delaying taxation lowers near-term costs but requires steeper later increases. The lowest overall welfare losses occur when the tax begins about ten years before the emission target is reached and reaches its midpoint roughly seven years prior. The only caveat to this result is that it assumes that the government can fully commit to following through on the promise to raise taxes in the future.

Beyond its emission reduction targets, the Fit-for-55 package also includes binding commitments to improve energy efficiency across all EU member states. We incorporate this into our simulations by assuming an exogenous increase in the productivity of producing energy services. This lowers the required final tax rate on the brown technology to 100.1% and increases the price of energy only by 13.4%. Consequently, the effects on aggregate output or inequality are less than half as severe. GDP losses are now only 2.9% in the new steady state, with proportional effects on all agents. However, improvements in energy efficiency might not come for free, and therefore, the results should be interpreted accordingly.

Importantly, the analysis abstracts from direct climate damages, focusing instead on the economic cost of achieving climate neutrality. This assumption is arguably appropriate for European economies where the direct damages of climate change are moderate but allows us to isolate how the design and timing of carbon policies affect both efficiency and equity. The results underscore that the transition to net-zero emissions entails substantial costs but that these costs can be mitigated through complementary improvements in energy efficiency.

Related literature. Research on the aggregate effects of the green transition is growing rapidly. A non-exhaustive list of some papers includes: Acemoglu et al. (2012), Golosov et al. (2014), Fried (2018), Hassler et al. (2021a,b), Bartocci et al. (2024), Džubur and Pointner (2024), Acharya, Engle III, and Wang (2025), and Acharya, Giglio, et al. (2025). A particular strand of the literature focuses specifically on its effects on inflation and the consequences for monetary policy: e.g. Airaudo et al. (2022), Del Negro et al. (2023), Nakov and Thomas (2023), Olovsson and Vestin (2023), Ferrari and Nispi Landi (2024), and Dietrich et al. (2025). Empirical evidence of carbon taxes or carbon pricing schemes on inflation is scarce. Konradt and Weder di Mauro (2023) and Känzig (2023) provide some evidence that these policies lead to increases in the price of energy. Känzig (2023) and Broer et al. (2025) also find that shocks to energy prices disproportionally affect poor households. Since carbon pricing policies increase the price of energy, it is also relevant to point out papers that study the distributional implications of energy price shocks. Auclert et al. (2023) and Bobasu et al. (2025) look at this question in a heterogeneous-agent New Keynesian (HANK) framework and also find that poor agents are more adversely affected by an energy price shock.

Research on the distributional consequences of the green transition in general is much more limited. A closely related paper that also looks at the distributional effects of a carbon tax is Fried, Novan, and Peterman (2018), who use an overlapping generations model (OLG) and non-homothetic preferences over consumption and energy to study the implications for current and future generations. Similar to that paper is Boehl and Budianto (2024), which also investigates the inter- and intra-generational inequality in an OLG model but without energy consumption on the side of households. Both papers find implications for inequality, but differ in their conclusions whether the current or future generations are better off. An even more closely related paper to the present paper is Ascari et al. (2025).[1] They employ a similar framework to the one in this paper, with some differences. First, they model inequality using a standard incomplete markets model, whereas we use a five-agent construct and complete markets; we can therefore fix wealth inequality at an empirically reasonable level by simply assuming an initial wealth distribution and allow the distribution to change in the new steady state, whereas they

[1]We developed our paper independently and only very recently became aware of its existence.

generate an initial steady state with large inequality based on random discount factors in the population.[2] Second, we allow endogenous labor supply, which de-facto makes the economy somewhat more flexible in the short run. Overall, however, the two papers make similar modeling assumptions and reach results that appear broadly consistent with each other.

The paper proceeds as follows. Section 2 introduces the model framework with non-homothetic preferences and energy on the consumption- as well as production-side, Section 3 discusses details on the calibration for the initial steady state, Section 4 presents the simulation results of the transition to a new climate-neutral steady state, and Section 5 summarizes the conclusions.

2 Model

The model is kept very simple and consists of five households, one for each disposable income quintile as observed in the data. The production side is standard apart from the introduction of an energy sector that uses the final output good to convert it into energy services using two imperfectly substitutable technologies: a brown technology, that also produces GHG emissions, and an emission-free green technology. Thereby, firms producing the energy services can endogenously select the productivity of the brown and green technology from a technology menu subject to adjustment costs. This should also reflect the necessary investments needed to undergo the transition. The choice that energy is produced with the final output good as an input is motivated by the fact that in the absence of an open-economy model, it still captures that a substantial share of fossil fuels are imported into the EU and real resources leave the union in exchange for them. Households directly consume energy services. The production of the final output good uses energy services as a complementary input with capital and labor. The government can impose a tax and give a subsidy for the use of the two technologies to produce energy services. Alternatively, the government can also decide to return tax revenues as lump-sum transfers to households. Moreover, it needs to run a balanced budget and cannot issue debt. A more detailed description of all the elements follows.

[2]Thus, initially poor people in their model are on average poor by choice.

2.1 Households

Consider five infinitely-lived households indexed by i. They have the following preferences over a stream of expenditures and units of labor supply $\{E_{i,t}^H, l_{i,t}\}_{t=0}^{\infty}$:

$$V_{i,0} = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[v(E_{i,t}^H, P_t^E, P_t^C) - g(l_{i,t}) \right], \tag{1}$$

where

$$g(l_{i,t}) = \mu \frac{l_{i,t}^{1+\phi}}{1+\phi} \tag{2}$$

is the household's disutility of labor, ϕ the inverse Frisch elasticity of labor supply, $v(e, P^E, P^C)$ the per-period indirect utility function for the consumption of the energy services and consumption good. The indirect utility function represents non-homothetic preferences of the Price Independent Generalized Linearity (PIGL) class, as defined by (Muellbauer, 1975, 1976). We follow Boppart (2014) and adopt the following form of the PIGL indirect utility function:

$$v(E_{i,t}^H, P_t^E, P_t^C) = \frac{1}{\varepsilon} \left[\left(\frac{E_{i,t}^H}{P_t^C} \right)^{\varepsilon} - 1 \right] - \frac{\nu}{\gamma} \left[\left(\frac{P_t^E}{P_t^C} \right)^{\gamma} - 1 \right]. \tag{3}$$

with the parameters $\varepsilon, \gamma \in (0,1)$ and $\nu \geq 0$. Prices of the energy services and consumption good are denoted P_t^E and P_t^C respectively and expenditures satisfy $E_{i,t}^H = P_t^E c_{i,t}^E + P_t^C c_{i,t}^C$. The household budget constraint is:

$$P_t^E c_{i,t}^E + P_t^C c_{i,t}^C + B_{i,t+1} = W_t \xi_i l_{i,t} + R_{t-1} B_{i,t} + T_{i,t}, \tag{4}$$

where the left-hand side represents expenditures $E_{i,t}^H$ and future holdings of nominal bonds B_{t+1}, the right-hand side represents labor income $W_t \xi_i l_{i,t}$ where ξ_i represents the permanent labor efficiency of individual i, current holdings of nominal bonds $B_{i,t}$ with gross return R_{t-1}, and lump-sum transfers from the government $T_{i,t}$. In the following, we normalize all variables with the price of the consumption good P_t^C. Thus, we can write the budget constraint in real terms as:

$$p_t^E c_{i,t}^E + c_{i,t}^C + b_{i,t+1} = w_t \xi_i l_{i,t} + (1 + r_{t-1}) b_{i,t} + t_{i,t} \tag{5}$$

and real expenditures are defined as $e_{i,t} = p_t^E c_{i,t}^E + c_{i,t}^C$. Lower-case variables now denote real variables, i.e. $b_{i,t+1} = \frac{B_{i,t+1}}{P_t^C}$ and $1 + r_{t-1} = \frac{R_{t-1}}{\pi_t^C}$ with $\pi_t^C = \frac{P_t^C}{P_{t-1}^C}$.[3]

[3] Writing the household problem first in nominal terms with prices on both the consumption good and the energy good is a consequence of the PIGL indirect utility function and needed for the derivation of the demand functions using Roy's identity.

Since the five households differ in their permanent labor efficiency ξ_i, they also supply different amounts of labor $l_{i,t}$. Furthermore, households are only allowed to save and borrow in nominal bonds. The initial endowments of bonds $B_{i,0}$ differ between the agents and will be given exogenously.

Household i maximizes (1) subject to the budget constraint (4) and the standard no-Ponzi-scheme constraints:

$$\lim_{t\to\infty} \left(b_{i,t+1} \prod_{s=0}^{t} \frac{1}{1+r_s} \right) \geq 0 \tag{6}$$

by choosing a sequence of consumption $\{c_{i,t}^E, c_{i,t}^C\}_t$ and bond holdings $\{B_{i,t+1}\}_{t>0}$ taking prices $\{P_t^E, P_t^C, R_t, W_t\}_t$, transfers $\{T_{i,t}\}_t$ and initial bond holdings $B_{i,0}$ as given. Furthermore, households have perfect foresight about the aggregate state of the economy and do not face any idiosyncratic uncertainty.

To solve the household problem, we can break it down into two sub-problems: an inter-temporal problem for the consumption-savings decision and an intra-temporal problem for allocating consumption between the energy services and consumption goods.

The inter-temporal problem. In the first stage, the household decides on total expenditures $e_{i,t}$ and the amount of bonds to hold in each period. This gives rise to an Euler equation for all unconstrained agents:

$$\frac{v_E(E_{i,t}^H, P_t^E, P_t^C)}{v_E(E_{i,t+1}^H, P_{t+1}^E, P_{t+1}^C)} = \left(\frac{E_{i,t+1}^H}{E_{i,t}^H} \right)^{1-\varepsilon} \left(\frac{P_{t+1}^C}{P_t^C} \right)^{\varepsilon} = \beta R_t, \tag{7}$$

which we can also write in real terms as:

$$\left(\frac{e_{i,t+1}}{e_{i,t}} \right)^{1-\varepsilon} = \beta \frac{R_t}{\pi_{t+1}^C} = \beta(1+r_t). \tag{8}$$

Note that equation (7) implies that expenditure growth is the same for all agents and therefore in principle still allows for aggregation in the absence of any borrowing constraints.

