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, poorer 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 168% tax on the fossil-based technology. The output losses from this tax are substantial, and GDP is 9.3% lower in the new steady state. The burden falls primarily on the poor agent who is 50% more worse off than the rich agent. The output losses can be compensated for if the economy achieves a 1.49% annual 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

The transition to a more sustainable economy presents a critical policy challenge in many countries. In Europe, this transition is guided by legally binding frameworks such as the Fit-for-55 package, which aims to reduce net greenhouse gas (GHG) emissions by at least 55% by 2030 and achieve climate neutrality by 2050. Policies like the European Union's Emission Trading System (ETS), alongside other regulatory and fiscal measures, are designed to phase out environmentally harmful technologies while promoting innovation in cleaner alternatives. While there has been ample research on the aggregate effects of such policies, the distributional implications of these policies have not been extensively studied. Poor households, in particular, have a larger share of expenditures on emission-intensive energy goods. Therefore, it is reasonable to assume that the costs of this transition to a more sustainable economy may not be equally distributed. In this paper, we examine not only the aggregate effects but, in particular, the distributional consequences of a policy that directly raises the cost of emission-intensive technologies.

To study these effects, we develop a parsimonious macroeconomic general equilibrium framework with two agents and non-homothetic preferences over consumption and energy goods. 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 poor agent has a higher energy expenditure share than the rich agent. The parameter in the model controlling the degree of non-homotheticity can then easily be calibrated with empirical observations on household expenditures. 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.

We use the model 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 two agents in the initial steady state is set exogenously such that the rich agent holds all wealth in the economy, and the poor agent only consumes labor income. Importantly, the final steady state 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.

Our simulation results show that reducing emissions to the target outlined in the Fit-for-

55 package with only a tax on the brown technology requires a tax rate of 168% that is gradually introduced following a linear path over the next 25 years. Under the assumed elasticity of substitution between the brown and green technology for producing energy services, this leads to a 49% increase in the price of energy. This increase has substantial implications for aggregate consumption and output. GDP is 9.3% lower in the new steady state and compared to the rich agent the poor agent suffers about 50% more in terms of expenditure equivalent losses. The poor agent is permanently worse off partly due to the fact that its debt level increases by 38.8% of its annual income to finance consumption during the transition. The results turn out to be quite sensitive to the elasticity of substitution between the brown and green technology, and using alternative values of 2 or 5 instead of 3 can almost double or half the aggregate effects. Furthermore, a comparison with homothetic preferences yields that the aggregate effects are 26% smaller without any effects on inequality. This indicates that non-homothetic preferences are particularly important to consider when evaluating the distributional effects of this policy.

In this paper, we do not explicitly incorporate the damages from climate change; one reason for this is that the damages are likely not so large in European countries. An implication, however, is a rather striking difference in how different paths toward climate neutrality imply different costs: it is generally much better to delay taxation of carbon as long as possible, while announcing this decision immediately, since it will make the first 25 years less costly to endure. The final tax rate required to achieve the emission reduction target is only slightly higher than when the tax is raised slowly, and the aggregate output losses in the new steady state are similar. 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 emissions 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 136% and keeps the price of energy almost unchanged. Consequently, there are hardly any effects on aggregate output or inequality. In fact, GDP is even 1.1% higher in the new steady state, with the poor agent benefiting more from that. However, improvements in energy efficiency might not come for free, and therefore, the results should be interpreted accordingly.

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. (2024) 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 more 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 two-agent construct and complete markets; we can therefore fix wealth inequality at an empirically reasonable level by simply assuming an initial wealth distribution, whereas they 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. Third, in our analysis we do not consider transfer schemes to avoid negative consequences for inequality. 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.

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

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

2 Model

The model is kept very simple and consists of two households, one rich and one poor. 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. We choose this setup because in the absence of an open-economy model, it still captures the fact 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 only impose a tax or give a subsidy for the use of the two technologies to produce energy services. Moreover, it needs to run a balanced budget and cannot issue debt. A more detailed description of all the elements follows.

2.1 Households

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

$$V_{i,0} = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[v(E^H_{i,t}, P^E_t, P^C_t) - g(l_{i,t}) \right], \tag{1}$$

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 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:

$$v(E^H_{i,t}, P^E_t, P^C_t) = \frac{1}{\varepsilon}\left[\left(\frac{E^H_{i,t}}{P^C_t}\right)^{\varepsilon} - 1\right] - \frac{\nu}{\gamma}\left[\left(\frac{P^E_t}{P^C_t}\right)^{\gamma} - 1\right]. \tag{3}$$

with the parameters $\varepsilon, \gamma \in (0,1)$ and $\nu \geq 0$. Prices of the energy and consumption good are denoted P^E_t and P^C_t respectively and expenditures satisfy $E^H_{i,t} = P^E_t c^E_{i,t} + P^C_t c^C_{i,t}$. The household budget constraint is:

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

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, and current holdings of nominal bonds $B_{i,t}$ with gross return R_{t-1}. 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:

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

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]

Since the two 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 two 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 $\{P_t^E, P_t^C, R_t, W_t\}_t$, profits $\{\Pi_{i,t}\}_t$ 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 either.

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 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

[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.

equation for all unconstrained agents:

$$\frac{v_E(E^H_{i,t}, P^E_t, P^C_t)}{v_E(E^H_{i,t+1}, P^E_{t+1}, P^C_{t+1})} = \left(\frac{E^H_{i,t+1}}{E^H_{i,t}}\right)^{1-\varepsilon} \left(\frac{P^C_{t+1}}{P^C_t}\right)^{\varepsilon} = \beta R_t, \tag{7}$$

which we can also write in real terms as:

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

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:

$$c^E_{i,t} = -\left(\frac{\partial v}{\partial P^E_t} \Big/ \frac{\partial v}{\partial E^H_{i,t}}\right) = \frac{E^H_{i,t}}{P^E_t}\left[\nu \left(\frac{P^C_t}{E^H_{i,t}}\right)^{\varepsilon} \left(\frac{P^E_t}{P^C_t}\right)^{\gamma}\right], \tag{9}$$

$$c^C_{i,t} = -\left(\frac{\partial v}{\partial P^C_t} \Big/ \frac{\partial v}{\partial E^H_{i,t}}\right) = \frac{E^H_{i,t}}{P^C_t}\left[1 - \nu \left(\frac{P^C_t}{e_{i,t}}\right)^{\varepsilon} \left(\frac{P^E_t}{P^C_t}\right)^{\gamma}\right] \tag{10}$$

or in real terms:

$$c^E_{i,t} = \frac{e_{i,t}}{p^E_t}\left[\nu e_{i,t}^{-\varepsilon} \left(p^E_t\right)^{\gamma}\right] \tag{11}$$

$$c^C_{i,t} = e_{i,t}\left[1 - \nu e_{i,t}^{-\varepsilon} \left(p^E_t\right)^{\gamma}\right] \tag{12}$$

with the corresponding expenditure shares on energy $\omega^E_{i,t}$ and consumption $\omega^C_{i,t}$ 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 good a necessity good and the consumption good a luxury good.

