How Fast Should Carbon Taxes Rise? Efficiency Gains at Distributional Costs

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Abstract

I study the timing trade-off in phasing in a carbon tax and how it interacts with revenue recycling. Front-loaded carbon taxes curb cumulative emissions sooner and achieve a climate target with a lower peak tax, reducing future wage and GDP declines. However, rapid tax implementation can cause short-run resistance because household adjustment frictions, especially credit constraints among poorer households, delay green technology adoption and increase exposure to higher energy costs during the transition. Both effects may be amplified when green subsidies are used to recycle revenues. To quantify these trade-offs, I develop a heterogeneous-agent general equilibrium model with discrete, costly household electrification subject to financing frictions, continuous firm electrification, and electricity generated using fossil and renewable energy. Using policy experiments, I calculate welfare effects across income and age groups under alternative recycling schemes, and estimate the role of the adjustment friction. The calibrated model matches the observed income gradient in electrification: rich households electrify earlier, while poor households remain exposed to fossil energy. I find an intertemporal trade-off in carbon-tax timing: a rapid phase-in raises short-run welfare losses, especially for low-income households, because taxes increase before electricity-sector productivity gains materialize, generating a deeper temporary wage decline and higher energy costs than under a gradual path. At the same time, rapid implementation improves long-run outcomes by accelerating decarbonization and increasing future GDP and aggregate welfare. I also show that revenue recycling reshapes this ranking: under subsidies, compensation is concentrated among households able to electrify early, whereas lump-sum transfers provide broad insurance to financially constrained low-income households. Consequently, lump-sum recycling mitigates short-run welfare costs of rapid implementation without sacrificing its long-run gains.

Keywords: Green transition, Climate Policy, Carbon tax path, Inequality, Electrification

1 Introduction

The pace of carbon-tax implementation and the instrument used for revenue recycling are first-order decisions for policymakers seeking to reduce emissions. In practice, countries differ widely not only in the level of the existing carbon tax, but also in the speed at which those taxes are increased over time, and the way they recycle revenues[1]. For a given climate objective, such as a cap on total temperature increase, policymakers can choose between a front-loaded or a more gradual carbon tax path. They can furthermore choose to recycle the carbon tax revenues in several ways, such as directly redistributing it back to households, subsidizing green technology adoption by end-users or in the electricity sector, or use it as a financing tax for government expenditure.

The timing and recycling choice embed clear trade-offs. With respect to the timing, a front-loaded carbon tax path offers the advantage of a diminished increase in the total carbon stock and can therefore attain the same climate objective with a lower peak tax rate. Lower tax rates, in turn, attenuate output drops and general-equilibrium effects operating through factor prices, including wage declines. At the same time, rapid implementation of the carbon tax can spur resistance as households face adjustment frictions that slow the adoption of green technologies, such as heat pumps and electrical vehicles, in order to adapt to the climate tax. These frictions are especially salient for households with limited financial resources, who may be less able to finance green technology adoption and are therefore more exposed to higher energy costs during the transition. This mechanism is amplified by the fact that energy is a necessary good, such that poor households cannot easily substitute away from it. A similar trade-off exists for the revenue recycling instrument. Green subsidies can decrease the peak tax rate required to curb temperature increases, but might disproportionally go to households who have the financial capacity to electrify. Therefore, the gain in long-term efficiency might come at a high distributional cost due to the adjustment friction. The quantitative magnitude of these policy trade-offs remain insufficiently understood. This paper evaluates how the carbon-tax implementation horizon and revenue recycling instrument affects welfare across heterogeneous households under an exogenous temperature target when adjustment to green technologies is subject to financing frictions for households. It also examines possible interaction effects between the implementation horizon and recycling instrument.

Household electrification, i.e. the adoption of green technologies such as heat pumps and electrical vehicles, is central to the energy transition. Direct household energy use, primarily for heating and transport, accounts for 20% of total emissions. Therefore, meeting a temperature target requires, next to a cleaner electricity supply, electrification of end-use energy demand[2]. A key feature of household electrification is that

[1] Carbon Pricing Dashboard (April 2023), World Bank, Washington, D.C. (2023). Available from: https://carbonpricingdashboard.worldbank.org/

[2] IPCC (2022), Sixth Assessment Report.

it entails substantial upfront, investment costs. Empirical evidence from Danish near-universe register data, as documented by Berg et al. (2024) exploiting exogenous variation in unexpected inheritances, demonstrates that financial constraints constitute a key barrier to the adoption of electricity-based durables.

Examining data from the Netherlands (2018) for homeowners, there is a clear correlation between income and the early adoption of heat pumps, as can be seen in figure 1. This income gradient indicates that exposure to carbon pricing is systematically unequal along the income distribution. Low income households who lack the financial capacity to adapt to a green, electricity driven technology see a larger increase in energy prices, and therefore energy expenditures. This same logic is reinforced by the fact that energy is a part necessary good. This creates a non-homotheticity in energy demand: poor households cannot substitute away from energy when relative prices rise. Together, financing frictions in technology adoption and limited substitution elasticities for energy demand create a case for a gradual increasing path of carbon prices at the cost of a higher peak carbon tax.

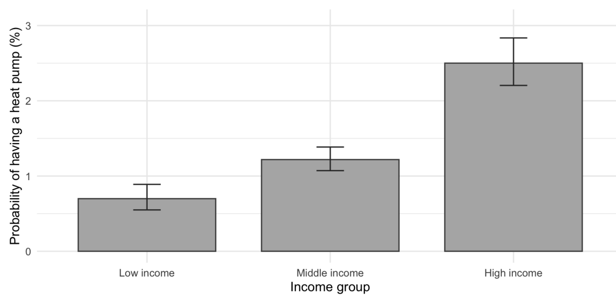

Figure 1: The predicted share of households for different income groups with a heatpump in 2018 using the WOon-dataset from Statistics Netherlands, for homeowners (37750 obs.), mean is 1.41% (dashed line). The correlation persists when controlling for square meters. The correlation is also found, and even stronger, for 2021 and 2024.