The intra-temporal problem. By Roy's identity, we get the demand functions for the consumption of energy and consumption goods:

$$c_{i,t}^E = -\left(\frac{\partial v}{\partial P_t^E} \Big/ \frac{\partial v}{\partial E_{i,t}^H} \right) = \frac{E_{i,t}^H}{P_t^E} \left[\nu \left(\frac{P_t^C}{E_{i,t}^H} \right)^{\varepsilon} \left(\frac{P_t^E}{P_t^C} \right)^{\gamma} \right], \tag{9}$$

$$c_{i,t}^C = -\left(\frac{\partial v}{\partial P_t^C} \Big/ \frac{\partial v}{\partial E_{i,t}^H} \right) = \frac{E_{i,t}^H}{P_t^C} \left[1 - \nu \left(\frac{P_t^C}{e_{i,t}} \right)^{\varepsilon} \left(\frac{P_t^E}{P_t^C} \right)^{\gamma} \right] \tag{10}$$

or in real terms:

$$c_{i,t}^{E} = \frac{e_{i,t}}{p_t^E}\left[\nu e_{i,t}^{-\varepsilon}\left(p_t^E\right)^{\gamma}\right] \tag{11}$$
$$c_{i,t}^{C} = e_{i,t}\left[1-\nu e_{i,t}^{-\varepsilon}\left(p_t^E\right)^{\gamma}\right] \tag{12}$$

with the corresponding expenditure shares on energy $\omega_{i,t}^E$ and consumption $\omega_{i,t}^C$ shown in brackets.[4] The PIGL demand system with $\varepsilon \in (0,1)$ implies that in the limit, when expenditures $e_{i,t}$ approach infinity, the expenditure share on energy asymptotically approaches zero. Likewise, the expenditure share on consumption goods asymptotically approaches one. Thus, this makes the energy services a necessity and the consumption good a luxury.

The labor supply decision. The derivation of the first-order condition for labor supply is standard and yields:

$$l_{i,t} = \left(\frac{\xi_i w_t}{\mu e_{i,t}^{1-\varepsilon}}\right)^{\frac{1}{\phi}}. \tag{13}$$

From this expression, we can note that labor supply decreases with a higher level of expenditures, effectively making leisure a luxury good as well.

2.2 Production

2.2.1 Energy producer

The representative and perfectly competitive energy-producing firm takes the final output good and produces the energy services according to the following production function:

$$Y_t^E = \left[\left(A_t^b I_t^b\right)^{\frac{\rho_E-1}{\rho_E}} + \left(A_t^g I_t^g\right)^{\frac{\rho_E-1}{\rho_E}}\right]^{\frac{\rho_E}{\rho_E-1}} \tag{14}$$

where A_t^b is the productivity with which the firm converts I_t^b units of the final consumption good using the brown technology into energy services, and A_t^g and I_t^g are the respective variables for the green (or emission-free) technology.

[4]As in Boppart (2014), the elasticity of substitution between consumption goods and energy goods depends on preference parameters, prices, and the expenditure level, and is given by:

$$\sigma_t(e_{i,t}) = 1-\gamma-\frac{\nu\left(p_t^E\right)^{-\gamma}}{\left(e_{i,t}\right)^{\varepsilon}-\nu\left(p_t^E\right)^{-\gamma}}\left(\gamma-\varepsilon\right).$$

This can slightly be rearranged to obtain:

$$Y_t^E = \theta_t^{-\psi_E} A_t^g \left[\left(\theta_t^{\psi_E - 1} I_t^b \right)^{\frac{\rho_E - 1}{\rho_E}} + \left(\theta_t^{\psi_E} I_t^g \right)^{\frac{\rho_E - 1}{\rho_E}} \right]^{\frac{\rho_E}{\rho_E - 1}} \tag{15}$$

with $\theta_t = \frac{A_t^g}{A_t^b}$.

This representation allows us to adopt the tractable framework with different short-run and long-run elasticities of substitution by León-Ledesma and Satchi (2019). In this framework firms can not only choose the inputs in their production function, but also the (relative) technology terms A_t^b and A_t^g subject to adjustment costs. Assuming a long-run elasticity of substitution ρ_E^{LR} different from unity (as will arise in our calibration and sensitivity analysis), the technology frontier for choosing A_t^b and A_t^g is given by:

$$G(A_t^b, A_t^g; X_t) \equiv \ln(X_t) + \frac{1}{\mathcal{R}\zeta} \ln \left[\psi_E^{\zeta} + (1 - \psi_E)^{\zeta} \left(\frac{A_t^g}{A_t^b} \right)^{-\mathcal{R}\zeta} \right] - \ln(A_t^b) = 0 \tag{16}$$

where $\mathcal{R}$ governs the long-run elasticity of substitution given by $\rho_E^{LR} = \frac{1}{1-\mathcal{R}}$ and ρ_E is the short-run elasticity of substitution. They satisfy $\frac{\rho_E - 1}{\rho_E} < \mathcal{R} < 1$. We define $\zeta \equiv \frac{\rho_E - 1}{\rho_E - 1 - \rho_E \mathcal{R}}$ and ψ_E is a share parameter. The expression $\ln(X_t)$ represents the location of the frontier, with an increase in X_t shifting the frontier outwards. We assume an exogenous path for X_t.[5]

Using Equation (16), we can rearrange the equation for the frontier to get $\theta_t^{-\psi_E} A_t^g \equiv \hat{X}_t = X_t \theta_t^{1-\psi_E} \left[\psi_E^{\zeta} + (1 - \psi_E)^{\zeta} \theta_t^{-\mathcal{R}\zeta} \right]^{\frac{1}{\mathcal{R}\zeta}}$. This allows us to write

$$Y_t^E = \hat{X}_t \left[\left(\theta_t^{\psi_E - 1} I_t^b \right)^{\frac{\rho_E - 1}{\rho_E}} + \left(\theta_t^{\psi_E} I_t^g \right)^{\frac{\rho_E - 1}{\rho_E}} \right]^{\frac{\rho_E}{\rho_E - 1}}, \tag{17}$$

where $\hat{X}_t$ potentially is a function of θ_t, depending on the value of $\mathcal{R}$.

We also follow León-Ledesma and Satchi (2019) and assume that changing the relative technology θ_t incurs output losses and also adopt their choice of the functional form, which is given by:

$$\varphi \left(\frac{\theta_t}{\theta_{t-1}} \right) = 1 - \exp \left(-\frac{\tau}{2} \left(\frac{\theta_t}{\theta_{t-1}} - 1 \right)^2 \right). \tag{18}$$

For convenience, we will omit the argument and denote adjustment costs as φ_t from hereon.

[5] We think an interesting extension would be to make this endogenous to changes in the relative technology term to reflect learning-by-doing effects.

The firm has to either pay a tax $\tau_t^b > 0$ for using the brown technology or receive a subsidy $\tau_t^g < 0$ for using the emission-free technology. We will use I_t^b and I_t^g to define the green energy share as $I_t^g/(I_t^b + I_t^g)$ and measure emission reductions as changes of I_t^b from the initial steady state-value: $I_t^b/\bar{I}^b$, where $\bar{I}^b$ is the value from the initial steady state.

Thus, we can write the profit maximization problem that incorporates this technology frontier with the adjustment costs for the choice of A_t^b and A_t^g as:

$$\max_{\{\theta_t, I_t^b, I_t^g\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \left\{ \left[\prod_{s=1}^{t} \left(\frac{1}{1 + r_{s-1}} \right) \right] \left[p_t^E \left(1 - \varphi_t\right) Y_t^E - (1 + \tau_t^b) I_t^b - (1 + \tau_t^g) I_t^g \right] \right\}, \tag{19}$$

where Y_t^E is given by Equation (17) and φ_t by Equation (18).

We can use the first order conditions from this problem (in Appendix A.1) and solve for the unit cost of producing energy:

$$p_t^E = \frac{1}{(1 - \varphi_t)\hat{X}_t} \left[\left(\theta_t^{1-\psi_E} (1 + \tau_t^b) \right)^{1-\rho_E} + \left(\theta_t^{-\psi_E} (1 + \tau_t^g) \right)^{1-\rho_E} \right]^{\frac{1}{1-\rho_E}} \tag{20}$$

and get the demand-schedules for the inputs as:

$$I_t^b = \theta_t^{(1-\rho_E)(1-\psi_E)} \hat{X}_t^{\rho_E - 1} \left(\frac{1 + \tau_t^b}{p_t^E (1 - \varphi_t)} \right)^{-\rho_E} Y_t^E \tag{21}$$

$$I_t^g = \theta_t^{-(1-\rho_E)\psi_E} \hat{X}_t^{\rho_E - 1} \left(\frac{1 + \tau_t^g}{p_t^E (1 - \varphi_t)} \right)^{-\rho_E} Y_t^E. \tag{22}$$

2.2.2 Output-good-producing firm

A representative firm produces output goods, which can directly be consumed by households or be used as an input into energy production, by choosing rented capital K_t, labor L_t and energy E_t to produce with the following CES-production function:

$$Y_t = \left[(1 - \psi) \left(K_t^{\alpha} L_t^{1-\alpha} \right)^{\frac{\rho-1}{\rho}} + \psi \left(A_E E_t \right)^{\frac{\rho-1}{\rho}} \right]^{\frac{\rho}{\rho-1}} \tag{23}$$

where $\alpha, \psi \in (0, 1)$ and A_E is the relative technology of energy. Let us denote the rental rate of capital and wage as r_t^k and w_t, where $r_{t+1}^k = r_t + \delta$ needs to equal the net interest rate plus capital depreciation. Then, the firm's cost-minimization problem gives the cost of producing Y_t units of output as:

$$S_t(Y_t) = \min_{K_t, L_t, E_t} r_t^k K_t + w_t L_t + p_t^E E_t \quad \text{s.t.: } (23). \tag{24}$$

where marginal cost of producing another unit of output are $mc_t = \partial S_t(Y_t)/\partial Y_t$ and given by:

$$mc_t = \left[(1-\psi)^\rho \left(\left[\frac{r_t^k}{\alpha} \right]^\alpha \left[\frac{w_t}{(1-\alpha)} \right]^{1-\alpha} \right)^{1-\rho} + \left(\psi A_E^{\frac{\rho-1}{\rho}} \right)^\rho \left(p_t^E \right)^{1-\rho} \right]^{\frac{1}{1-\rho}}. \tag{25}$$

This leads to the standard first-order conditions (reported in Appendix A.2) that allow us to solve for all optimal factor input choices K_t, L_t, and E_t as a function of aggregate demand $Y_{j,t}$.

2.3 The government

The role of the government in the model is only to tax the use of the emission-intensive energy technology to lead the economy towards climate-neutrality. The tax revenues are always rebated in the same period to ensure a balance budget and can be done in two ways. First, the government can subsidize the use of the emission-free energy technology. Following the budget constraint for the government this implies $\tau_t^g = -\tau_t^b \frac{I_t^b}{I_t^g}$. Second, it can also rebate all the tax revenues back to the households as lump-sum transfers, which requires that $\tau_t^b I_t^b = \frac{1}{5} \sum_i t_{i,t}$.