The labor supply decision. The derivation of the first-order condition for labor supply

[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:

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

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-good-producing firm

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

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

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 the energy good, and A_t^g and I_t^g are the respective variables for the green (or emission-free) technology. 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.

The firm's cost-minimization problem gives the cost of producing Y_t^E units of the energy good as:

$$S^E(Y_t^E) = \min_{I_t^b, I_t^g} (1+\tau_t^b) I_t^b + (1+\tau_t^g) I_t^g \quad \text{s.t.: (14)}. \tag{15}$$

Thus, the price of one effective unit of brown energy is given by $\frac{1+\tau^b}{A_t^b}$ and for the green technology by $\frac{1+\tau^g}{A_t^g}$. From cost-minimization, we have that the price of one unit of the energy good is $p_t^E = \partial S_t^E(Y_t^E)/\partial Y_t^E$ and given by:

$$p_t^E = \left[(1-\psi_E)^{\rho_E} \left(\frac{1+\tau_t^b}{A_t^b} \right)^{1-\rho_E} + \psi_E^{\rho_E} \left(\frac{1+\tau_t^g}{A_t^g} \right)^{1-\rho_E} \right]^{\frac{1}{1-\rho_E}} \tag{16}$$

and their demand for inputs into the green and brown technology as:

$$I_t^g = \frac{(\psi_E)^{\rho_E}}{A_t^g}\left[\left(\frac{1+\tau_t^g}{A_t^g p_t^E}\right)\right]^{-\rho_E} Y_t^E \tag{17}$$

$$I_t^b = \frac{(1-\psi_E)^{\rho_E}}{A_t^b}\left[\left(\frac{1+\tau_t^b}{A_t^b p_t^E}\right)\right]^{-\rho_E} Y_t^E. \tag{18}$$

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:

$$Y_t = \left[(1-\psi)\left(K_t^\alpha L_t^{1-\alpha}\right)^{\frac{\rho-1}{\rho}} + \psi\left(A_E E_t\right)^{\frac{\rho-1}{\rho}}\right]^{\frac{\rho}{\rho-1}} \tag{19}$$

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:

$$S_t(Y_t) = \min_{K_t, L_t, E_t} r_t^k K_t + w_t L_t + p_t^E E_t \quad \text{s.t.: (19)}. \tag{20}$$

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

$$mc_t = \left[(1-\psi)^\rho \left(\left[\frac{r_t^k}{\alpha}\right]^\alpha \left[\frac{w_t}{(1-\alpha)}\right]^{1-\alpha}\right)^{1-\rho} + \left(\psi A_E^{\frac{\rho-1}{\rho}}\right)^\rho \left(p_t^E\right)^{1-\rho}\right]^{\frac{1}{1-\rho}}. \tag{21}$$

This leads to the standard first-order conditions:

$$r_t^k = mc_t Y_t^{\frac{1}{\rho}} (1-\psi)\left(K_t^\alpha L_t^{1-\alpha}\right)^{\frac{-1}{\rho}} \alpha \left(\frac{L_t}{K_t}\right)^{1-\alpha} \tag{22}$$

$$w_t = mc_t Y_t^{\frac{1}{\rho}} (1-\psi)\left(K_t^\alpha L_t^{1-\alpha}\right)^{\frac{-1}{\rho}} (1-\alpha) \left(\frac{K_t}{L_t}\right)^{\alpha} \tag{23}$$

$$p_t^E = mc_t Y_t^{\frac{1}{\rho}} \psi A_E^{\frac{\rho-1}{\rho}} E_t^{\frac{-1}{\rho}}. \tag{24}$$

These 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 and to subsidize the use of the emission-free energy technology in the same period. Therefore, the government's budget constraint needs to satisfy:

$$\tau_t^b I_t^b = -\tau_t^g I_t^g \quad \iff \quad \tau_t^g = -\tau_t^b \frac{I_t^b}{I_t^g}. \tag{25}$$

2.4 Market clearing and equilibrium definition

The productivity terms A_t^g and A_t^b of the energy producing firm is exogenously given and together with a given tax-policy for τ_t^b and τ_t^g pins down the price of energy. Thus, we can take $\{p_t^E\}_t$ as exogenously given.

Aggregating the demand for consumption and energy from households, we get that $c_t^C = \frac{1}{2}\sum_i c_{i,t}^C$ and $c_t^E = \frac{1}{2}\sum_i c_{i,t}^E$. Likewise, aggregate bond holdings are $b_t = \frac{1}{2}\sum_i b_{i,t}$ and need to equal capital demand: $b_t = K_t$. Further, aggregate labor supply needs to equal labor demand: $\frac{1}{2}\sum_i \xi_i l_{i,t} = L_t$.

Market clearing of the energy good implies:

$$Y_t^E = E_t + c_t^E. \tag{26}$$

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. For robustness (but not in our benchmark), we also entertain a formulation with adjustment costs to investment equaling $\frac{\chi}{2}\left(\frac{K_{t+1}}{K_t} - 1\right)^2 K_t$.

Given the price of energy $\{p_t^E\}_t$ and initial wealth share $\omega_1^B \equiv \frac{b_{1,0}}{b_{1,0}+b_{2,0}}$ of agent $i = 1$ are exogenously given, we can define an equilibrium as a set of endogenous prices $\{r_t, w_t\}_t$ and 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 $\{E_t\}_t$, 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 firm's first order conditions in (22), (23), and (24) 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. 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.[5]

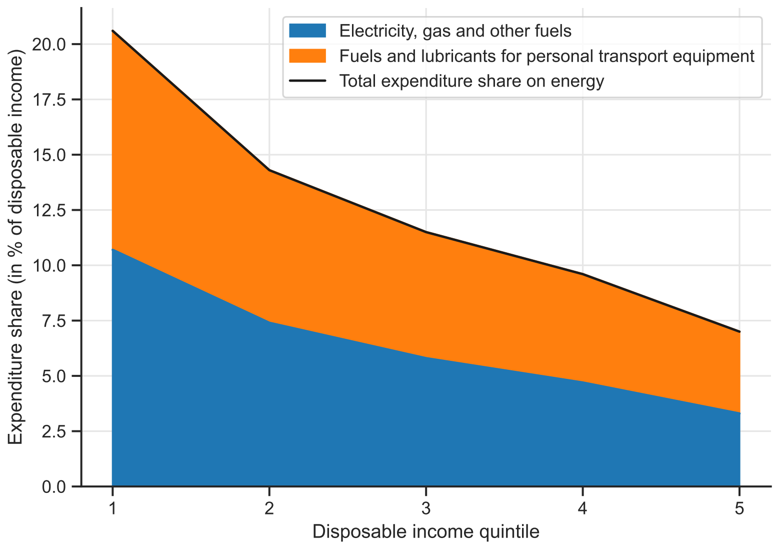

Figure 1: Household's expenditure share on energy by income.