Unequal rates of going green along the income and liquid wealth distribution are measured in empirical work in the Netherlands Dröes & Van Der Straten (2024) and for OECD countries Ameli & Brandt (2015). Furthermore, Kuhn & Schlattmann (2024) show that due to this heterogeneity, subsidizing the electrification process can induce transfers from poor to rich households. Crucitti et al. (2024) discuss how the adoption of green technologies such as heat pumps differs over the life-cycle. They find that as older households usually own bigger houses, they benefit more from proportional subsidies. A similar finding is found in Schlattmann (2024), where richer households own larger houses and therefore benefit more from a lower energy price. In this paper, I abstract from modeling a size complementarity and only focus on the extensive margin of electrification and examine how it affects the inequality versus inefficiency trade off in the policy decisions at hand.

In order to do so I build a quantitative life-cycle model with heterogeneous households, calibrated to the EU economy in 2015 (the Paris Agreement baseline year). Households are initially endowed with a brown durable but can choose to invest in a green durable enduring a large upfront investment cost. The durable is interpreted as a composite of heating and transport technologies (heat pump + EV for green versus gas boiler + gasoline car for brown). The two durables differ in fuel type used (electricity vs. fossil fuel) and energy efficiency, with the green durable more efficient.

On the production side, a representative firm combines a capital-labor composite with an energy aggregate to produce the final good. Energy is a CES bundle of electricity and fossil fuels, so firms adjust their input mix frictionless with relative prices. Electricity is produced from renewable and fossil-based technologies in a CES structure: renewable generation is capital-intensive, while fossil generation uses capital and fossil inputs. The electricity block is frictionless, so the renewable share responds contemporaneously to relative prices.

Durables are produced from the final good at technology-specific productivities, implying durable prices equal inverse productivity (with the green durable initially more expensive, converging over the transition). The government implements carbon-tax paths and alternative revenue-recycling schemes subject to a balanced budget. I abstract from endogenous climate damages and impose an exogenous temperature objective, which allows a clean comparison of alternative tax-implementation horizons.

Across all policy experiments, I find that carbon taxation accelerates both household electrification and the decarbonization of electricity, but the distributional and quantitative emissions outcomes depend on how revenues are recycled, and how fast the tax is implemented. When subsidies are used to rebate the tax revenue, a lower carbon tax suffices for the same temperature target. However, subsidy recycling makes the carbon tax regressive as mostly high-income households electrify early and therefore benefit from the subsidies. This effect is amplified when the tax is introduced more rapidly, which increases the current welfare burden. The rapid increase in taxes, while productivity has not yet grown to its maximum level leads to a short-term larger wage dip, plus higher energy costs. This especially burdens households who do not adopt a green technology. Older, poorer households are hit the hardest by the carbon tax, and this is driven by the fact that they cannot electrify to adapt to the carbon tax. When the subsidy is directed at renewable electricity, the overall welfare losses are smaller compared to an electrification subsidy, primarily because the lower carbon tax and suppression of the electricity price decrease wage declines. I furthermore find that using a lump-sum redistribution works progressively: poor households gain in terms of welfare, while the richer loose. This is caused by the fact that in absolute terms, rich households consume more energy and therefore lump-sum redistributes from the rich to the poorer households. Rapid implementation of the carbon tax does not lower the total welfare gain achieved in 2015 with lump-sum recycling, while substantially increasing future GDP and welfare compared to the gradual implementation. The fact that the timing trade-off between future efficiency gains and current distributional losses disappears when using lump-sum, together with the fact that lump-sum redistribution works progressive makes that it is the superior option for revenue recycling, especially when implemented rapidly.

I contribute to the current literature in three ways. First, to my knowledge this is the first paper to assess the distributional effects of climate policy targeting both dimensions of the transition, electrification and electricity decarbonization, in a model capturing rich heterogeneity on assets, income, age and the type of durable good owned by the household. This allows for a broad comparison of revenue redistribution schemes among each other. Especially it offers insights into the trade-offs between subsidizing the different sides of the transition, and the pace at which this should be implemented. Second, I measure the relative importance of the electrification margin for inequality considerations in climate policy next to the more often examined mechanisms that work via general equilibrium effects and the non-homotheticity of energy demand. This allows me to identify how the friction in household electrification affects overall welfare considerations, when interacting with these other mechanisms. Together, these findings offer policy-makers guidance on how to balance equity and decarbonization objectives in climate policy. Lastly, the combination of the electrification channel and age heterogeneity allows for an analysis of the life-cycle effects of climate policy. The third contribution is to show that climate policy has systematically different welfare effects across age cohorts.

The remainder of the paper is structured as follows. In section 1.1, I relate this paper to the existing literature on the green transition and inequality. In section 2, I extensively discuss the model, that I parametrize in section 3. In section 4, I conduct several policy instruments and analyze the results for equity and effectiveness in reaching an exogenously set climate goal. I conclude in section 5.

1.1 Related literature

A recent surge in interest has led to an increasing number of quantitative papers assessing inequality along the green transition. Benmir & Roman (2022) and Boehl et al. (2024) study how climate policy affects inequality in a setting where energy is modeled as a carbon-emitting input into the production process. In this setting, inequality arises from different channels such as changes in labor income, revenue redistribution or a decrease in future damages. More closely related to the framework developed in this paper is the literature that explicitly models energy as both a production input and a consumption good. Känzig (2023) examines the effect of carbon pricing in an economy where energy is modeled as a fossil fuel, and serves as an input in the production process and non-homothetically enters the utility function. A carbon tax affects households in two ways, indirectly via reduced economic activity and hence their income, and directly as the households consume energy. In a similar fashion, Fried et al. (2024) use a heterogeneous agent model with non-homothetic preferences for energy to examine the effect of a carbon tax with different rebate instruments on inequality. They find that rebating tax revenues via decreasing distortionary taxes and increasing the progressivity of labor taxes increases welfare more than lump-sum redistribution does.