For our analysis, we assume that the government issues no debt and thus has to balance its budget period by period. In our transition analysis, allowing government debt would enable inter-temporal tax smoothing - potentially subsidizing early green energy early on while deferring the tax on the brown until the technology frontier has moved out. This could improve welfare by reducing distortions during the transition. We see this as a valuable direction for future research.

2.4 Market clearing and equilibrium definition

The sequence of tax rates on the brown technology τ_t^b together with the choice of the redistribution of the tax revenues and the location of the technology frontier X_t is assumed to be exogenously given.

Aggregating the demand for consumption and energy from households, we get that $c_t^C = \frac{1}{5} \sum_i c_{i,t}^C$ and $c_t^E = \frac{1}{5} \sum_i c_{i,t}^E$. Likewise, aggregate bond holdings are $b_t = \frac{1}{5} \sum_i b_{i,t}$ and need to equal capital demand: $b_t = K_t$. Further, aggregate labor supply needs to equal labor demand: $\frac{1}{5} \sum_i \xi_i l_{i,t} = L_t$.

Market clearing of the energy good implies:

$$Y_t^E = \frac{E_t + c_t^E}{1 - \varphi_t}, \tag{26}$$

where the denominator on the right-hand-side captures the amount of energy that is being lost due to adjustment costs.

Aggregate consumption needs to equal the aggregate supply of the final consumption good:

$$c_t^C + K_{t+1} - (1 - \delta)K_t + I_t^b + I_t^g = Y_t. \tag{27}$$

Note that the capital stock is measured in units of the consumption good.

Given an exogenous initial wealth distribution for each agent $\omega_i^B \equiv \frac{b_{i,0}}{5b_0}$, we can define an equilibrium as a set of endogenous prices $\{r_t, w_t, p_t^E\}_t$, quantities on the household side $\{c_{i,t}^C, c_{i,t}^E, l_{i,t}, b_{i,t+1}\}_{i,t}$ as well as the quantity of energy-input in production $\{E_t\}_t$ and inputs into the production of energy $\{I_t^b, I_t^g\}_t$ with the relative technology terms $\{\theta_t\}_t$, such that the market clearing conditions above hold, the household's inter- and intra-temporal first order conditions in (7), (9) and (10) hold, the household's labor-supply condition in (13) holds, and the firms' first order conditions in Equations (29) to (34) hold.

Finally, we define GDP as the following quantity:

$$GDP = c_t^C + p_t^E c_t^E + K_{t+1} - (1 - \delta)K_t, \tag{28}$$

which excludes the part of output that is needed to produce the energy input for the output production.

3 Calibration

A notable feature of this paper is its focus on household inequality in the context of the green transition. We want to capture differences in consumption patterns stemming from non-homothetic preferences, in addition to more standard measures of inequality in income and wealth. We therefore begin with a closer examination of the expenditures of households with varying income levels. Eurostat released experimental statistics on income, consumption, and wealth that are particularly interesting for a calibration to the EU or the euro area. It compiles data from the Household Finance and Consumption Survey (HFCS) and produces expenditure shares on energy (among other consumption categories) by disposable income, which we can use to calibrate the strength of non-homothetic preferences.[6]

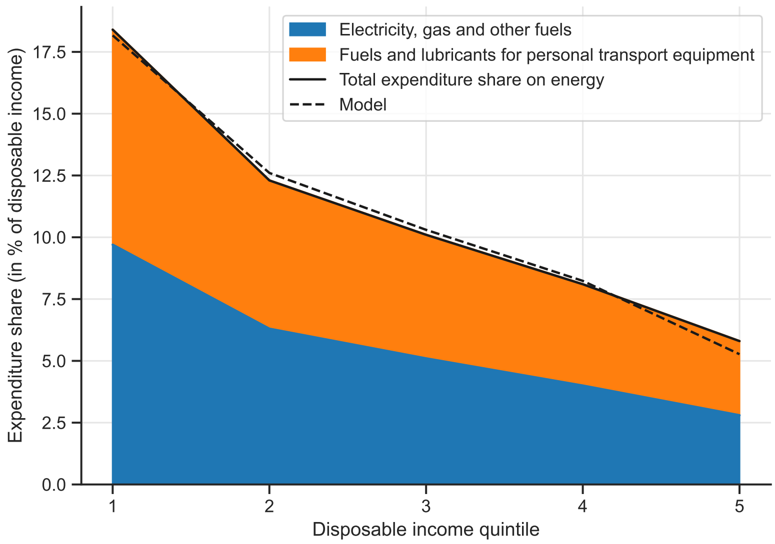

Figure 1: Household's expenditure share on energy by income.

Notes. Data is for the euro area in 2020 and come from Eurostat (Experimental statistics on income, consumption and wealth), which compiles information from the Household Finance and Consumption Survey (HFCS). Electricity, gas and other fuels refers to the COICOP number CP045 and includes following sub-categories: electricity, gas, liquid fuels, solid fuels and heat energy. Fuels and lubricants for personal transport equipment refers to the COICOP number CP0722 and includes following sub-categories: diesel, petrol, other fuels for personal transport equipment, and lubricants.

Figure 1 shows the expenditure share of two broad consumption categories that we interpret as representing expenditures on energy. The figure shows that the bottom income quintile has around three times as high expenditure share on energy than the top income quintile and this holds for both sub-components individually as well. To calibrate the initial steady-state expenditure shares of the five agents in our model, we choose an appropriate parameter value for ε, such that we match the resulting steady-state expenditure shares by minimizing the squared residuals. The dashed line in the figure shows the expenditure shares in the model and how well they can be matched using only on preference parameter. The second parameter value for γ, featuring in the PIGL preferences, is calibrated by estimating this parameter using the same data and methodology as in Hochmuth et al. (2023), but with a split between energy and all other consumption goods.[7] The estimation delivers a value of $\gamma = 0.639$, which implies an elasticity of substitution (EoS) between consumption goods and energy services $\sigma(e)$ of 0.35 for the aggregate. Note that this elasticity is dependent on the level of income and slightly higher for the high-income agent.[8] This elasticity is well in line with the low elasticity of

[6] For more details on the data we refer to: https://ec.europa.eu/eurostat/web/experimental-statistics/income-consumption-wealth.

[7] Data comes from the Consumption Expenditure Survey (CEX). We perform a non-linear GMM estimation of Equation (11) with household-level data, where we instrument expenditures with household-income, to obtain an estimate for γ. The identifying variation comes from time-series variation of p_t^E.

[8] The precise values for the elasticity of substitution between consumption and energy goods are:

substitution also found in Hassler et al. (2021a).

We continue with the calibration of the wealth and income inequality. The experimental statistics on income, consumption, and wealth directly deliver data on net wealth and household income by income quintiles. This informs the exogenous wealth share ω_i^B for the five agents of the model. Second, we use the permanent labor productivity of the five agents ξ_i to target the income distribution in the data.

On the production side, there are three key parameters. Two of them are the short- and long-run elasticity of substitution between the brown and the green energy technology, ρ_E and ρ_E^{LR}, which we set to 0.5 and 5. This range covers the often used estimate of 3 by Papageorgiou et al. (2017). The other is the elasticity of substitution between the capital-labor aggregate and energy, ρ, which we set to 0.1 to reflect the realistically low elasticity and lies in the ballpark of elasticities used in e.g. Hassler et al. (2021a), Fried, Novan, and Peterman (2022) and Olovsson and Vestin (2023).

Furthermore, there are two more less important share parameters on the production side. One is the share-parameter in the CES-production function of the final-output-good producing firm ψ, which is inconsequential since we use the productivity term A_E to target the fact that 10% of output is spent on energy in developed economies (see Box 1.2 in OECD, 2022). The other is the share-parameter in the production function of the energy producer ψ_E, which we calibrate to match the fact that 24.5% of energy production is coming from green and emission-free technologies (Eurostat, 2025).

The residual parameters are standard in the literature and are listed in Table 1 among all other parameters discussed previously.

Table 1: Calibration of parameters

Parameter	Value	Description	Comment
α	2/3	Capital share in the KL-aggregate	standard
β	0.9902	Discount factor	4 % interest rate p.a.
ε	0.5223	Degree of non-homotheticity	target exp. share in the data
γ	0.639	Parameter controlling the EoS b/w c^C and c^E	estimated from CEX data
ν	1	Level shifter for the expenditure share of c^E	normalization
ϕ	2	Inverse Frisch elasticity of labor supply	standard Frisch elasticity of 0.5
μ	1	Scaling factor for the disutility of labor	normalization
ξ_i	[0.126, 0.257, 0.364, 0.515, 1.033]	Labor productivity	target income quintiles
ω_i^B	[0.065, 0.098, 0.131, 0.206, 0.499]	Initial wealth shares	target net wealth by income quintile
ρ_E	0.5	Short-run EoS b/w brown and green technology	our assumption
ρ_E^{LR}	5	Long-run EoS b/w brown and green technology	our assumption
ψ_E	0.755	Share parameter for I^b in energy production	24.5% of energy from renewables
X	1.9414	Location of the technology frontier	normalization s.t. initial $p^E = 1$
ρ	0.1	EoS b/w KL-aggregate and E	realistically low at 0.1
δ	0.03	Depreciation rate	K/Y-ratio of 16 (standard)
ψ	0.05	Share parameter for E in the production function	from Hassler et al. (2021a)
A_E	17.2485	Productivity for E in the production function	10 % of output spent on energy

$[0.335, 0.344, 0.348, 0.351, 0.355]$ for the five agents in the initial steady state.

4 Becoming climate neutral

Now we consider a government policy similar to the Fit-for-55 package, which aims to make the EU climate-neutral by 2050. In order to achieve this, the EU needs to reduce emissions by 90% compared to the 1990 levels. The residual 10% of emissions is assumed to be absorbed by various carbon sinks. Up until today, the EU has already managed to reduce emissions by 33% compared to the 1990 levels. This means that the EU needs to reduce its emissions by 85% in the coming 25 years compared to today's emission levels. This is the target we set for the transition of our model economy from the initial steady state.

To simulate this transition to a climate-neutral economy in the model, we assume in the baseline that the government gradually introduces a tax on the brown technology with $\tau_t^b > 0$ while subsidizing the green technology with $\tau^g < 0$. This policy should be interpreted as capturing the essence of both emission trading systems (ETS1 and ETS2) as well as various national carbon tax schemes. In the baseline we re-distribute the tax revenues as a subsidy on the green technology, but also consider a direct transfer to households. The baseline tax policy we consider is a linear increase of τ_t^g from zero to a final value in 25 years, after which the tax rate will be kept constant forever. This is motivated by the fact that the Fit-for-55 package also specifies intermediate goals not explicitly targeted in our simulation, but we also explore other transition policies. Initially, the model economy is in a steady state in which the government has no ambition to become climate-neutral. In period $t = 0$ the agents are surprised by the announcement of the path for the tax τ_t^b, and thus immediately adjust their behavior and have perfect foresight about all variables for the infinite future without any doubt about the commitment by the government to enforce the tax scheme. Further, in the absence of any trend growth in the model, the results from the simulation should be interpreted as deviation from trend growth.