Notes. Data from Eurostat (Experimental statistics on income, consumption and wealth) for 2015, which compiles information from the Household Finance and Consumption Survey (HFCS).

Figure 1 shows the expenditure share of two consumption categories that we interpret as representing expenditures on energy. The figure shows that the bottom income quintile

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

has a more than twice as high expenditure share on energy than the top income quintile and this holds for both sub-components individually as well. In order to map this into steady-state expenditure shares of the two agents in our model, we roughly calibrate the expenditure share on energy for the poor agent to be around 18% and 7.5% for the rich agent. We do this by choosing appropriate parameter values for ε and ν, such that we match the resulting steady-state expenditure shares. The remaining parameter value 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.[6] The estimation delivers a value of $\gamma = 0.639$, which implies an elasticity of substitution (EoS) between consumption goods and energy goods $\sigma(e)$ of just below 0.4. Note that this elasticity is dependent on the level of income and slightly lower for the rich agent.[7] This elasticity is well in line with the low elasticity of substitution also found in Hassler et al. (2021a).

We continue with the calibration of the wealth and income inequality. Taking the stylized facts on inequality from Krueger et al. (2016), which roughly hold for Europe as well, and mapping them into the two agents of the model, we first postulate that the rich agent holds all the wealth while the poor agent holds zero net assets. This informs the exogenous wealth share ω_1^B of the model. Note that there exists a range of different initial steady states depending on our assumed exogenous wealth share. Second, we use the permanent labor productivity of the two agents ξ_i to target that 25% of aggregate expenditures can be attributed to the poor agent.

On the production side, there are two key parameters. One is the elasticity of substitution between the brown and the green energy technology, ρ^E, which we set to 3 following the estimates of 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). The two share-parameters in the respective CES-production functions ψ_E and ψ are broadly inconsequential since we use the respective productivity terms A^b, A^g, and A_E to target the fact that 10% of output is spent on energy in developed economies (see Box 1.2 in OECD, 2022) and 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. The parameters for the New Keynesian version of the model refer to the model extension described in Appendix B.

[6] The data comes from the Consumption Expenditure Survey (CEX).

[7] The precise values for the elasticity of substitution between consumption and energy goods are 0.374 for the rich agent and 0.396 for the poor agent.

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	0.7969	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	13.409	Level shifter for the expenditure share of c^E	target exp. share in the data
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_1	1	Labor productivity of agent 1	normalization
ξ_2	0.6578	Labor productivity of agent 2	target: 25 % of agg. expenditures
ω_1^B	1	Initial wealth share of agent 1	our assumption
ρ^E	3	EoS b/w brown and green energy technology	Papageorgiou et al. (2017)
ψ_E	0.5	Share parameter for I^g in energy production	our assumption
A^b	2.457	Productivity of brown technology	24.5% of energy from renewables
A^g	1.4	Productivity of green technology	24.5% of energy from renewables
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	21.3121	Productivity for E in the production function	10 % of output spent on energy
New Keynesian version (for model in the appendix)			
σ	10	Demand elasticity intermediate good producers	profit share of 10 percent
ζ	200	Price adjustment cost	slope of Philips curve, $\sigma/\zeta = 0.05$
χ	0 (10)	Investment adjustment costs	our assumption(s)
ϕ_π^C	1.6	Coefficient on π^C in the Taylor rule	standard

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 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 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. We re-distribute the tax revenues as a subsidy on the green technology rather than as a transfer to households to capture the fact that the rather small tax revenues from the ETS systems are primarily used to finance the green transition. 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.

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 two 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 two 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 two groups during the transition period. Our solution method, which is fully non-linear, thus cannot rely on solving backwards from a known steady state.

4.1 Baseline transition path

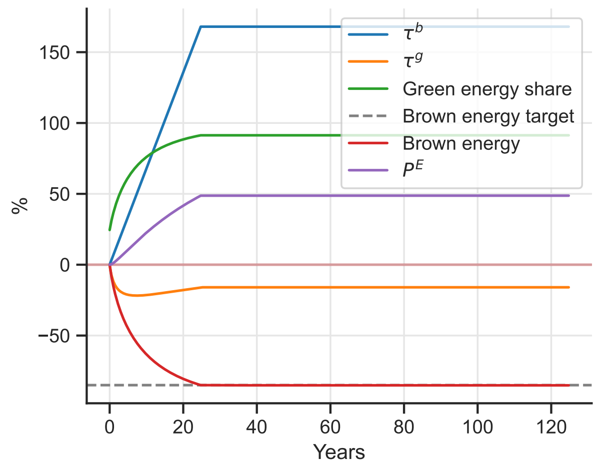

Figure 2: Transition path for taxes, price of energy, and energy usage.

Notes. Model simulation of a gradual introduction of a 168% tax on the brown technology τ_t^b.

Figure 2 shows that a final value of a 168% 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. This implies that the effective price of fossil fuels needs to almost triple in order to meet the target emissions reduction. Along this transition path, the final price of energy p^E relative to consumption goods increases by about 49%, 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. But as the green energy share in the economy increases and fewer tax revenues can be generated from the brown technology, also the subsidies decline.

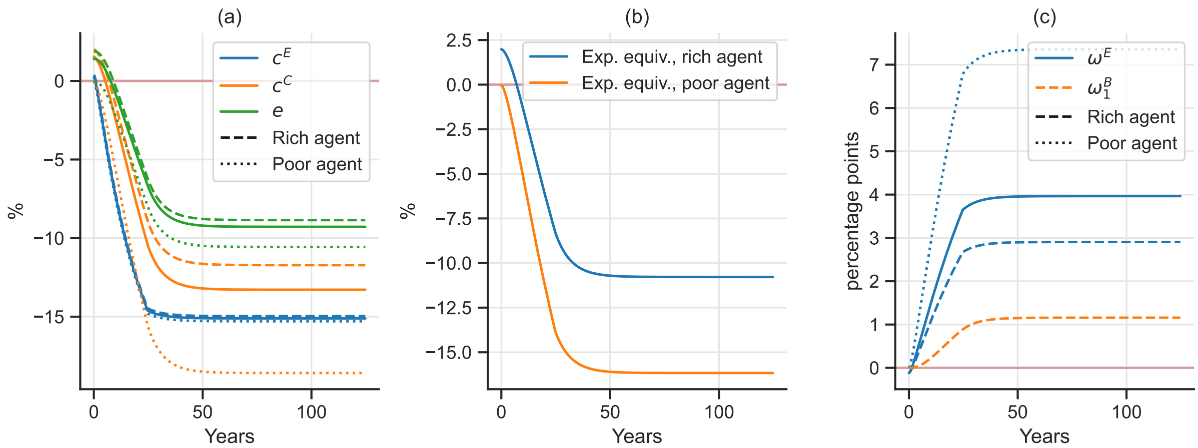

Figure 3: Transition path for consumption, expenditures, expenditure equivalent, expenditure share on energy of the two agents as well as the wealth share of the rich agent.