Other papers make an explicit distinction between green and brown energy sources. In this set-up, climate policy reduces carbon emissions through decarbonization of the production of energy, i.e. electricity. In Ascari et al. (2025), the authors model two distinct energy sources, brown (fossil fuels) and green (renewable). A profit-maximizing energy firm aggregates these two sources of energy in a frictionless manner, based on relative prices and productivity, into a bundle of energy sold to every household and firm. A carbon tax raises the price of fossil fuels, such that the optimal mix contains more green energy. In their model opposed to my model, all households consume this same optimized bundle, such that the main inequality concern between rich and poor households stems from the non-homotheticity: the share of energy expenditures over income decreases in income. Closely related to their paper, is the paper by Hochmuth et al. (2025) which similarly models a non-homothetic demand for energy from households, and assesses the distributional effects of a carbon tax in an economy transitioning towards a carbon-neutral economy. In their paper too, all agents and firms consume the same bundle of energy. They find that both the elasticity of substitution between green and brown energy as well as the degree of non-homotheticity determine the quantitative degree of the inequality effects.

In the current paper, I explicitly model both of these types of energy by adding an electrification margin for firms and households: one type that is purely a fossil fuel, and another type, electricity, which is a composite of fossil fuel and renewable sources. The goal of climate policy is then to reduce emissions through both increased electrification and decarbonization of electricity production. A very similar distinction between types of energy is made in work examining the spatial margin in this decision by Labrousse & Perdereau (2024), who also model two sources of energy, brown (fossil fuel) and green (electricity), that are both available for production and consumption. They include a household-specific CES optimized energy bundle based on locational choice (rural versus urban). This implies that a household consumes its own optimal mix of brown and green energy, which is determined by the households' location, and the relative energy prices. Locational choice plays a key role in their electrification decision, as households in more rural areas have a stronger preference for fossil fuels than households in urban areas, and therefore are disproportionately hit by a carbon tax. Closely related to this, is the paper by Schlattmann (2024) which incorporates spatial heterogeneity in carbon demand, exploiting the fact that rural households emit more via direct energy demand (heating, transport). The paper analyzes the effect of a carbon tax on locational choice and energy demand. Contrary to the spatial dimension in these two papers, I exploit the fact that electrification requires a large upfront investment, rather than a moving decision. I therefore analyze a different mechanism behind the household decision to adjust to greener energy demand.

A paper that also examines this margin is the work by Kuhn & Schlattmann (2024). In their paper, they have a similar set up of modern versus old commitment goods, where the latter are thought of as more polluting. The authors examine the effect of subsidies for switching from the old to the modern commitment good on inequality. In a partial equilibrium setting, they analyze the effect of a subsidy that decreases the purchasing costs for modern commitment goods - implicitly defined as goods reliant on electricity rather than fossil fuels - with different financing instruments on inequality and transition efficiency. Similarly, Crucitti et al. (2024) focuses on heat pump uptake over the life-cycle in a setup where a large upfront investment is required. They analyze and compare the effects of a proportional versus a lump-sum subsidy. These papers, however, refrain from modeling an electricity sector and thus only focus on the electrification decision. In my paper I model a complete transition to see how this adjustment friction affects the equity-efficiency trade-off in climate policy. In the paper by Fried (2026), green technology adoption serves as adaption against rising temperature variance caused by climate change rather than climate policy. Rich households can adapt to heat pumps that allow for cheaper regulation of the inside temperature in periods of extreme heat or cold. In this paper, I study the policy trade-off that arises from unequal green technology adoption rather than transfers from climate.

Lastly, this paper relates to the inter-generational comparison of climate policy burden. Fried et al. (2018) examine the distributional effects of different carbon tax revenue recycling instruments between generations by modeling a non-homothetic demand. They find that the generation that carries the biggest welfare burden of a carbon tax is highly conditional on the policy instrument used. They employ a steady state comparison, and evaluate how the future born generation is affected by the use of different revenue redistribution instruments. As opposed to their paper, I examine the short versus long-term effects over the transition, which are caused by the adoption friction rather than a steady state comparison.

2 Model

2.1 Households

Demographics Time is discrete. Households' age is indexed by $j = 1, 2, ..., J$. After period $J-1$ the household dies with certainty. A household works for J_w periods, and then retires with certainty. The economy is populated by a continuum of households with mass one. At birth, households differ with respect to their income $y_{i,0}$, initial wealth $a_{i,0}$ and the durable good they are born with, $\phi_{i,0}$. Households are indexed by i, however for notational convenience this index is dropped in most cases.