For our economy and any set of constant policy parameters, there is a continuum of steady states because of the freedom to "choose" an initial wealth distribution. This feature is standard in the case where markets are complete and there are several consumer types with the same discount factors. Furthermore, in a model with homothetic preferences, these steady states would also yield the same aggregate outcomes and differ only in the allocation of consumption and labor across the consumer groups. Because of the non-homotheticity here, however, the distribution of wealth will affect the aggregate consumption levels of the two goods. This also means that solving for a transition path in our economy is challenging since the long-run steady state to which the economy will converge is endogenous and depends on the relative asset accumulation of the consumer groups during the transition period. Our solution method, which is fully non-linear, thus cannot rely on solving backwards from a known steady state. To obtain the entire transition, we numerically solve for the new steady-state values of expenditures for each agent $e_{i,T}$, the full path of interest rates r_t, wages w_t, and relative technology terms θ_t by applying a standard root-solving algorithm on the residuals arising from the equilibrium conditions.

4.1 Baseline transition path

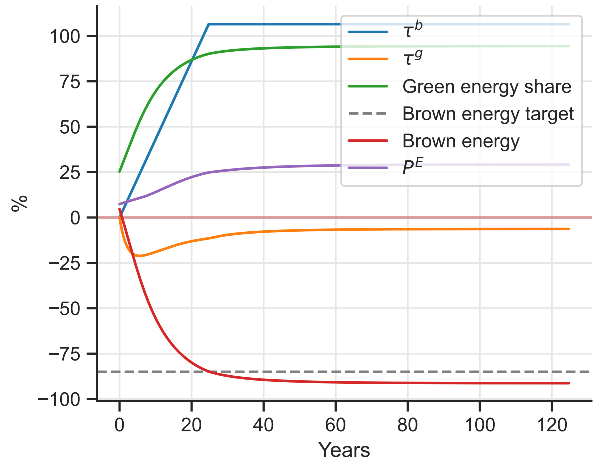

Figure 2: Transition path for taxes, price of energy, and energy inputs.

Notes. Model simulation of a gradual introduction of a 106.5% tax on the brown technology τ_t^b.

We first examine the benchmark transition required to meet the EU's Fit-for-55 emission-reduction target. This scenario illustrates the magnitude of output and welfare costs under realistic elasticities of substitution. Figure 2 shows that a final value of a 106.5% for the tax on the brown technology in 25 years achieves an exact reduction of the use of the brown energy technology by 85% in 25 years. The transition even continues and emission eventually are reduced by 91% in the new steady state. This implies that the effective price of fossil fuels needs to more than double in order to meet the target in the emission reduction. Along this transition path, the final price of energy p^E relative to consumption goods increases by about 25%, which has large implications for output that are discussed in more detail later on. Moreover, the tax revenues generated from the tax on the brown energy initially allow the government to hand out quite sizable subsidies for the green technology. But as the green energy share in the economy increases and fewer tax revenues can be generated from the brown technology, also the subsidy rate declines.

The implications of this transition to a climate-neutral economy for households are also quite large. As we can see in Figure 3, Panel (a), all agents reduce their energy consumption $c_{i,t}^E$ by about 11.5% compared to the initial steady state. The response is very

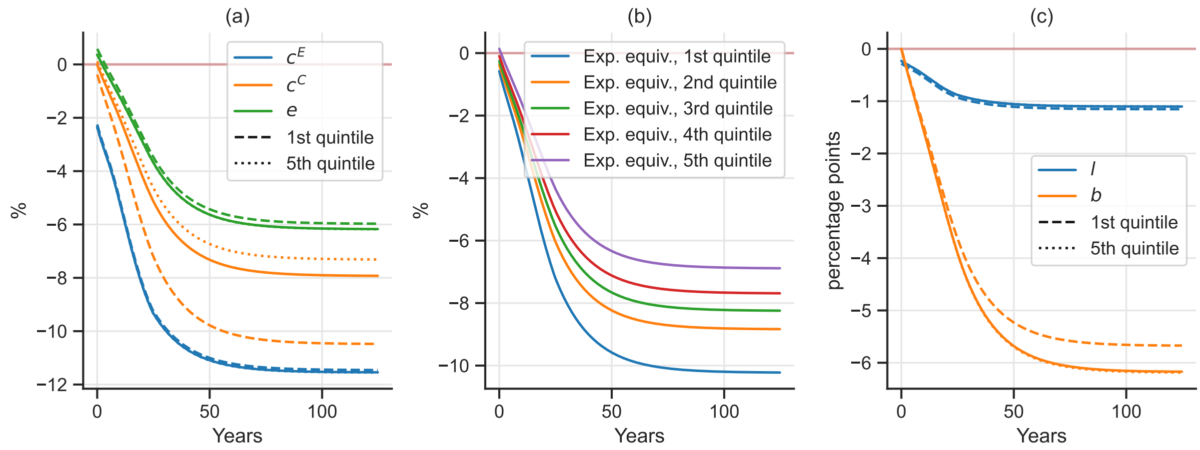

Figure 3: Transition path for consumption, expenditures, expenditure equivalent, labor supply as well as the wealth shares.

Notes. The figure shows the percent deviations of the respective variables from their initial steady state. The solid lines show the aggregate, and the dashed and dotted lines are for the first and fifth agent representing the respective income quintile. The deviation in the expenditure equivalent (exp. equiv.) in Panel (b) is defined as x in: $v\left((1+x)e_i, p^E\right) - g(l_i) = v\left(e_{i,t}, p_t^E\right) - g(l_{i,t})$, where variables without a time-subscript denote the initial steady state.

similar among all agents because energy is a necessity good. However, the response of the consumption good $c_{i,t}^C$ differs more between the agents, with a substantially larger drop for the lowest-income agent (first quintile), who has a higher exposure to the increase in energy prices because of the higher expenditure share on energy. Therefore, this agent faces a larger income effect coming from the price increase on energy and is forced to cut the consumption of the consumption good by more.

Next, we converting these dynamics into equivalent expenditures, i.e. the percentage change in steady-state expenditures necessary to match the flow utility during the transition. Figure 3, Panel (b), shows the equivalent expenditures as percentage changes from their respective initial steady state values. It highlights quite a dramatic decline of 10.2% in equivalent expenditures for the low-income agent (first quintile) and a 6.8% drop for the high-income agent (fifth quintile), which is a 48% larger drop for the poor agent than the rich agent.

Figure 3, Panel (c), shows the labor supply along with the asset holdings of the low- and high-income agent. While the labor supply reacts very similarly and drops by around one percent, shifts in the asset distribution between the agents are more pronounced. In particular, the asset holdings of the low-income agent drops by 0.5 pp less than the high-income agent, implying a higher wealth share for the low-income agent. However, expressed in percent of annual labor income, the picture is reversed. The low-income agent reduces asset holdings by 221% and the high-income agent only by 177% of their annual labor income.

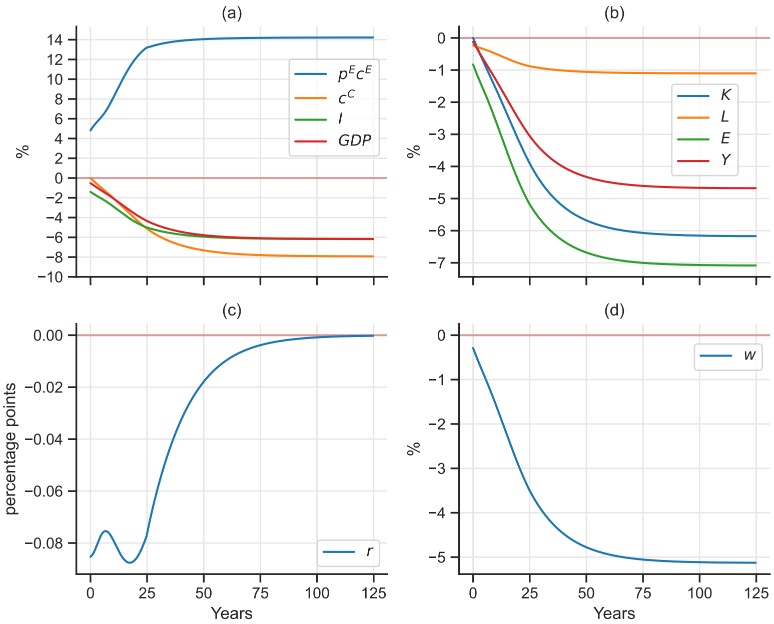

Figure 4: Transition path for GDP with its components, output with its factor inputs, the real interest rate, and wages.

Notes. The figure shows the percent deviations of the respective variables from their initial steady state. The deviations for the real interest rate is shown in annualized percentage point deviations.

The transition to a climate-neutral economy also has profound impact on the production side of the economy. Figure 4, Panel (a), summarizes the effects on GDP and its components. Overall, GDP falls by 6.2% in the new steady state, while the drop in total output Y_t shown in Panel (b) is only 4.7%. This reflects the fact that the price of energy increased and now relatively more output goods are needed for the production of energy services. However, energy as an input in production drops by 7.1% due to the increase in its price. The drop in capital mirrors the drop in GDP with 6.2% and labor as an input only falls by 1.1% on account of a large drop in wages by 5.1%. Finally, the change in the real interest rate shown in Panel (c) is relatively small and falls by less than 10 basis points.

In the background of this transition are the energy producers that react to the tax and subsidy system by choosing the ratio of technology terms θ_t. The framework with the technology frontier allows us to distinguish between a short-run and a long-run elasticity of substitution between the brown and green technology. In the model, this is achieved by choosing the respective technology terms. If the price of the brown technology increases, e.g. through a tax, then the energy producers have the incentive to improve the technology of this input factor, i.e. increase the productivity of the brown technology, as this allows them to produce more energy with a lower use of the brown technology as input. This is exactly what Figure 5, Panel (a) shows. It plots the evolution of technology terms as the log difference to the initial steady state and highlights a strong improvement in the technology term of the brown technology while the technology term of the green technology actually decreases. This might appear surprising at first glance, but in the model this only means that energy-service-producing firms can produce more energy services with the green technology instead of the brown technology. One way to interpret this change in technology terms is that the economy becomes less dependent on the brown technology through, e.g. investments in grid-scale battery storage.