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 rich and poor agents, respectively. 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.

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), both agents reduce their energy consumption $c_{i,t}^E$ by about 15% compared to the initial steady state. The response is very similar among the two agents because energy is a necessity good. However, the response of the consumption good $c_{i,t}^C$ differs more between the two agents, with a substantially larger drop for the poor agent. The poor agent has a higher exposure to the increase in energy prices because of the higher expenditure share on energy. Therefore, the poor 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, which increases the poor agent's expenditure share on energy further. Interestingly, we can also see that consumption of the consumption good as well as total expenditures for the rich agent immediately jump to about a 2% higher level. This is because the rich agent is permanently better off in the new steady state and has a higher ability to front-load consumption.

Next, we are looking at these dynamics from the perspective of equivalent expenditures, i.e. the necessary change in only expenditures of the two agents in the initial steady state without the tax such that they receive the same flow utility as 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 10.8% in equivalent expenditures for the rich agent and 16.2% drop for the poor agent, which is a 50% larger drop for the poor agent than the rich agent.

Figure 3, panel (c), shows the expenditure share on energy ω^E for the two agents along with the wealth share of the rich agent ω_1^B. While the expenditure share on energy merely reflects the dynamics visible in panel (a), the wealth share of the rich agent reveals interesting shifts in the wealth distribution between the two agents. Since the rich agent already holds all wealth in the initial steady state, a further increase in its wealth share implies indebtedness of the poor agent. In fact, the poor agent took up quite sizable debt in the amount of 38.8% of its annual income in the new steady state.

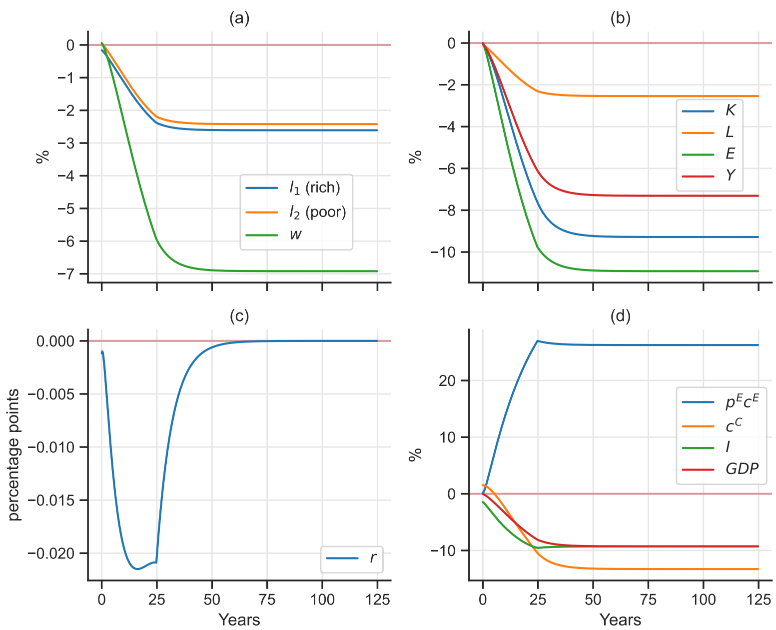

Figure 4: Transition path for labor supply, wages, output and its factor inputs, the real interest rate and GDP with its components.

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 percentage deviations.

Turning to the labor supply of the two agents, Figure 4, panel (a), shows a relatively similar decline for both agents in response to the almost 7% decline in the real wage. The rich agent decreases its labor supply by 0.2 p.p. more than the poor agent, reflecting the fact that the decline in expenditures is also smaller for the rich agent in the new steady state.

On the side of the production of the output good in Figure 4, panel (b), we can see that the price increase of energy also leads to a 10.9% reduction as a factor input in production. Since the capital-labor aggregate is highly complementary in production, also 9.3% less capital is used. The drop in labor as an input is much smaller at 2.5%, which comes from the fact that the wage rate drops so much. In contrast, the real interest rate is almost unaffected and temporarily drops only by 0.02 percentage points. In total, aggregate output is reduced by 7.3%. However, as panel (d) of Figure 4 shows, the drop in GDP is actually much larger at 9.3%. This is because a larger share of the aggregate output in the new steady state is used to convert them into energy services. This comes from the fact that the brown and green technology are not perfect substitutes for producing energy services. Intuitively, this can also be thought of reflecting the more difficult storage capacity of green energy sources in the real world.

We note, finally, and none of the time paths we just reported are much affected by the introduction of adjustment costs to investment (by raising χ from 0 to 10). This is not surprising as the tax rate is also changing very smoothly in our benchmark.

4.2 Alternative transition paths

The gradual and linear introduction of the tax τ_t^b is somewhat arbitrary but 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 three alternative transition paths. One scenario considers an immediate introduction of a permanent tax after one year of the announcement, the second a full and permanent introduction after 12.5 years of the announcement and the third an introduction after 25 years of the announcement. Given the differences in the timing of the introduction of the tax, it is also necessary to adjust the level of the tax in order to hit the target of a 85% reduction in emissions. However Figure 5, panel (a), shows that the necessary tax rates are all very close to each other; the scenario in which the tax is not introduced until 25 years into the transition requires a tax rate of 172% instead of the 168% of the baseline. This also implies that the bulk of the reduction in emissions occurs much earlier for the first two scenarios. Indeed, the emissions in the scenario where the tax is introduced already after one year achieves a 84.3% reduction in emissions after the first year. However, since the emissions do not feed back into the economy—we do not model climate damages here—an earlier attainment of the emission reduction target delivers no welfare advantage. This is also confirmed by the following analysis.