Preferences Households maximize expected life time utility denoted as

$$U = E\Bigg[\sum_{j=1}^{J-1} \beta^{j-1} u(c_j, s_j) + \beta^{J-1} w(b)\Bigg], \tag{1}$$

where β is the discount factor, $c > 0$ is consumption of the final consumption good and s is services derived from energy. Flow utility is a Stone-Geary utility function nested in a CRRA

$$u(c_j, s_j(\phi_j, e_j)) = \frac{1}{1-\sigma}(c_j^{\gamma}(s_j(\phi_j, e_j) - \bar{s})^{1-\gamma})^{1-\sigma}, \tag{2}$$

where γ denotes the households' relative taste for the final consumption good, $\frac{1}{\sigma}$ is the intertemporal elasticity of substitution and $\bar{s}$ is a subsistence level for services derived from energy. A subsistence level is included to capture the fact that energy demand is non-homothetic.[3]

The amount of services s, is a function of the level of energy consumption e and the type of durable good $\phi \in \{0, 1\}$ (brown vs. green), i.e. $d_\phi = \phi d_G + (1 - \phi) d_B$. The type of the durable good, ϕ, determines the rate at which energy translates into services, such that

$$s(\phi_j, e_j) = \begin{cases} A_{s,G} e_j & : \text{if } \phi = 1 \implies d = d_G \\ A_{s,B} e_j & : \text{if } \phi = 0 \implies d = d_B. \end{cases} \tag{3}$$

Akin to the technologies described in Fried (2024), each durable good transforms energy (fossil fuels, electricity) into services of mobility and heating at a different rate, hence a higher productivity implies a more energy efficient durable good. The energy efficiency of the durable good is thus pinned down by its productivity parameters $A^{s,G}$ and $A^{s,B}$ for the green and brown durable good respectively[4].

A dying household receives utility from bequeathing its savings and a scrap value, φ, of its durable good. The utility derived from this is denoted as

$$w(b) = \eta \frac{(b + \underline{b})^{1-\sigma}}{1-\sigma} \tag{4}$$

with a strength of the bequest motive η, and where $\underline{b}$ denotes the extent to which bequeathing is a luxury good, similar to De Nardi (2004). Furthermore, the size of the bequest is defined as

$$b = a'_{J-1} + ((1 - \phi'_{J-1}) P^{d_B} + \phi'_{J-1} P^{d_G}). \tag{5}$$

[3] Most papers either use a subsistence level to capture this non-homotheticity Wöhrmüller (2024); Schlattmann (2024); Fried et al. (2024)9 or alternatively the flexible indirect utility function of Boppart (2014), adopted by among others Ascari et al. (2025); Hochmuth et al. (2025)

[4] These productivities are calibrated as the coefficient of performanceas defined by the International Energy Agency of the respective durable goods.

Durable good and energy As mentioned, there are two types of durable goods in the economy, a green, sustainable durable d_G and a brown, non-sustainable durable d_B. A durable good converts energy e into services (mobility, heating) at a rate specific to that durable good, $A_{s,G}$ or $A_{s,B}$[5]. Furthermore, the different types of durable good, require different types of energy. A green durable good is fueled with electricity, while a brown durable good requires fossil fuels. Hence, purchasing a green durable good is referred to as electrification.

Each household owns one type of durable good which is denoted using a binary state variable ϕ, such that the durable good owned by the household is given by $d_\phi = \phi d_G + (1-\phi)d_B$. At the start of its life, a household receives either a brown or green durable good from a warm-glow bequests, with a conditional probability based on its initial income level and determined by the dying cohorts' distribution. A household can electrify by selling its brown durable durable good ($\phi = 0$) for a scrap value φP^{d_B}, and buying a green durable good ($\phi' = 1$) for $P^{d_G}(1-s_{durable})$, where $s_{durable}$ is a government subsidy for electrifying households. A household is not allowed to switch from a green to a brown durable good, hence electrification is an absorbing state.

As said, the two goods d_G and d_B differ in the type of energy they require as fuel: the green durable good d_G relies on electricity (green energy), E with price P^E, whereas the brown durable good d_B relies on fossil fuels (brown energy), FF, with price P^{FF}. When the government levies a carbon tax τ_c, this increases the costs of fossil fuels. Household aggregate demand for electricity and fossil fuels are given as

$$E_H = \sum_{j=0}^{J-1} \int \phi_j e_j d\mu_j, \tag{6}$$

$$FF_H = \sum_{j=0}^{J-1} \int (1-\phi_j) e_j d\mu_j. \tag{7}$$

In case the household chooses to electrify, it can make use of a secured borrowing scheme to pay for the durable, denoted by m, subject to a down-payment constraint, i.e.

$$m' \leq \lambda^{LTV} P^G (1 - s_{durable}) \tag{8}$$

The household is required to repay the loan following an amortization schedule, which implies a payment of

$$\pi^m = \frac{(r + r_m)(1 + (r + r_m))^{J-j}}{(1 + (r + r_m))^{J-j} - 1} m, \tag{9}$$

such that next periods loan is equal to $m' = (1 + r^m)m - \pi^m$. The interest rate includes a premium r^m for borrowing by households.

[5]This can be thought of as electricity or fossil fuels being translated into services of mobility (heating) by an electrical vehicle (heatpump) or gasoline vehicle (regular boiler)

A durable good requires maintenance, which is paid every period and is given by $\delta_\phi = \phi\delta_G P^G + (1-\phi)\delta_B P^B$.

Income and wealth Households supply their labor inelastically and receive income as an endowment each period. Labor income is denoted as $wY_{j,i}$, where $Y_{i,j}$ denotes labor productivity of a household i at age j, and is given by

$$log(Y_{j,i}) = \xi(j) + z_{j,i}. \tag{10}$$

such that labor productivity $Y_{j,i}$ consists of a deterministic life-cycle component $\chi(j)$ and an individual component, $z_{j,i}$, representing productivity differences between households. During the first J_w years, the idiosyncratic part of labor productivity $z_{j,i}$ of a household is stochastic and follows an AR(1) process,

$$z_{j,i} = \rho_y z_{j-1,i} + \epsilon_{j,i}. \tag{11}$$

After J_w periods, the household retires. After retirement, it deterministically receives a certain proportion f_{ret} of the income it received in the last period as a pension for the remaining $J - J_w$ periods.
Households can save in a risk-free asset denoted by a. They receive interest rate r on their savings every period. Unsecured borrowing is not allowed. Initial wealth is exogenously drawn from a mixture of a degenerate mass-point at zero wealth with probability p_0 and a univariate log-normal wealth distribution with variance $\sigma^2_{a_0}$ that integrates up to the savings bequeathed by dying households in that period.