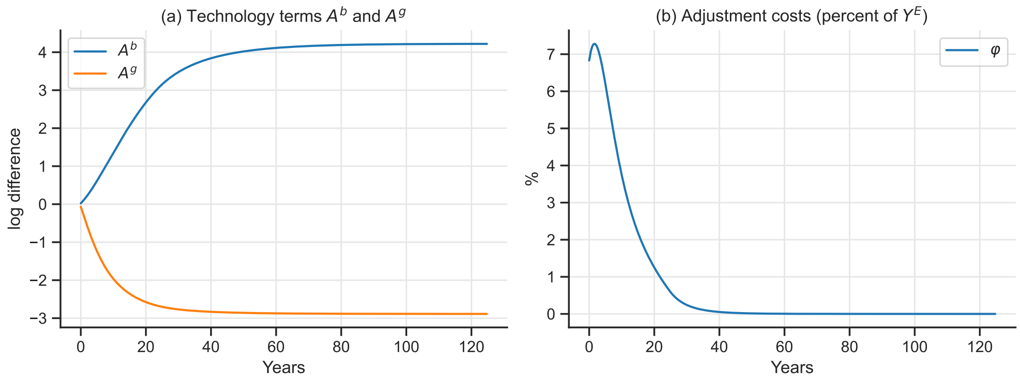

Figure 5: Transition path for the technology terms A_t^g and A_t^b along with the adjustment costs φ_t paid by the energy producers.

Notes. Panel (a): The figure shows the log difference of the technology terms to their respective steady-state values. Panel (b): The adjustment costs φ_t are expressed in percent of total energy production Y_t^E.

Finally, we want to highlight the robustness of this transition in aggregate to two variations. First, reducing the number of agents in the model to only one representative agent has no distinguishable differences in the dynamics of the aggregates.[9] Second, we note that none of the time paths we just reported are much affected by the introduction of investment adjustment costs for capital (by raising χ from 0 to 10). This is not surprising as the tax rate is changing very smoothly in our baseline and the adjustment costs for the relative technology terms on for energy producers play a much bigger role.

4.2 Alternative transition paths

The gradual and linear introduction of the tax τ_t^b is just one possibility to introduce the tax and is inspired by the fact that the Fit-for-55 package not only sets a goal of becoming climate-neutral by 2050, but also sets intermediate goals of a 55% reduction of emissions by 2030. This section explores four alternative transition paths. All alternative transition functions are logistic functions with the same smoothness of the transition but with alternative midpoints. The first alternative scenario considers a relatively fast introduction of a permanent tax that reaches its midpoint in around 6 years after the

[9] We omit a comparison between the one-agent and the five-agent model because the differences are visually indistinguishable. This result is less surprising, since the PIGL preferences allow for aggregation.

announcement, while the other three alternative scenarios reach their midpoint in around 12, 18, and 23 years. Given the differences in the timing of the introduction of the tax, it is also necessary to adjust the final level of the tax in order to hit the target of a 85% reduction in emissions after 25 years. Figure 6, Panel (a), shows that the necessary tax rates are strongly increasing the later the introduction of the tax takes place. The scenario that introduces the tax only after 23 years requires a tax rate of 200%, around double that of the baseline. This also implies that the bulk of the reduction in emissions occurs much later in this scenario and given the high final tax rate reduces emissions in the new steady state to 98%.

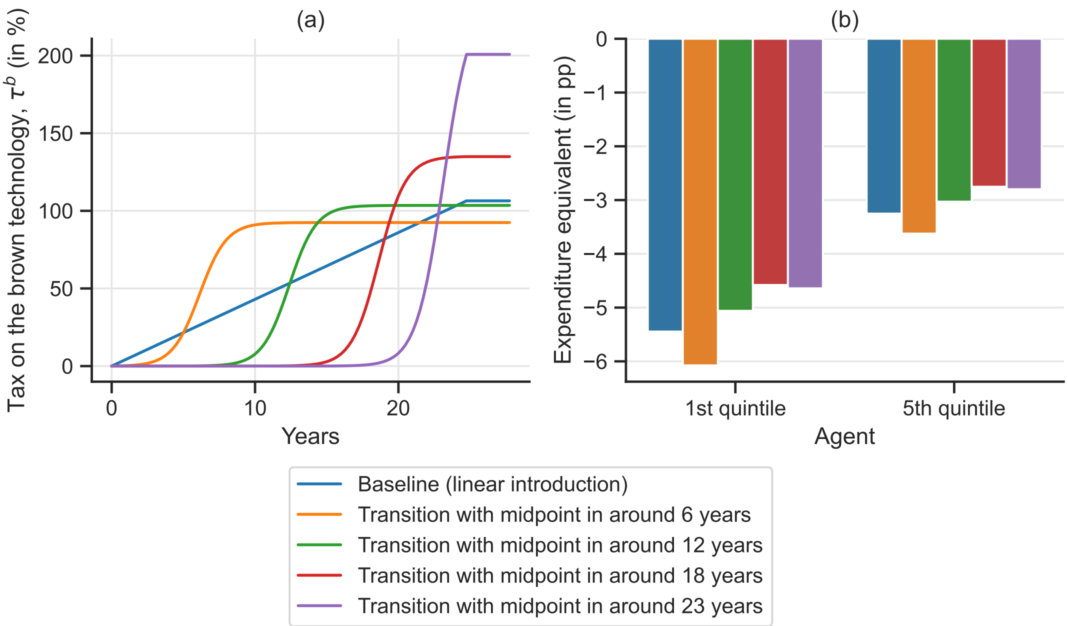

Figure 6: Alternative scenarios for the introduction of the tax τ_t^b with a welfare comparison.

Notes. Panel (a) shows the different paths for the tax on the brown technology τ_t^b. Panel (b) shows the deviation of the present discounted value (discounted with β) of the expenditure equivalent for each scenario from steady state as percentage point deviations.

We can compare the welfare of different scenarios using the deviation of the present discounted value of the expenditure equivalent from steady state.[10] This is what Figure 6, Panel (b) shows. The welfare losses from the introduction of the tax in the baseline implies a loss of 5.4% and 3.3% over the entire transition for the low-income and high-income agent respectively. Introducing the tax earlier with a midpoint in around 6 years increases this loss up to 6.1% for the low-income agent, while introducing it later minimizes the loss below 5%. The smallest losses of 4.6% occur if the transition reaches its midpoint in 18 years. This allows the economy to still enjoy the benefits of the more efficient initial steady

[10]We discount with the discount factor β. Since the movements in the real interest rate are relatively small, there is effectively no difference to discounting with the real rate instead, but using β facilitates the comparison across different paths.

state for a while longer, while still reaching the target on time. If the midpoint is pushed further back to, for example, 23 years, this increases the welfare losses again. Although the agents are forward-looking, they do not initiate the adjustment of the technology terms without changes to the tax rate. Once the tax rate is introduced, a much higher level of it is required in order to provide the necessary incentives for the transition to take place in that short amount of time. The model ignores other important elements that are possibly relevant for the practical implementation of such a tax in the very short-run. For example, this would have much larger implications for inflation, which could trigger a wage-price spiral through shifts in inflation expectations.

To summarize, there are three main points worth noting. First, since the introduction of the tax is necessarily decreasing the level of output in the new steady state without any direct benefits in the model, it is better to start the transition rather later than earlier (for the low-income there is a close to 1.5 percentage-point difference between late and early implementation). Second, since there are technology adjustment costs on the side of energy producers which leads to a gradual transition, waiting too long might require a painfully high tax on the brown technology to eventually meet the emission target in 25 years. Third, the welfare implications are much starker for the low-income agent than for the high-income agent. This is intuitive, as the tax on the brown technology affects the low-income agent more due to their higher exposure to energy prices. Hence, the tax is regressive.

4.3 Sensitivity with respect to some parameters

One of the key parameters in the model is ρ_E^{LR}, which controls how easy it is to substitute the brown technology with the green technology in the long-run. In the baseline we calibrate this value to five. Given the dependence of this parameter on the horizon considered, it is particularly difficult to calibrate this number to some precise estimates from the literature. Papageorgiou et al. (2017) estimate a value of two, but the literature uses a range of parameters for this elasticity. Acemoglu et al. (2012), for example, consider a value of 3 and 10 for the elasticity of substitution between a "clean" and "dirty" technology. Golosov et al. (2014) argue that high values of around 10 is certainly on the rather optimistic side. Fried (2018) uses a slightly lower value of 1.5 in a CES-function of green energy and a composite of fossil fuels and oil imports.

Given this large uncertainty surrounding this parameter, we now consider two alternative values for the long-run elasticity of substitution between the brown and green technology, ρ_E^{LR}.[11] First, we consider a lower elasticity with $\rho_E^{LR} = 3$ and, second, a higher value of

[11] We've also carried out a robustness analysis around the short-run elasticity of substitution, but this

$\rho_E^{LR} = 8$. Although these are relatively small deviations from the baseline value of $\rho_E^{LR} = 5$, these alternative values already have quite strong implications for the new steady state of the model.

Table 2: Sensitivity of the new steady state values to alternative values of ρ_E^{LR}.

	Baseline	Low elasticity	High elasticity
Elasticity of substitution: ρ_E^{LR}	5	3	8
Necessary τ_t^b to meet target	106.45	197.39	69.99
Corresponding increase in p^E	29.12	54.25	17.94
Change in GDP	-6.17	-11.16	-3.85
Expenditure equivalent, 1st quintile	-10.22	-18.17	-6.43
Expenditure equivalent, 5th quintile	-6.89	-12.39	-4.31

Notes. All numbers, except τ_t^b, report the percent deviations of the new steady state compared to the initial steady state.

Table 2 shows the tax rate on τ_t^b necessary to achieve the same 85% reduction in emissions along with some selected values in the new steady state. Decreasing the elasticity of substitution ρ_E^{LR} to 3 almost doubles the necessary tax, and increasing ρ_E^{LR} to 8 reduces it to 70%. Similar statements hold for the price of energy p^E and the other values shown in the table as well. This illustrates how sensitive the results are to this parameter. Plots to the transition of most variables can be found in Appendix C.