When we use a simple welfare measure (the change in utility measured in terms of an average change in expenditures per period) for the two agents over the transition period in

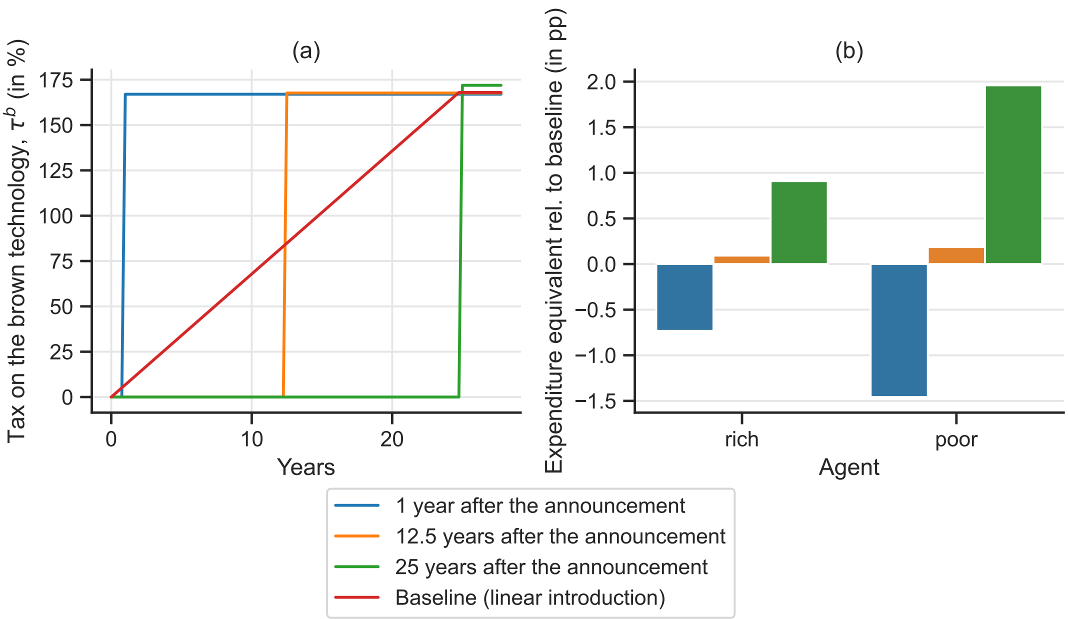

Figure 5: Alternative scenarios for the introduction of the tax τ_t^b with a welfare comparison.

Notes. Welfare for each agent is defined in terms of the average per-period expenditure change relative to baseline.

Figure 5, panel (b), 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, it is always better—and significantly so—-to transition to the new steady state as late as possible (for the poor there is a close to 3.5 percentage-point difference between late and early implementation). Second, the welfare implications are much starker for the poor agent than for the rich agent, as indicated by the percentage deviations of welfare from the linear baseline case. This is intuitive, as the tax on the brown technology affects the poor agent more due to their higher exposure to energy prices. Hence, the tax is regressive. Third, introducing the tax gradually as compared to a quick introduction from one period to the next does not seem to have any obvious welfare benefits and yield very similar welfare measures. The last point is certainly only true in this simple model setup. In a more realistic setup, such a quick introduction of a tax can be expected to introduce substantial reaction in the economy and threaten its stability even though the policy change is announced well in advance. The zero adjustment costs to investment in the benchmark of our model make this issue small, but in our robustness check, where we introduce such a cost (recall that we then raise χ from 0 to 10), we do observe a different marked outcome: the real interest rate plummets, in the very short run. This, of course, is because the capital stock is suddenly too high, and the interest rate adjusts to reflect this fact, but no major effect is seen on quantities: the adjustment costs prevent this. Hence, the higher adjustment costs do not play a major role for welfare.

4.3 Sensitivity with respect to the elasticity of substitution between the brown and green technology

One of the key parameters in the model is ρ^E, which controls how easy it is to substitute the brown technology use with the green technology use. In the baseline we calibrate this value to estimates in Papageorgiou et al. (2017), 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.

We now consider two alternative values for the elasticity of substitution between the brown and green technology, ρ^E. First, we use a higher elasticity with $\rho^E = 5$ and, second, a lower value of $\rho^E = 2$. Although these are relatively small deviations from the baseline value of $\rho^E = 3$, 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.

	Baseline	High elasticity	Low elasticity
Elasticity of substitution: ρ^E	3	5	2
Necessary τ_t^b to meet target	167.98	78.63	354.44
Corresponding increase in p^E	48.72	23.92	98.04
Change in GDP	-9.28	-4.69	-17.70
Expenditure equivalent, rich agent	-10.78	-5.47	-20.46
Expenditure equivalent, poor agent	-16.16	-8.25	-30.29
Poor agent's debt (as % of annual income)	38.82	18.95	78.35

Notes. All numbers except ρ^E and the poor agent's debt 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. Increasing the elasticity of substitution ρ^E to 5 cuts the necessary tax roughly in half, and lowering ρ^E to 2 doubles it. The same holds for the increase in 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 single parameter.

4.4 The role of non-homothetic preferences

A key feature in this paper is its application of non-homothetic preferences on the consumption side. This is important for capturing the differences in the expenditure shares on energy between the poor and the rich agents. 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.

We illustrate the impact of this non-homotheticity in our model by setting $\varepsilon = 0$ in the PIGL indirect utility function. This 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 make ν individual-specific and adjust it to 0.075 and 0.18 for the rich and the poor agent.[8] This allows us to replicate the same expenditure shares on energy for the rich and the poor agent as in the baseline. We also adjust γ to 0.556 to match the same aggregate elasticity of substitution between the energy good and the consumption good as in the baseline. Hence, we depart from the identical initial steady state and any differences to the baseline are coming from non-homothetic preferences instead of differing expenditure shares.

The aggregate responses in a transition with homothetic preferences differ quite substantially from the baseline. GDP is only 6.9% lower (compared to 9.3% in the baseline). The main reason for why the GDP losses are smaller in the homothetic variant is because labor supply returns to the same level as in the initial steady state. This results from a change in ε, which causes the income and substitution effects of a wage rate change to offset each other. Although the wage rate in the new steady state falls to the same level as in the baseline model, labor supply is unaffected, which leads to a higher overall level of output.

Taking a closer look at the consumption side, Figure 6, panel (a), shows that the drop in aggregate energy consumption is much stronger in the homothetic version than in the baseline version. Consequently, this allows both agents to have a higher level of consumption of the consumption good. Note that this figure does not show the response of the individual agents as they are very close to each other and almost identical to the aggregate response.

The distributional consequences are quite different as well: the effects are now much smaller than in the benchmark. Figure 6, panel (b), shows that the difference in the expenditure equivalent between the two agents is almost zero. Therefore, both agents are affected by the transition in almost the same way. Looking at the changes in the wealth shares in panel (c) of Figure 6 also shows much smaller deviations. The poor agent only

[8]The difference in ν can be interpreted as different tastes for the energy and consumption good between the two agents. Alternatively, we can also give both agents the same aggregate expenditure share on energy as in the baseline, which does not require us to make ν individual-specific. We tried both versions and the results are almost indistinguishable.