2.1.1 Recursive formulation household problem

A household is born with initial wealth a_0, income y_0, and durable good ϕ_0. Thereafter, it solves the following problem during its lifetime, so for $j = 0, ..., J-1$, the household solves

$$V_j(a, \phi, m; Y, P) = \max\{V_j^{NoAdjust}(a, \phi, m; Y', P'), V_j^{Electrify}(a, \phi, m; Y', P') - \epsilon_\phi\} \tag{12}$$

Where $P = \{r, w, P^E, P^{FF}, P^G, P^B, \tau_c\}$ denotes the price vector. ϵ_ϕ is a negative preference shock, which represents a type-I extreme value shock. These shocks can be interpreted as a (temporary) aversion to change. It allows for the adjustment decision to be a probability rather than a discrete choice. Probability of adjustment grows in the difference between $V_j^{Electrify}(a, \phi, m; Y', P') - V_j^{NoAdjust}(a, \phi, m; Y', P')$, but it spreads the mass. This helps in the calibration. Furthermore,

$$V_j^{NoAdjust}(a, \phi, m; Y, P) = \max_{a', c, e} u(c, s) + \beta E[V_{j+1}(a', \phi, m'; Y', P')] \tag{13}$$

subject to

$$wY + \mathcal{T} + (1+r)a \geq c + a' + e[(1-\phi)(P^{FF} + \tau_c) + \phi P^E] + \delta_\phi P^{d_\phi} + f(j)m \tag{14}$$

$$a' \geq 0 \tag{15}$$

$$f(j) = \frac{r_m(1+r_m)^{J+1-j}}{(1+r_m)^{J+1-j} - 1} \tag{16}$$

$$m' = (1 + r_m - f(j))m \tag{17}$$

And

$$V_j^{Electrify}(a, \phi, m; Y, P) = \max_{a', m', c, e} u(c, s) + \beta E[V_{j+1}(a', \phi' = 1, m'; Y', P')]. \tag{18}$$

subject to

$$wY + \mathcal{T} + (1+r)a + m' \geq c + a' + e\phi' P^E + \delta_\phi P^{d_\phi} + (P^{d_G}(1 - s_{durable}) - \varphi P^{d_B}) \tag{19}$$

$$a' \geq 0, m' \leq \lambda P^{d_G}(1 - s_{durable}) \tag{20}$$

Lastly $V_J = w(b)$ as in equation 4.

2.2 Production

There are three sectors on the production side of the economy, one for the final good Y^C, one for electricity Y^E and one for each durable good Y^{d_G} and Y^{d_B}. Fossil fuels are imported into the economy.

Final consumption good A representative firm produces output goods which can be used for production or converted in durable goods. Inputs are capital, labor and electricity with costs equal to interest rate plus depreciation, wage and the price of electricity. The technology is a constant returns to scale CES

$$Y^C(K_C, L_C, E_C, FF_C) = \left[(1-\psi)^{\frac{1}{\nu}} \left(A_{KC} K_C^{\alpha_c} L_C^{1-\alpha_c}\right)^{\frac{\nu-1}{\nu}} + \psi^{\frac{1}{\nu}} M^{\frac{\nu-1}{\nu}}\right]^{\frac{\nu}{\nu-1}} \tag{21}$$

where the energy composite M is given as

$$M = \left[\kappa^{\frac{1}{\iota}} (A_{EC} E_C)^{\frac{\iota-1}{\iota}} + (1-\kappa)^{\frac{1}{\iota}} (A_{FFC} FF_C)^{\frac{\iota-1}{\iota}}\right]^{\frac{\iota}{\iota-1}} \tag{22}$$

Electricity There is an electricity producer that inputs capital and fossil fuels and converts it into electricity.

The profits of the electricity firm are given as follows by an aggregator of renewable and fossil generated electricity multiplied by the price of electricity, minus the costs for inputs, hence

$$\Pi(K_{E_R}, K_{E_F}, FF_E) = P_E\big(\alpha_R^{\frac{1}{\lambda}}(Y^{E_R}(K_{E_R}))^{\frac{\lambda-1}{\lambda}} + \alpha_F^{\frac{1}{\lambda}}(Y^{E_F}(K_{E_F}, FF_E)^{\frac{\lambda-1}{\lambda}}\big)^{\frac{\lambda}{\lambda-1}} \tag{23}$$

$$- (r+\delta)(1-s_{GE})K_{E_R} - (r+\delta)K_{E_F} - (P^{FF}+\tau_c)FF_E \tag{24}$$

Where s_{GE} denotes the subsidy for the cost of green electricity generation. The production technologies for renewable and fossil generated electricity are

$$Y^{E_R}(K_{E_R}) = A_{KR}K_{E_R} \tag{25}$$

$$Y^{E_F}(K_{E_F}, FF_E) = [\zeta^{\frac{1}{\omega}}(A_{KF}K_{E_F})^{\frac{\omega-1}{\omega}} + (1-\zeta)^{\frac{1}{\omega}}FF_E^{\frac{\omega-1}{\omega}}]^{\frac{\omega}{\omega-1}} \tag{26}$$

Durable goods In this economy, the durable goods can be produced by converting the consumption good (with price 1, as it is the numeraire) at some rate A_G, A_B, such that production functions are given as

$$Y^{d_G}(C_G) = A_G C_G \tag{27}$$

$$Y^{d_B}(C_B) = A_B C_B \tag{28}$$

These imply input demand functions

$$C_G = \frac{1}{A_G}Y^{d_G} \tag{29}$$

$$C_B = \frac{1}{A_B}Y^{d_B} \tag{30}$$

and prices $P^G = \frac{1}{A_G}$, $P^B = \frac{1}{A_B}$.