We also carried out a sensitivity analysis with respect to other parameters and the respective figures can also be found in Appendix C. Changes in the short-run elasticity of substitution ρ_E have some impact on the aggregates, but are in general much less important than changes in the long-run elasticity ρ_E^{LR} as just discussed above. Interestingly, changes in the adjustment costs τ appear to have quantitatively very similar effects as changes in the short-run elasticity ρ_E. They are not unimportant, but less important than changes in the long-run elasticity of substitution. Changing the preference parameter γ from 0.639 to 0.5 or 0.75 in the PIGL indirect utility function has surprisingly little effects on the transition and overall GDP losses are always the same. The only difference is on the demand-side, where it influences how strong the elasticity of substitution between the energy services and the consumption good is, but even that leaves the changes in the expenditure equivalent almost unchanged. Changes in the elasticity of substitution between the capital-labor aggregate and energy services in the production of the final output good also turns out to be inconsequential.

turned out to be inconsequential for the results. This highlights that the important parameter is the long-run elasticity.

4.4 The role of non-homothetic preferences

A key feature in this paper is its application of non-homothetic preferences for consumption. This is important for capturing the differences in the expenditure shares on energy across the income quintiles. However, it also changes the elasticity of substitution between the necessity and the luxury good depending on the level of expenditures. Non-homothetic preferences make it harder to substitute away from the necessity good, especially for low levels of expenditures, and most of the adjustment takes place on the side of the luxury good.

Since the dynamics of the aggregates in baseline model are robust to the number of agents, we illustrate the impact of the non-homothetic preferences in a model setup with one representative agent. This facilitates the re-calibration of the homothetic model-variant to match the initial steady state. We can turn off non-homotheticities by setting $\varepsilon = 0$ in the PIGL indirect utility function, which yields homothetic preferences with expenditure shares that are independent of the level of expenditures. This can easily be seen in Equations (11) and (12). We then adjust ν, ξ, and γ to match the expenditure share on energy in the aggregate, the share of GDP spent on energy, and the elasticity of substitution between consumption and energy from the baseline. Hence, we depart from the identical initial steady state and any differences to the baseline are coming purely from non-homothetic preferences.

Overall, the aggregate responses in a transition with homothetic preferences are somewhat weaker as Figure 7, Panel (a) shows. GDP is only 5.1% lower (compared to 6.2% in the baseline). The main reason for why the GDP losses are smaller in the homothetic variant is because labor supply returns to the initial steady state value. This results from a change in ε to zero, which causes the income and substitution effects of a wage rate change to offset each other and can be clearly seen in Equation (13). Although the wage rate in the new steady state falls to the same level as in the baseline model, labor supply is unaffected, leading to a higher overall level of output.[12]

Taking a closer look at the consumption side, Figure 7, Panel (b), shows that the drop in aggregate energy consumption is much stronger in the homothetic version than in the baseline version, while consumption of the consumption good is higher. This results from the elasticity of substitution being independent of the level of expenditures in the homothetic version. In the non-homothetic version, this elasticity becomes lower with a lower level of expenditures and thereby dampens the substitution effect in the new steady state with a lower level of expenditures.

[12] We also implemented a homothetic version with CES preferences and found slightly larger GDP losses of 6.5%, which also comes from differential reaction of labor supply.

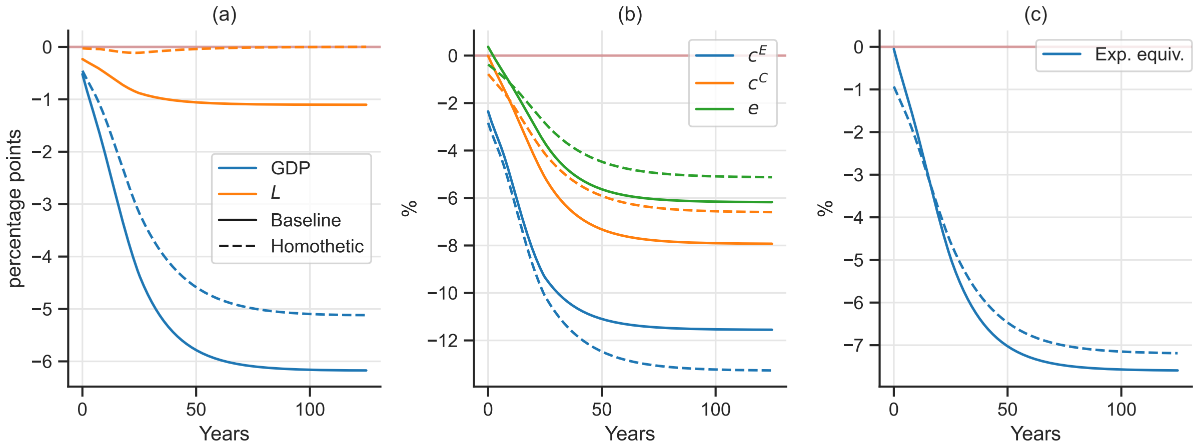

Figure 7: Comparison of the transition with homothetic (dashed lines) instead of non-homothetic (solid lines) preferences.

Notes. The figure shows the percent deviations of the respective variables from their initial steady state. The solid lines show the aggregate of the baseline model and the dashed lines the counterpart in the homothetic model version. The expenditure equivalent deviation (exp. equiv.) in the left panel is defined as x in: $v\left((1+x)e_i, p^E\right) - g(l_i) = v\left(e_{i,t}, p_t^E\right) - g(l_{i,t})$, where variables without a time-subscript denote the initial steady state.

Summarizing the overall differences in changes to the expenditure equivalent, which also incorporates changes in labor supply, shows only small differences. While the reduction in expenditure equivalent is 7.6% in the baseline model, this reduction is only 7.2% in the homothetic model version.

4.5 Considering an improvement in energy efficiency

The Fit-for-55 package also contains a binding target for energy efficiency and requires each EU member country to improve energy efficiency on average by about 1.49% annually. The transition of the model considered up to now only considers an increase in the tax on the brown technology in order to reduce emissions by 85%. But how do the conclusions change if we simultaneously consider an increase in energy efficiency?

In order to incorporate this additional requirement from the Fit-for-55 package in the model simulation of the transition, we consider an exogenous increase in the technology frontier of the energy producers. However, since the model simulations are expressed in deviations from trend growth and the EU has seen an improvement in energy efficiency of around one percent annually in the last 20 years, we only consider the additional growth required to meet the target. Thus, we assume a simultaneous increase in X_t of 0.5% annually during the transition in the first 25 years. The location of the technology frontier ends up being 13% higher in the new steady state. Since the increased energy efficiency directly reduces the use of the brown and the green technology, we need to solve for a new path of taxes with a different final value to achieve the same 85% reduction in emissions in 25 years. With a simultaneous increase in energy efficiency, this is achieved with a 100.1% tax on the brown technology.

Table 3: New steady-state values after a transition with a simultaneous improvement in energy efficiency.

	Baseline	Improved efficiency
Necessary τ_t^b to meet target	106.45	100.14
Corresponding increase in p^E	29.12	13.36
Change in GDP	-6.17	-2.89
Expenditure equivalent, 1st quintile	-10.22	-4.84
Expenditure equivalent, 5th quintile	-6.89	-3.23

Notes. All numbers, except τ_t^b, report the percent deviations of the new steady state compared to the initial steady state.

Not surprisingly, the aggregate and distributional consequences arising from a transition with a simultaneous increase in energy efficiency are substantially weaker as Table 3 shows. First, GDP losses are now only 2.89%, less than half compared to the baseline. The price of energy only increases by 13.36% and the effects on the expenditure equivalent are also roughly half as severe.

This raises the question of how much energy efficiency has to improve in order to exactly offset the output losses from the increase in the tax on the brown technology while reducing emissions by 85%. The answer is roughly a 25% improvement in energy efficiency over the first 25 years or 0.9% annually (beyond the 1% trend growth) with a 95.1% tax on the brown technology.

One caveat of this experiment, of course, is that an improvement in energy efficiency might not come for free as this purely exogenous increase assumes. There might be substantial costs associated with achieving this improvement that are not modeled in this framework. However, the results from this section still spread careful optimism that the transition might be significantly less painful than the baseline scenario predicts.

4.6 Alleviating all inequality via lump-sum transfers

In the baseline we assume that all tax revenues from the tax on the brown technology are redistributed as subsidies to the green technology. We now consider an alternative redistribution via lump-sum transfers $t_{i,t}$ to the households. More specifically, we assume an egalitarian redistribution scheme across the agents that equalizes the losses of the introduction of the tax in the new steady state. Hence, we solve for the share of tax revenues that goes to each agent such that all agents experience the same percentage drop in their expenditure equivalent in the new steady state.

When redistributing the tax revenues from a tax on the brown technology as lump-sum transfers to households without adjusting the tax rate, energy producers lose part of the incentive to switch from the brown to the green technology as there are no subsidies any longer. Therefore, a higher tax rate on the brown technology is needed to achieve the same reduction in emissions. With an egalitarian redistribution the required tax rate is now 136%, which is 29.5 pp higher than in the baseline. Consequently, the price on energy in total increases by 38.8% instead of 29.1% in the baseline.

The higher price on energy lowers the marginal product of capital, which leads households to consume more out of their asset holdings and thereby lowers the aggregate stock of capital even though they receive lump-sum transfers. As a result, GDP in the new steady state is 7.7% lower than in the initial steady state. This is 24% more than in the baseline.

Taken together, alleviating all inequality comes at the cost of additional aggregate output losses that are not negligible. GDP losses are 24% higher with egalitarian lump-sum transfers than in the baseline with a subsidy on the green technology.

4.7 Model limitations and directions for future work

The analysis so far abstracts from several mechanisms that could materially affect the results and their policy interpretation.

First, the government is constrained to balance its budget period by period. Allowing debt issuance would enable intertemporal tax smoothing—for instance, subsidizing green technology more aggressively early on and financing these subsidies with future carbon-tax revenues once the technology frontier has advanced. Such borrowing could reduce transitional distortions and improve welfare, especially when adjustment costs are high.

Second, the model focuses on closed-economy dynamics and abstracts from cross-border energy trade and capital flows. In practice, openness could amplify or attenuate distributional effects, depending on how import prices and energy dependencies evolve across EU member states.

Third, the framework treats the technology frontier for green energy as exogenous. Endogenizing innovation—through learning-by-doing, R&D investment, or spillovers—could further lower the long-run cost of decarbonization and change the optimal sequencing of taxes and subsidies. Further, we abstract from potentially important distributional effects on the income side. If clean energy sectors or innovation activities employ predominantly higher-skilled, higher-income workers, then tax-induced reallocation from brown to green could have regressive effects that partially or fully offset the progressive redistribution from lump-sum transfers.

Finally, we omit explicit climate-damage functions. While this omission allows for a clean focus on the economic cost of mitigation, incorporating damages would permit a fuller welfare evaluation of different transition paths, including the optimal timing of taxation when environmental externalities are taken into account.

Addressing these extensions would deepen our understanding of the joint design of fiscal, technological, and environmental policy in achieving a climate-neutral economy.