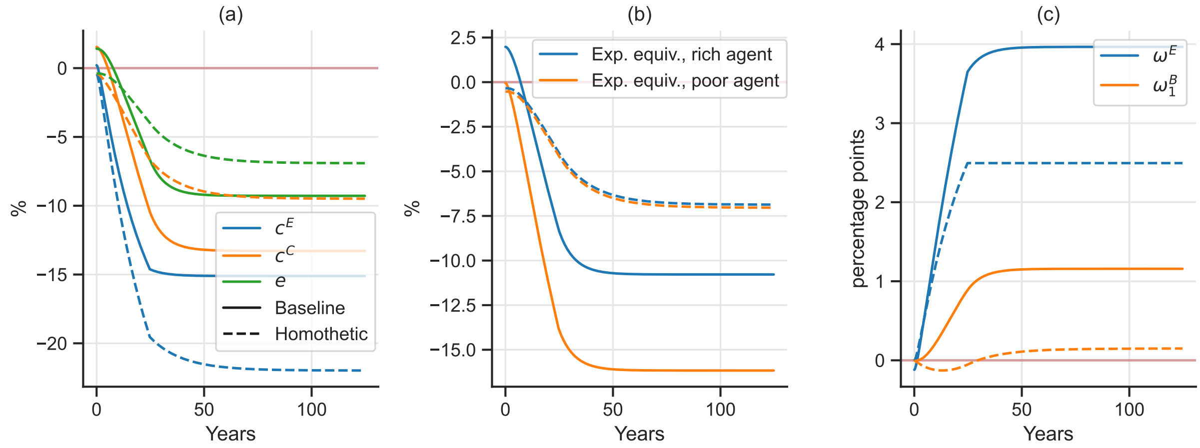

Figure 6: Comparison of the transition with homothetic instead of non-homothetic preferences.

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.

accumulates around 5% of annual income as debt over the transition period. Interestingly, the poor agent first accumulates some wealth before taking up some debt.

Therefore, we can conclude that a transition to a climate-neutral economy in our framework only has quantitatively significant distributional consequences if preferences are indeed non-homothetic. With homothetic preferences, but maintaining differing expenditure shares on energy, the transition affects the two agents in almost identical ways.

4.5 Considering an improvement in energy efficiency

The Fit-for-55 package also contains a binding target for energy efficiency. It says that each EU member country needs 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 exogenously increase the total factor productivity of the energy-good-producing firm. That is, we are scaling A_t^b and A_t^g by 1.49% annually during the transition in the first 25 years. The energy-good-producing firm ends up having a 45% higher productivity 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 on the brown technology with a different final value to achieve the same 85% reduction in emissions. With a simultaneous increase in energy efficiency, a 136.3% tax on the brown technology achieves the required reduction in emissions without a reduction of output.

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	167.98	136.31
Corresponding increase in p^E	48.72	-5.5
Change in GDP	-9.28	1.11
Expenditure equivalent, rich agent	-10.78	1.31
Expenditure equivalent, poor agent	-16.16	1.97
Poor agent's debt (as % of annual income)	38.82	-4.01

Notes. All numbers except the poor agent's debt report the percent deviations of the new steady state compared to the initial steady state.

The aggregate and distributional consequences from a transition with a simultaneous increase in energy efficiency are substantially different. First, GDP even increases by 1.1% compared to the 9.3% loss in the baseline. Table 3 also compares other variables in the new steady state to the baseline. It shows that the price of energy even decreases by 5.5% and that the poor agent gains more. In fact, the poor agent accumulates some assets in the amount of 4% of annual income.

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 a 42.2% improvement in energy efficiency over the first 25 years or 1.42% annually with a 137.9% tax on the brown technology. This scenario maintains a relative price of energy p^E at unity without any GDP losses and practically no distributional consequences.

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.

5 Conclusions

The necessary tax on the emission-intensive brown technology needed to transition to a new climate-neutral steady state in the baseline of our model framework is 168% . The implied reduction in emissions is 85% compared to the initial steady state and increases the price of energy by 49%. Consequently, GDP drops by around 9.3%. The welfare costs are disproportionally borne by the poor, who suffer a loss in expenditure equivalent of 16.2% compared to the initial steady state, which is 50% higher than the loss for the rich. The distributional consequences of the tax are thus substantial. Furthermore, to finance consumption during the transition, the poor agent ends up accumulating debt equal to 38.8% of their annual income. One caveat of these quantitative results is that they are quite sensitive to the assumed elasticity of substitution between the brown and green technologies. Unfortunately, good empirical evidence for this elasticity is scarce, and one has to acknowledge the uncertainty around these estimates and how exactly they map into our model framework.

In the baseline, we consider a gradual increase in the tax on the brown technology. Comparing the welfare effects of alternative paths for the introduction of the tax shows that it is optimal to introduce the tax as late as possible, with an announcement as early as possible. The level of the tax needed is not influenced more than marginally by different timing assumptions. Therefore, taking solely economic efficiency into account, it is optimal to remain in the good state for as long as possible, while achieving the target of becoming climate-neutral within 25 years with a minimally higher final tax rate. Of course, if the climate damages were to be taken into account as well, one may reach a different conclusion. The flow damages caused by warming will remain the same after 25 years, given that the total accumulated emissions are the same by then. An updated account of climate science asserts that the temperature at a future point in time depends (almost) only on the total, historically accumulated emissions up to that point. However, the same reasoning also implies higher damages during the first 25 years if the emissions reductions are not made until after 25 years, because such a path would imply a warmer path during the transition. This negative consequence of delaying taxation would likely outweigh the economic efficiency gains, as we suspect that the optimal carbon tax is roughly proportional to output in our model, as in Golosov et al. (2014). It should thus be high from the very beginning, at least absent significant adjustment costs.

Non-homothetic preferences play a crucial role in shaping both the aggregate responses and the distributional consequences. In a model version with purely homothetic preferences but different expenditure shares on energy across the two agents, the aggregate responses are 26% smaller and has an almost identical impact on the welfare of the two agents. This shows that it is very important to take non-homothetic preferences into account when analyzing the transition to a new climate-neutral steady state. However, the introduction of non-homothetic preferences also complicates the analysis if one wishes to integrate long-run growth into the framework, especially if the model-setup does not allow for a balanced growth path.

The Fit-for-55 package also contains targets for the improvement in energy efficiency for each EU member country. Therefore, we also consider a scenario in which energy efficiency increases by 1.49% annually during the transition. This reduces the necessary tax rate to 136% and even over-compensates for the output losses such that GDP is 1.1% higher in the new steady state with the poor agent benefiting slightly more from these gains. One limitation of the paper is that it does not feature endogenous growth for the productivity of the brown and green technology. This is particularly important when considering improvements in energy efficiency, because the assumed exogenous growth in this setup might not come without additional costs. This would be fruitful to explore in further research on this topic.