2.3 Government

The government runs a balanced budget. It receives a carbon tax every period, and gives out a lump-sum uniform transfer, a subsidy for capital costs to generate renewable energy generation or a subsidy for the costs of electrification, such that

$$G + \mathcal{T} + s_{E_R}K_{E_R}(r+\delta) + s_{durable}P^G\sum_{j=0}^{J-1}\int(\phi'-\phi)d\mu_j = \tau_c[FF_H + FF_E + FF_C] \tag{31}$$

2.4 Equilibrium

Given an exogenous fossil fuel price P^{FF} and a carbon tax τ_c, equilibrium is defined by a price vector $P : \{P^{FF}, \tau_c, r, w, P^E, P^G, P^D\}$ and distribution μ over state variables (a, ϕ, m, y, j) such that

1. Given prices, households maximize utility giving rise to value functions $V_j(a,\phi;y,P,\mathcal{T})$, $V_j^{NA}(a,\phi;y,P,\mathcal{T})$, $V_j^{A}(a,\phi;y,P,\mathcal{T})$ and policy functions $a_j'(a,\phi,m;y,P,\mathcal{T})$, $c_j(a,\phi,m;y,P,\mathcal{T})$, $e_j(a,\phi,m;y,P,\mathcal{T})$, $\phi_j'(a,\phi,m;y,P,\mathcal{T})$ and $m_j'(a,\phi,m;y,P,\mathcal{T})$

2. The final-output good firm, electricity firm, and the durable good firms maximize profits

3. All financial wealth bequeathed and all durables bequeathed equals the initial, aggregate wealth of the new-born generation, that is, for wealth

$$\int a'(\mathbf{x})d\mu_{J-1} = \int a d\mu_{-1}, \tag{32}$$

and durable goods are passed on conditional on initial income level, such that the joint distribution of durables and income is similar in the dying and newborn generation

4. The government budget constraint holds

$$G + \mathcal{T} + s_{E_R}K_{E_R}(r+\delta) + s_{durable}P^G\sum_{j=0}^{J-1}\int(\phi'-\phi)d\mu_j = \tau_c[\sum_{j=0}^{J-1}\int e(1-\phi')d\mu_j + FF_E + FF_C] \tag{33}$$

5. Prices are such that markets clear for

$$\text{Capital:} \quad \sum_{j=0}^{J-1}\int a_t d\mu_j = K_{C,t} + K_{E_R,t} + K_{E_F,t} \tag{34}$$

$$\text{Labor:} \quad \sum_{j=0}^{J-1}\int y d\mu_j \ = L_C \tag{35}$$

$$\text{Gr. Durable:} \quad Y^{D_G} = \sum_{j=0}^{J-1}\int \phi\delta_G + (\phi'-\phi)d\mu_j \tag{36}$$

$$\text{Br. Durable:} \quad Y^{D_B} = \sum_{j=0}^{J-1}\int (1-\phi)\delta_B - \varphi(\phi'-\phi)d\mu_j \tag{37}$$

$$\text{Electricity:} \quad Y^{E} = \sum_{j=0}^{J-1}\int e\phi' d\mu_j + E_C \tag{38}$$

and the aggregate resource constraint clears by Walras law.

3 Parametrization baseline model

In order to assess the quantitative trade-offs behind climate policy during the green transition, I parametrize the economy to match the initial steady state to the pre-transition period. I focus on the European green transition, and calibrate to the year 2015.

Preferences Households are born at age 25, work until 65 and die at 75. This implies J is 50, and J_w is 40. All generations are equally sized, hence the size of a generation equals $N = 1/J$. I set the intertemporal elasticity of substitution $1/\sigma$ to 1/2, which is a standard value in the lifecycle literature. The remaining preferences parameters - $\beta, \gamma, \bar{s}, \eta, \underline{b}$ - are calibrated internally using a simulated method of moments. The key moments targeted in order to discipline these parameters are the mean savings in the economy, the average energy expenditure over total expenditure, the degree of non-homothetecity in energy expenditures, the change in saving holdings during the retirement phase and inequality in bequests. This is discussed in more detail below.

Durable good and Energy The composite durable converts energy into heat and mobility services. I follow Kuhn & Schlattmann (2024) in defining 2/3 of the composite good as the car and the remaining part as the heating system, according to expenditures on energy for both components.

The rate at which energy is translated into services, $A^{s,G}$ and $A^{s,B}$ for the green and brown durable good respectively are defined as energy efficiency. I calibrate the efficiency levels of the two technologies separately for heat and for mobility and then aggregate them for the composite good.

Energy efficiency is defined as the rate at which a unit of energy, either fossil fuel or electricity, translates into useful energy by the technology at hand. That is, how much useful energy is extracted from using the primary (or secondary for electricity) source of energy. Due to transformation losses or gains at the time of usage, energy services consumed is not the same as final energy demand.

To start with heating, I follow energy efficiency estimates from IEA (2022)[6]. They define the concept of useful energy as energy available to satisfy the needs of the user, and refer to this as energy services demand, similar to my model. In their report, they refer to the difference between useful energy and energy used to run the technology as the coefficient of performance (COP), which directly translates into $A_H^{s,G}$ and $A_H^{s,B}$ in my model. They state that heat pumps have a COP of around 4, while there is a huge range from industrial heat pumps having a COP of 3 and district heating networks with large heat pumps showing a COP of 8. I choose to set $A_H^{s,G}$ to 4. Natural gas boilers on the other hand exhibit a COP of around 0.8, hence I set $A_H^{s,B}$ to 0.8.