5 Conclusions

This paper quantifies the aggregate and distributional costs of Europe's transition to climate neutrality using a dynamic general equilibrium model with non-homothetic preferences and an explicit energy-production sector. The framework captures how differences in expenditure patterns across income groups shape the economic burden of decarbonization policies such as those embedded in the EU's Fit-for-55 package. Three main lessons emerge.

First, achieving the EU's emission-reduction targets entails sizable macroeconomic costs. A carbon-equivalent tax on fossil-based energy of roughly 100 percent—consistent with a 90 percent cut in emissions—reduces long-run GDP by about 6 percent in our baseline calibration.

Second, these costs are highly regressive. Because low-income households devote a larger share of spending to energy, welfare losses in the bottom income quintile are nearly 50 percent greater than those in the top quintile. This finding underscores that the green transition, if left unaccompanied by redistribution, risks widening economic inequality.

Third, technological progress and policy design can dramatically mitigate these costs. Modest improvements in energy efficiency, of the scale targeted in the Fit-for-55 plan, halve the decline in output and welfare. Likewise, credible announcements combined with gradual implementation minimize transitional distortions, while redistribution through lump-sum transfers can offset inequality at the expense of somewhat lower efficiency.

Beyond these quantitative results, the analysis highlights broader principles for climate-policy design. The timing and credibility of carbon taxation matter as much as its magnitude: early policy commitment with a predictable ramp-up allows households and firms to adjust smoothly. Complementary investment in energy efficiency and clean technology is a substitute for higher taxation. Finally, fiscal policy can play a key role in cushioning distributional impacts, though fully egalitarian transfers come with measurable efficiency costs.

Overall, the path to climate neutrality is economically costly but manageable. Credible long-term commitments, efficiency-enhancing investment, and targeted redistribution can ensure that Europe's transition is not only green but also fair.

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Appendix

A Additional model details

A.1 Energy producer

The corresponding first-order conditions for the energy producer Equation (19) are given by:

$$[\theta_t]: \quad \left[\frac{\partial \hat{X}_t}{\partial \theta_t}\frac{\theta_t}{\hat{X}_t} + \psi_E\right](1-\varphi_t) - \frac{1-\varphi_t}{1+\left(\theta_t \frac{I_t^g}{I_t^b}\right)^{\frac{\rho_E-1}{\rho_E}}}$$

$$-\varphi_t' \frac{\theta_t}{\theta_{t-1}} + \frac{1}{1+r_t}\frac{p_{t+1}^E Y_{t+1}^E}{p_t^E Y_t^E}\varphi_{t+1}' \frac{\theta_{t+1}}{\theta_t} = 0 \tag{29}$$

$$[I_t^b]: \quad \frac{p_t^E Y_t^E}{I_t^b}\frac{1-\varphi_t}{1+\left(\theta_t \frac{I_t^g}{I_t^b}\right)^{\frac{\rho_E-1}{\rho_E}}} = (1+\tau_t^b) \tag{30}$$

$$[I_t^g]: \quad \frac{p_t^E Y_t^E}{I_t^g}\frac{1-\varphi_t}{1+\left(\theta_t \frac{I_t^g}{I_t^b}\right)^{\frac{1-\rho_E}{\rho_E}}} = (1+\tau_t^g). \tag{31}$$

where $\frac{\partial \hat{X}_t}{\partial \theta_t}\frac{\theta_t}{\hat{X}_t} = (1-\psi_E) - \left[\left(\frac{\psi_E}{1-\psi_E}\right)^{\zeta}\theta_t^{\mathcal{R}\zeta} + 1\right]^{-1}$ and zero in the case of $\mathcal{R} = 0$.

A.2 Output-good-producing firm

The first order conditions for cost minimization of the output-good-producing firm are given by:

$$r_t^k = mc_t Y_t^{\frac{1}{\rho}}(1-\psi)\left(K_t^{\alpha}L_t^{1-\alpha}\right)^{\frac{-1}{\rho}}\alpha\left(\frac{L_t}{K_t}\right)^{1-\alpha} \tag{32}$$

$$w_t = mc_t Y_t^{\frac{1}{\rho}}(1-\psi)\left(K_t^{\alpha}L_t^{1-\alpha}\right)^{\frac{-1}{\rho}}(1-\alpha)\left(\frac{K_t}{L_t}\right)^{\alpha} \tag{33}$$

$$p_t^E = mc_t Y_t^{\frac{1}{\rho}}\psi A_E^{\frac{\rho-1}{\rho}} E_t^{\frac{-1}{\rho}}. \tag{34}$$

B The social planner's problem

The social planner maximizes the utility of the five agents:

$$\max_{\{c^C_{i,t}, c^E_{i,t}, l_{i,t}, K_t, I^b_t, I^g_t\}_{i,t}} \quad \sum_i \frac{1}{5} \sum_{t=0}^{\infty} \beta^t \left[v(e_{i,t}, \tilde{p}^E_t) - g(l_{i,t}) \right], \tag{35}$$

where the indirect utility function and the disutility of labor are given by:

$$v(e_{i,t}, \tilde{p}^E_t) = \frac{1}{\varepsilon} \left[e^{\varepsilon}_{i,t} - 1 \right] - \frac{\nu}{\gamma} \left[\left(\tilde{p}^E_t \right)^{\gamma} - 1 \right] \quad \text{and} \quad g(l_{i,t}) = \mu \frac{l^{1+\phi}_{i,t}}{1+\phi}, \tag{36}$$

subject to the initial condition $K_0 = \bar{K}$ and a series of constraints:

1. the definition of expenditures for the agents (consequence of the indirect utility function):

$$e_{i,t} = c^C_{i,t} + p^E_t c^E_{i,t} \tag{37}$$

2. aggregation of their labor supply and consumption:

$$L_t = \frac{1}{5} \sum \xi_i l_{i,t}, \qquad c^C_t = \frac{1}{5} \sum c^C_{i,t}, \qquad c^E_t = \frac{1}{5} \sum c^E_{i,t}. \tag{38}$$

3. the aggregate production function:

$$Y_t = \left[(1-\psi) \left(K^{\alpha}_t L^{1-\alpha}_t \right)^{\frac{\rho-1}{\rho}} + \psi \left(A_E E_t \right)^{\frac{\rho-1}{\rho}} \right]^{\frac{\rho}{\rho-1}} \tag{39}$$

4. the production function for producing energy services:

$$Y^E_t = \hat{X}_t \left[\left(\theta^{\psi_E - 1}_t I^b_t \right)^{\frac{\rho_E - 1}{\rho_E}} + \left(\theta^{\psi_E}_t I^g_t \right)^{\frac{\rho_E - 1}{\rho_E}} \right]^{\frac{\rho_E}{\rho_E - 1}} \tag{40}$$

together with the definition of $\hat{X}_t$:

$$\hat{X}_t = \begin{cases} X_t \theta^{1-\psi_E}_t \left[\psi^{\zeta}_E + (1-\psi_E)^{\zeta} \theta^{-\mathcal{R}\zeta}_t \right]^{\frac{1}{\mathcal{R}\zeta}} & \text{if } \mathcal{R} \neq 0 \\ X_t \left(\psi^{\psi_E}_E (1-\psi_E)^{(1-\psi_E)} \right)^{\frac{\rho_E}{\rho_E - 1}} & \text{if } \mathcal{R} = 0. \end{cases} \tag{41}$$

5. the resource constraint for the output good:

$$c^C_t + K_{t+1} - (1-\delta) K_t + I^b_t + I^g_t = Y_t \tag{42}$$

6. the resource constraint for the energy services:

$$Y_t^E = \frac{c_t^E + E_t}{1 - \varphi_t} \tag{43}$$

and the constraint of permanently reducing GHG emissions by 85% in 25 years and beyond, i.e. $I_t^b / \bar{I}^b \leq 0.15 \; \forall \; t \geq 100$ (quarterly calibration), where $\bar{I}^b$ is the steady-state value in a world without any ambition to become climate neutral.

C Additional figures

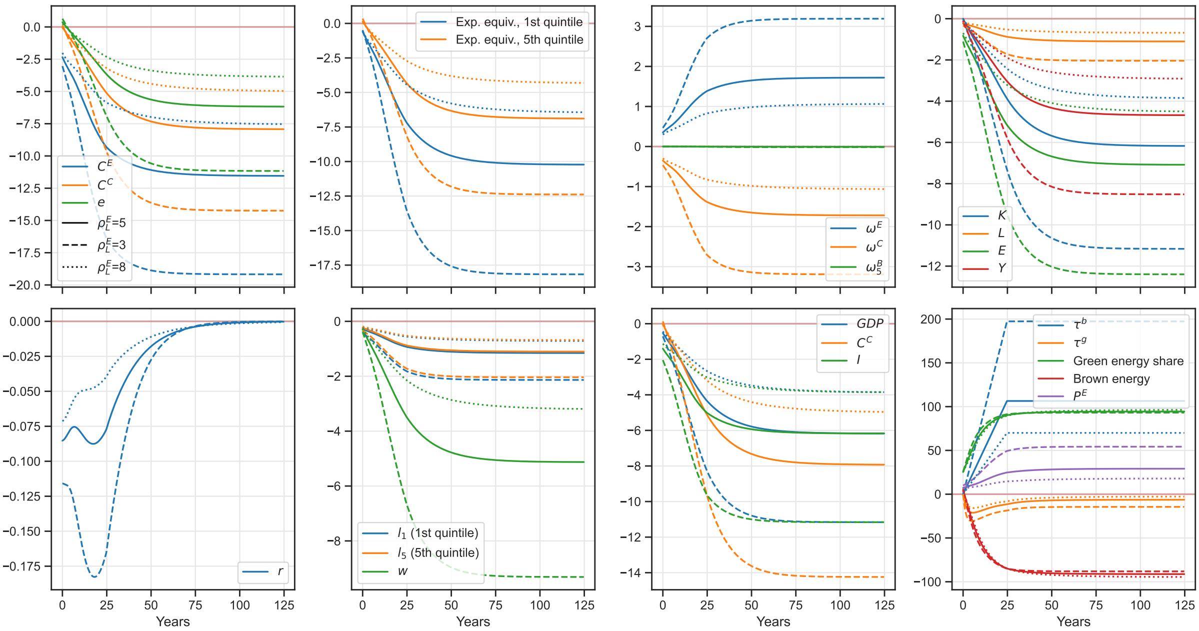

Figure 8: Sensitivity to the long-run elasticity of substitution between the brown and green technology ρ_E^{LR}.

Notes. The figure shows the percent deviations of the respective variables from their initial steady state. The deviations for the real interest rate is schown in annualized percentage point deviations.