Although the transition to a climate-neutral economy may incur considerable output losses and changes in inequality, the overall effects may not be as detrimental, depending on the degree of energy efficiency ultimately achieved. Overall, if seen over the entire transition period and relative to a growth path, the transition might affect aggregates, but the per-period effects can probably be endured.

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Appendix

A The social planner's problem

The social planner maximizes the utility of the two agents:

$$\max_{\{c^C_{i,t}, c^E_{i,t}, l_{i,t}, K_t, I^b_t, I^g_t\}_{i,t}} \quad \sum_i \frac{1}{2} \sum_{t=0}^{\infty} \beta^t \left[v(e_{i,t}, \tilde{p}^E_t) - g(l_{i,t}) \right], \tag{29}$$

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

$$v(e_{i,t}, \tilde{p}^E_t) = \frac{1}{\varepsilon} \left[e^{\varepsilon}_{i,t} - 1 \right] - \frac{\nu}{\gamma} \left[\left(\tilde{p}^E_t \right)^{\gamma} - 1 \right] \quad \text{and} \quad g(l_{i,t}) = \mu \frac{l^{1+\phi}_{i,t}}{1+\phi}, \tag{30}$$

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

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

$$e_{i,t} = c^C_{i,t} + p^E_t c^E_{i,t} \tag{31}$$

2. aggregation of their labor supply and consumption:

$$L_t = \frac{1}{2} \sum \xi_i l_{i,t}, \qquad c^C_t = \frac{1}{2} \sum c^C_{i,t}, \qquad c^E_t = \frac{1}{2} \sum c^E_{i,t}. \tag{32}$$

3. the aggregate production function:

$$Y_t = \left[(1-\psi) \left(K^{\alpha}_t L^{1-\alpha}_t \right)^{\frac{\rho-1}{\rho}} + \psi \left(A_E E_t \right)^{\frac{\rho-1}{\rho}} \right]^{\frac{\rho}{\rho-1}} \tag{33}$$

4. the production function for producing energy services:

$$Y^E_t = \left[(1-\psi_E) \left(A^b_t I^b_t \right)^{\frac{\rho_E-1}{\rho_E}} + \psi_E \left(A^g_t I^g_t \right)^{\frac{\rho_E-1}{\rho_E}} \right]^{\frac{\rho_E}{\rho_E-1}} \tag{34}$$

5. the resource constraint for the output good:

$$c^C_t + K_{t+1} - (1-\delta) K_t + I^b_t + I^g_t = Y_t \tag{35}$$

6. the resource constraint for the energy services:

$$Y_t^E = c_t^E + E_t \tag{36}$$

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

B The New Keynesian model-extension

In the New-Keynesian version of the model, the output-good-producing firm of the main text becomes one variant of an intermediate good that is eventually combined by a perfectly competitive final-good-producing firm combining all the intermediate goods.

B.1 Final-good producing firms

A representative final-good producing firm combines intermediate goods $Y_{j,t}$ indexed by $j \in [0,1]$ using a CES production technology:

$$Y_t = \left(\int_0^1 Y_{j,t}^{\frac{\sigma-1}{\sigma}} dj \right)^{\frac{\sigma}{\sigma-1}} \tag{37}$$

where σ is the elasticity of substitution across goods. Given a level of aggregate demand Y_t, cost minimization for the final goods producer implies that the demand for the intermediate good j is:

$$Y_{j,t} = Y(p_{j,t}; P_t^C, Y_t) = \left(\frac{p_{j,t}}{P_t^C} \right)^{-\sigma} Y_t \tag{38}$$

where $p_{j,t}$ is the price of the intermediate good and P_t^C the price of the final consumption good, which can be written in the standard way as the CES price index of the intermediate goods:

$$P_t^C = \left(\int_0^1 p_{j,t}^{1-\sigma} dj \right)^{\frac{1}{1-\sigma}} \tag{39}$$

B.2 Intermediate-goods producing firms

The problem is equivalent to the output-good-producing firm of the main text and on top of that also solves a price setting problem described here.

Price setting problem. Intermediate-goods producing firms also solve a price-setting problem subject to adjustment costs as in Rotemberg (1982). The adjustment costs are as-if and do not reduce aggregate resources available in the economy. The firm sets this period's price $p_{j,t}$ to maximize the present discounted value of profits:

$$V_t^{IGF}(p_{j,t-1}) \equiv \max_{p_{j,t}} (1+s)p_{j,t}Y(p_{j,t};P_t^C,Y_t) - P_t^C S(Y(p_{j,t};P_t^C,Y_t)) \tag{40}$$

$$-\frac{\zeta}{2}\left(\frac{p_{j,t}}{p_{j,t-1}}-1\right)^2 P_t^C Y_t + \frac{1}{R_t}V_{t+1}^{IGF}(p_{j,t}), \tag{41}$$

where $(1+s) = \frac{\sigma}{\sigma-1}$ is an output-subsidy financed by lump-sum taxes on the firms to undo the distortions from monopolistic competition. Solving this problem leads to the familiar New Keynesian Philips Curve:

$$mc_t = (1+s)\frac{\sigma-1}{\sigma} + \frac{1}{\sigma}\left[\zeta(\pi_t^C - 1)\pi_t^C - \frac{1}{1+r_t}\zeta(\pi_{t+1}^C - 1)\pi_{t+1}^C\frac{Y_{t+1}}{Y_t}\right] \tag{42}$$

The equilibrium profit net the lump-sum tax to finance the output subsidy of each intermediate goods producing firm is given by:

$$\pi_t = Y_t - S(Y_t) \tag{43}$$

and rebated to the households proportional to their asset holdings.

B.3 Financial intermediary

The financial intermediary is needed to incorporate standard investment-adjustment costs in New-Keynesian models with capital. The financial intermediary issues shares to households and invests these resources into productive capital. At the end of the period, the financial intermediary pays out dividends to households (i.e. return on capital minus investment and adjustment costs). The intermediary makes investment decisions by maximizing the sum of discounted dividends:

$$\max_{\{I_t,K_{t+1}\}_{t=0}^{\infty}} \sum_{t=0}^{\infty}\prod_{s=0}^{t-1}\left(\frac{1}{1+r_s}\right)\left[r_t^k K_t - I_t - \mathcal{C}(I_t,K_t)\right] \tag{44}$$

$$\text{s.t.: } K_{t+1} = (1-\delta)K_t + I_t \tag{45}$$

where $\mathcal{C}$ are investment adjustment costs and are given by:

$$\mathcal{C}(I_t, K_t) = \frac{\chi}{2}\left(\frac{I_t}{K_t} - \delta\right)^2 K_t = \frac{\chi}{2}\left(\frac{K_{t+1}}{K_t} - 1\right)^2 K_t \tag{46}$$

with

$$\frac{\partial \mathcal{C}(I_t, K_t)}{\partial I_t} = \chi\left(\frac{I_t}{K_t} - \delta\right) \tag{47}$$

$$\frac{\partial \mathcal{C}(I_t, K_t)}{\partial K_t} = \frac{\chi}{2}\left[\left(\frac{I_t}{K_t} - \delta\right)^2 - 2\left(\frac{I_t}{K_t} - \delta\right)\frac{I_t}{K_t}\right] \tag{48}$$