For mobility, I follow estimates from the US department of energy from 2024[7]. They find that for electrical

[6] The Future of Heatpumps report

[7] https://www.energy.gov/eere/vehicles/articles/fotw-1360-sept-16-2024-typical-ev-87-91-efficient-compared-30-conventional

Parameter	Description	Value	Internal	Target/source
Households				
Preferences				
β	Discount factor	0.941	yes	See table 2
$1/\sigma$	Intertemporal substitution	1/2	no	Standard value
γ	Taste for consumption	0.917	yes	See table 2
$\bar{s}$	Energy service subsistence level	7.6	yes	See table 2
η	Strength of bequest motive	31.49	yes	See table 2
$\underline{b}$	Luxury of bequest	3.27	yes	See table 2
Durable goods and energy				
$A_{s,G}$	Energy efficiency d_G	1.82	no	See text
$A_{s,B}$	Energy efficiency d_B	0.47	no	See text
δ_G, δ_B	Depreciation	0.02, 0.01	no	Schloter (2022)
φ	Resale value	0.27	no	Gilmore & Lave (2013)
$1-\lambda_{LTV}$	Down payment requirement	0.1	no	Own assumption
r_m	Loan premium	0.03	no	–
Income and wealth				
ρ_y	Persistence	0.98	no	DNB Household Survey
σ_ϵ	Std. dev. income	0.1	no	DNB Household Survey
σ_{a_0}	Std. dev. wealth at age 0	0.556	no	DNB Household Survey
p_0	Zero-wealth share at age 0	0.39	no	DNB Household Survey
Production				
Electricity				
α_R	Renewable share	0.5	no	Hochmuth et al. (2025)
λ	EoS green and brown electricity	1.8	no	Papageorgiou et al. (2017)
ζ	Capital share E_F	0.3	no	Own assumption
ω	EoS capital and fossil fuels in E_F	0.25	no	Coenen et al. (2024)
A_{KR}	Productivity green capital	14.72	yes	See table 2
A_{KF}	Productivity brown capital	17.46	yes	See table 2
Durable goods				
A_G	Productivity Y^{d_G}	0.86	no	Kuhn & Schlattmann (2024)
A_B	Productivity Y^{d_B}	2.2	no	Price of d_B
Final consumption good				
α_c	Capital share	0.33	no	Literature
ν	EoS capital-labor and energy	0.2	no	Realistically low
ψ	Capital-labor share	0.1	no	Hochmuth et al. (2025)
ι	EoS Electricity and Fossil Fuel	1.5	no	Papageorgiou et al. (2017)
κ	Electricity share	0.2	no	Papageorgiou et al. (2017)
A_{KC}	Productivity capital	1.092	yes	Normalization w
A_{EC}	Productivity electricity	0.015	yes	See table 2
A_{FFC}	Productivity fossil fuels	0.00048	yes	See table 2

Table 1: Parameter values

vehicles the energy conversion rate from energy input to useful energy, $A_M^{s,G}$ lies around 0.75[8]. For a gasoline car energy efficiency $A_M^{s,B}$ is lower, as it only translates 0.3 of total energy into useful energy and the remainder is lost as heat. This adds up to 1.82 for $A^{s,G}$, and 0.47 for $A^{s,B}$.

For other parameters, I follow the empirical literature. Following estimates from Schloter (2022), electrical vehicles depreciate faster than gasoline vehicles. Estimates for heat pumps are diverging. I set the depreciation for the green durable good to 2% as opposed to 1% for the brown durable good. Regarding the resale value, I follow a resale value for cars from Gilmore & Lave (2013) of 40% and 0% for heating systems. For the composite good, this implies a resale value of 27%.

The price of fossil fuels is calculated as a composite of the gasoline and the natural gas price, for mobility and heating purposes, converted to kWh. To start with the price of natural gas, from Eurostat[9], the price for one kWh of natural gas is 0.05 euros in Europe, 2015. From the weekly oil bulletin, the price of gasoline (Euro-super95) is 529.7 euros per 1000 liter. Taking as a conversion 9.3 kWh per liter of gasoline, the price of gasoline per kWh in the Europe, 2015 is 0.0569 euros. As the composite good consists of 67% mobility purposes, the price of fossil fuels would be 0.0546 euros per kWh. The model unit is defined as 1000 kWh, and normalized by dividing by mean income, such that the price in the model is set to 0.0023. [10]

With respect to the parameters governing the characteristics of secured borrowing for the purchase of a durable good. The minimum down-payment requirement is set to 10% by own assumption in order to set it realistically. Lastly, I set a premium on loans for households to match the fact that these loans often require high interest payments.

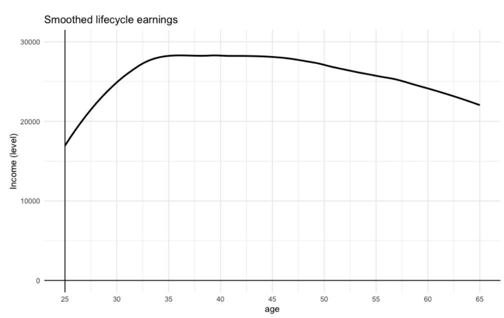

Figure 2: Deterministic life cycle component of productivity

[8]taking into account cars with and without regenerative breaking

[9]Online data code: nrg_pc_202

[10]This price pins down the tax in percentage to price per tCO2 unit. For example a tax of 150%. 150% of 0.0023 means 0.00345 per unit of FF, which implies $0.00345 * 26033 = 89.81$ euros. One unit of FF emits 233 kCO2. Hence 4.3 units emit a ton of CO2. So the price is $89 * 4.29 = 381$ euro per tCO2

Income and initial wealth Income is determined by the endogenous wage w and exogenous, idiosyncratic productivity $Y_{i,j}$. Productivity is split up in a deterministic lifecycle and a stochastic component. Average productivity is normalized, and together with the wage normalization adds up to an average net labor income of 26033 euros.