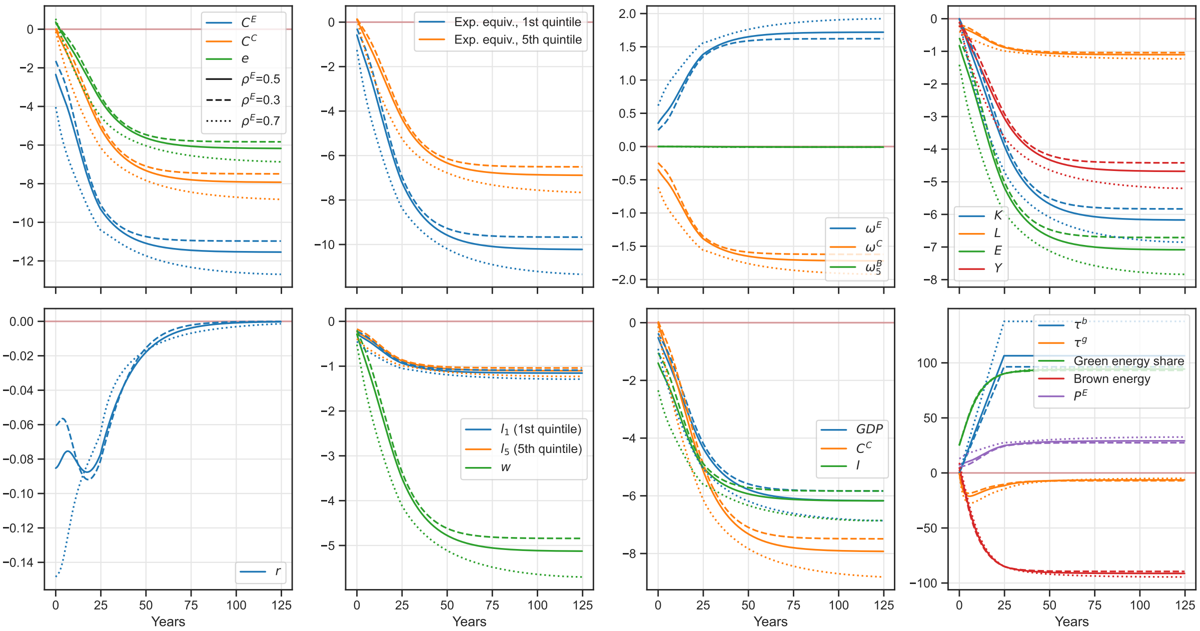

Figure 9: Sensitivity to the short-run elasticity of substitution between the brown and green technology ρ_E.

Notes. The figure shows the percent deviations of the respective variables from their initial steady state. The deviations for the real interest rate is schown in annualized percentage point deviations.

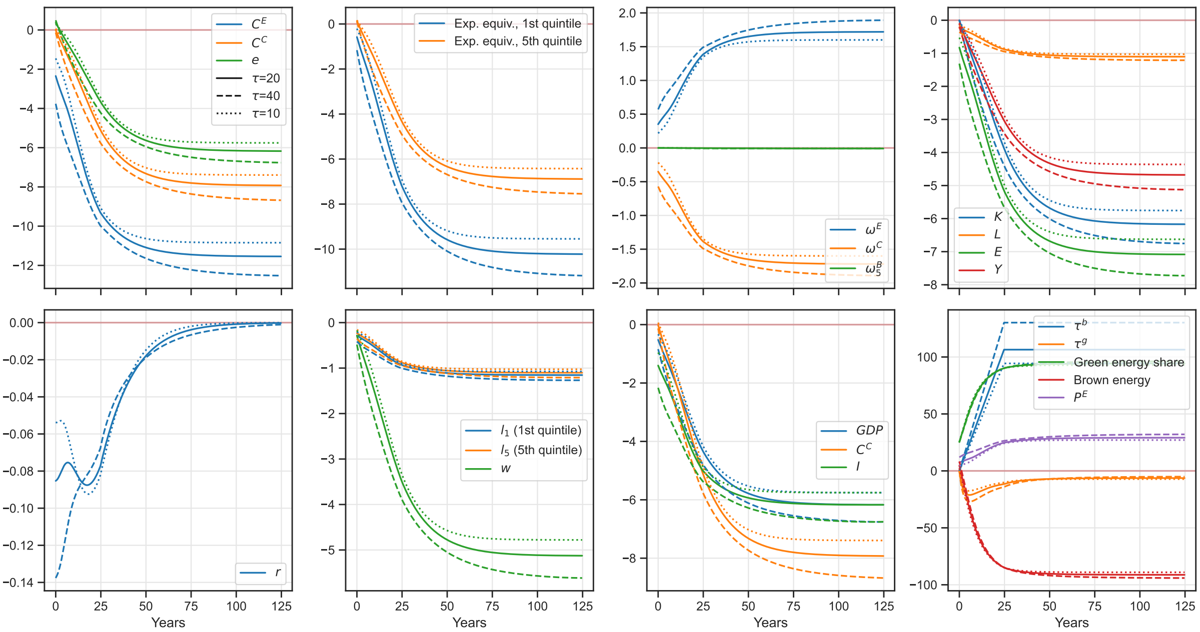

Figure 10: Sensitivity to the adjustment costs of the relative technology terms for energy producers τ.

Notes. The figure shows the percent deviations of the respective variables from their initial steady state. The deviations for the real interest rate is schown in annualized percentage point deviations.

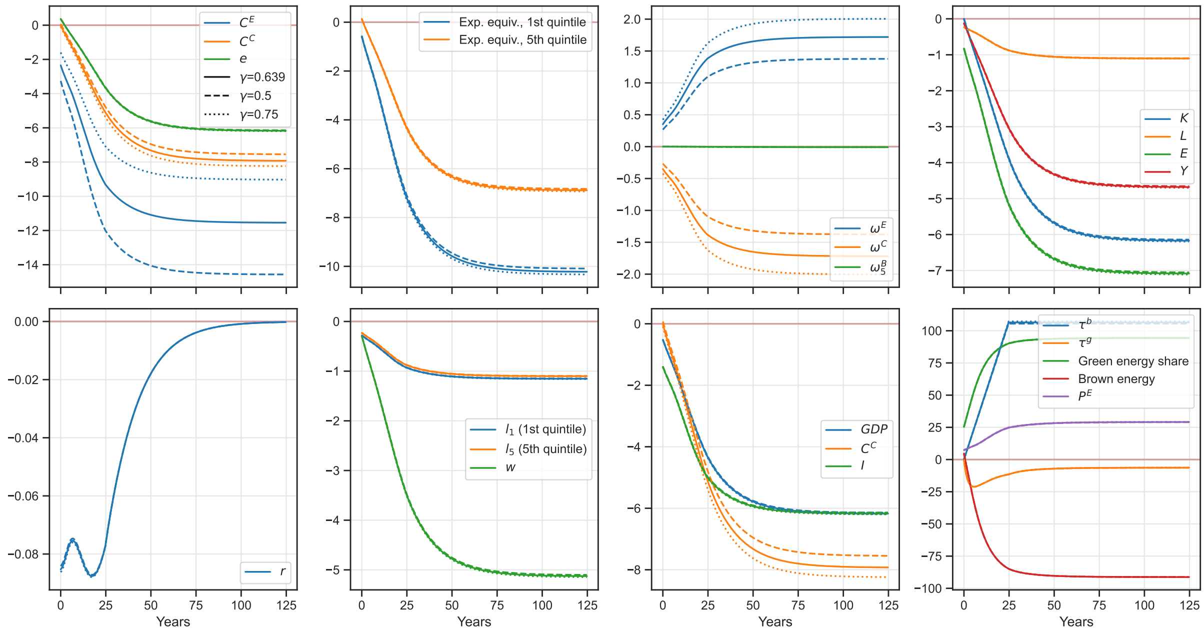

Figure 11: Sensitivity to the preference parameter γ.

Notes. The figure shows the percent deviations of the respective variables from their initial steady state. The deviations for the real interest rate is shown in annualized percentage point deviations.

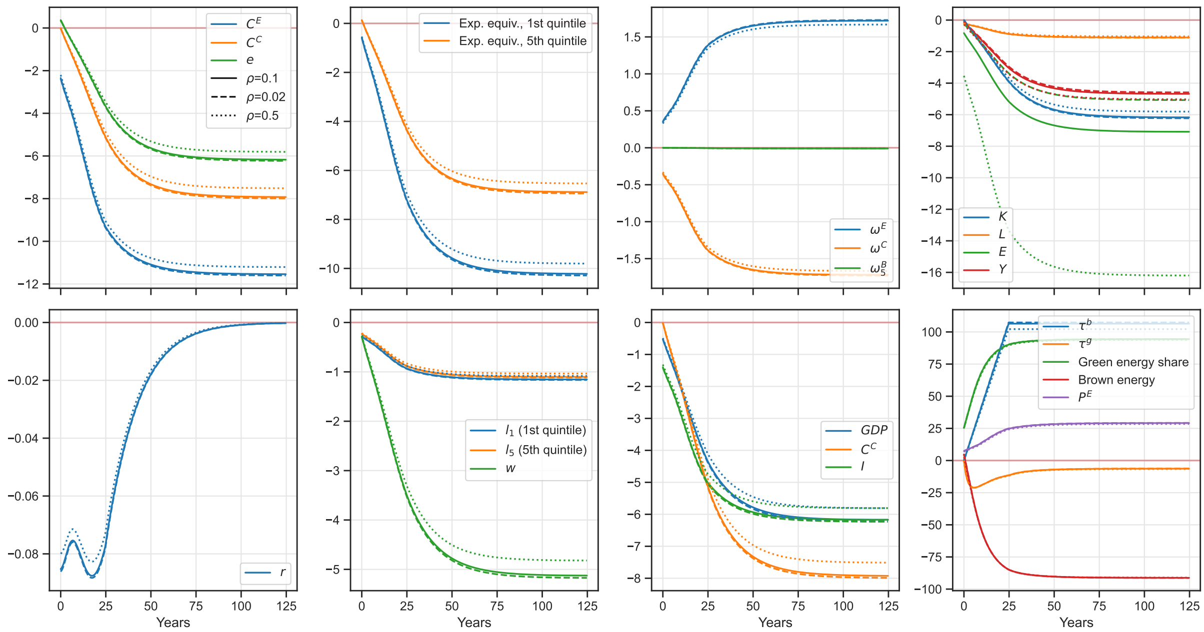

Figure 12: Sensitivity to the elasticity of substitution between the capital-labor aggregate and energy services ρ.

Notes. The figure shows the percent deviations of the respective variables from their initial steady state. The deviations for the real interest rate is shown in annualized percentage point deviations.