Let q_t denote the Lagrange-multiplier on the current-period capital accumulation constraint (i.e. Tobin's Q), then the FOCs w.r.t. I_t for this problem is:

$$\prod_{s=0}^{t-1}\left(\frac{1}{1+r_s}\right)\left(-1 - \frac{\partial \mathcal{C}(I_t, K_t)}{\partial I_t} + q_t\right) = 0 \tag{49}$$

$$q_t = 1 + \frac{\mathcal{C}(I_t, K_t)}{\partial I_t} = 1 + \chi\left(\frac{I_t}{K_t} - \delta\right) \tag{50}$$

$$\iff I_t = \left(\frac{q_t - 1}{\chi} + \delta\right) K_t \tag{51}$$

and w.r.t. K_{t+1}:

$$\prod_{s=0}^{t-1}\left(\frac{1}{1+r_s}\right) q_t = \prod_{s=0}^{t}\left(\frac{1}{1+r_s}\right)\left(r^k_{t+1} - \frac{\partial \mathcal{C}(I_{t+1}, K_{t+1})}{\partial K_{t+1}} + q_{t+1}(1-\delta)\right) \tag{52}$$

$$(1+r_t)q_t = r^k_{t+1} - \frac{\chi}{2}\left[\left(\frac{I_{t+1}}{K_{t+1}} - \delta\right)^2 - 2\left(\frac{I_{t+1}}{K_{t+1}} - \delta\right)\frac{I_{t+1}}{K_{t+1}}\right] + q_{t+1}(1-\delta) \tag{53}$$

In the absence of investment adjustment costs, we have $q_t = 1$ and this condition reduces to the standard case where:

$$1 + r_t = 1 + r^k_{t+1} - \delta. \tag{54}$$

The share price at the end of the period is given by the net present value of future dividend payments, i.e.:

$$j_t = \sum_{s=t}^{\infty}\prod_{j=t}^{s-1}\left(\frac{1}{1+r_j}\right)\left[r^k_{s+1}K_{s+1} - I_{s+1} - \mathcal{C}(I_{s+1}, K_{s+1})\right] \tag{55}$$

or written recursively as:

$$j_t = \frac{D_{t+1} + j_{t+1}}{1 + r_t} \tag{56}$$

where r_t is the ex-ante return. The ex-post return $1 + \tilde{r}_t = \frac{j_{t+1} + D_{t+1}}{j_t}$ can differ from the ex-ante return only in the first period upon arrival of a shock (e.g. an energy price shock).

With adjustment costs we have that $j_t = q_t K_{t+1}$. To show this, we start with (53) and write it as

$$q_t = \frac{1}{1 + r_t} \left[r^k_{t+1} - \frac{\chi}{2} \left[\left(\frac{I_{t+1}}{K_{t+1}} - \delta \right)^2 - 2 \left(\frac{I_{t+1}}{K_{t+1}} - \delta \right) \frac{I_{t+1}}{K_{t+1}} \right] + q_{t+1}(1 - \delta) \right] \tag{57}$$

Multiply it with K_{t+1} on both sides and use $K_{t+1} = \frac{1}{1-\delta} \left(K_{t+2} - I_{t+1} \right)$ for the last term:

$$\begin{aligned} q_t K_{t+1} = \frac{1}{1 + r_t} \Bigg\{ & r^k_{t+1} K_{t+1} - \frac{\chi}{2} \left[\left(\frac{I_{t+1}}{K_{t+1}} - \delta \right)^2 - 2 \left(\frac{I_{t+1}}{K_{t+1}} - \delta \right) \frac{I_{t+1}}{K_{t+1}} \right] \\ & + q_{t+1}(K_{t+2} - I_{t+1}) \Bigg\} \end{aligned} \tag{58}$$

Substitute for $q_{t+1} = 1 + \chi \left(\frac{I_{t+1}}{K_{t+1}} - \delta \right)$:

$$\begin{aligned} q_t K_{t+1} = \frac{1}{1 + r_t} \Bigg\{ & r^k_{t+1} K_{t+1} - \frac{\chi}{2} \left[\left(\frac{I_{t+1}}{K_{t+1}} - \delta \right)^2 - 2 \left(\frac{I_{t+1}}{K_{t+1}} - \delta \right) \frac{I_{t+1}}{K_{t+1}} \right] \\ & - \left[1 + \chi \left(\frac{I_{t+1}}{K_{t+1}} - \delta \right) \right] I_{t+1} + q_{t+1} K_{t+2} \Bigg\} \end{aligned} \tag{59}$$

$$q_t K_{t+1} = \frac{1}{1 + r_t} \left\{ r^k_{t+1} K_{t+1} - I_{t+1} - \mathcal{C}(I_{t+1}, K_{t+1}) + q_{t+1} K_{t+2} \right\} \tag{60}$$

We do a forward iteration of $q_{t+1} K_{t+2}$ and impose that $\lim_{T \to \infty} \prod_{j=t}^{T} \left(\frac{1}{1+r_j} \right) q_{T+1} K_{T+2} = 0$:

$$q_t K_{t+1} = \sum_{s=t}^{\infty} \prod_{j=t}^{s-1} \left(\frac{1}{1 + r_j} \right) \left[r^k_{s+1} K_{s+1} - I_{s+1} - \mathcal{C}(I_{s+1}, K_{s+1}) \right] = j_t \tag{61}$$

Thus, with adjustment costs, the share price is given by the value of the capital stock in the next period times the shadow price of capital installed in the current period. Without adjustment costs, $q_t = 1$ and the share price is equal to the value of the capital stock in the next period, i.e. $j_t = K_{t+1}$.

Further, all fractions of the unit share of the financial intermediary can be traded and the aggregate demand for shares from households needs to equal the share price of the financial intermediary:

$$j_t = \frac{1}{2}\sum_i b_{i,t+1}. \tag{62}$$

B.4 Monetary policy

In the New-Keynesian version of the model the central bank's objective is to stabilize the price of the consumption good and thus follows the following interest rate rule:

$$R_t = R\left(\pi_t^C\right)^{\phi_\pi^C}\left(\pi_t^L\right)^{\phi_\pi^L}\left(\pi_t^{PIGL}\right)^{\phi_\pi^{PIGL}} e^{\epsilon_t^m} \tag{63}$$

where R is the steady state interest rate, ϕ_π the Taylor coefficient on inflation of the respective inflation measure and ϵ_t^m a monetary policy shock.