The lifecycle component ξ is calibrated using the DNB household survey by regressing the log of net income on age dummies and year fixed effects. The smoothened life cycle pattern of productivity is shown in figure 2. The residual of the regression is then used to calibrate the idiosyncratic, stochastic part $z_{i,j}$. Further details on the data used in calibration of the income process can be found in the appendix.

Initial wealth is a combination of a degenerate distribution at zero wealth and a log-normal distribution over non-zero support, independent of income. I calibrate the fraction of households with a zero level of wealth, p_0 as those households with no or negative financial assets in the data at age 25. With respect to the log-normal distribution, the mean is determined endogenously in order to make sure that the value of assets held by the newborns integrates up to the value bequeathed by the dying households. The variance of the log normal distribution, $\sigma^2_{a_0}$ is calculated as the variance of all the observations with a positive amount of financial assets at age 25.

Electricity firm Similar to Hochmuth et al. (2025), I assume α_R to be 0.5. I take estimates for the elasticity of substitution from the literature, namely 1.8 for the EoS between green and brown sources in green electricity generation λ, from Papageorgiou et al. (2017) and 0.25 for the elasticity between capital and fossil fuels in brown electricity production, ω, from Coenen et al. (2024). The remaining parameter, ζ governs the capital share in the production of E_F, and is assumed to be 0.3.

Lastly, The productivity of capital in the electricity sector, for green capital A_{KR} and brown capital A_{KF} are chosen to match (1) the share of renewable electricity and (2) the relative price of electricity over fossil fuels, explained in more detail in the internal calibration section.

The results are robust to changes in ζ ranging from 0.1 to 0.5, as the parameter is relatively inconsequential due to the internal calibration of the productivity to match input shares.

Durable goods firms I set the productivity level of the firm producing the brown durable good such that the price of the brown durable good equals nearly half of the mean yearly income, namely 12000 euros. I set the price gap between the green and the brown durable to 1.9, similar to Kuhn & Schlattmann (2024) who calculate this for Germany.

During the transition, I let the price premium of the green durable shrink to zero by increasing the productivity A_G in a linear fashion, such that at time T, $P_T^{d_G} = P_T^{d_G}$. In order to determine T, I extrapolate the trend of the real price decrease in electrical vehicles and heat pumps over the period 2014-2020.

Final consumption good firm I follow the literature for both the capital-share in the capital-labor composite, and the the elasticity of substitution, ν. With respect to the latter, the literature agrees on a realistically low elasticity of substitution ranging from 0.1 (Hochmuth et al., 2025; Fried et al., 2022) to 0.2 (Olovsson & Vestin, 2023). In order to be on the conservative side in terms of the tax required to decrease industry emissions, but stay within the accepted range, I set ν to 0.2.

Next, with repspect to the capital-labor share, ψ, Hassler et al. (2021) show that this parameter is unimportant in this exact problem so long as ν is not close to one. Therefore I follow Hochmuth et al. (2025) and set it to a 50-50 share. To pin down the elasticity of subsitution between the different types of fossil, ι, I employ the empirical literature estimate from Papageorgiou et al. (2017), who estimates both ι and the electricity share κ.

I internally calibrate the rates at which energy is transformed into the final good, so productivities A_{EC} and A_{FFC} in order to match the electricity input share, and the amount of fossil fuels used in industry over total fossil fuels used. Lastly, the productivity of capital-labor is set to normalize the wage to one in the initial steady state.

3.1 Internally calibrated parameters

To discipline 9 parameters that lack a clear data counterpart, I target several implied moments in the simulated data. For exact identification, I use 9 moments, which are shown in table 2. I match the model

	Moment	**Calculation**	**Data**	**Model**
β	Mean wealth over mean income	$\int_{i,j} a_{i,j} \ / \int_{i,j} wy_{i,j}$	4.2	4.28
η	Decay of wealth	$\int_i a_{i,J} \ / \int_i a_{i,J_W}$	0.98	0.77
$\underline{b}$	Wealth inequality at death	$\int_{i\|D3} a_{i,J} \ / \int_{i\|D6} a_{i,J}$	5.71	5.87
γ	Mean energy expenditure share	$\int_{i,j} \frac{P^{\phi_{i,j}} e_{i,j}}{P^{\phi_{i,j}} e_{i,j}+c_{i,j}}$	0.125	0.126
$\bar{s}$	Degree of non-homotheticity	$\int_{i,j\|Q1} \frac{P^{\phi_{i,j}} e_{i,j}}{P^{\phi_{i,j}} e_{i,j}+c_{i,j}} \ / \int_{i,j\|Q5} \frac{P^{\phi_{i,j}} e_{i,j}}{P^{\phi_{i,j}} e_{i,j}+c_{i,j}}$	1.6	1.63
A_{KR}	Green electricity share	$\frac{E_R}{E_R+E_F}$	0.175	0.161
A_{KF}	Relative price of electricity	$\frac{P_E}{P_{FF}}$	2.40	2.43
A_{EC}	Input share electricity final good	$\frac{E_C}{E_C+FF_C}$	0.34	0.28
A_{FFC}	Final good fossil fuel share	$\frac{FF_C}{FF_C+FF_{HH}+FF_E}$	0.46	0.48

Table 2: Target moments in internal calibration

implied with their data counterparts using a simulated method of moments. In doing so I choose a vector of parameters $\iota = (\beta, \eta, \underline{b}, \gamma, \bar{s}, A_{KR}, A_{KF}, A_{EC}, A_{EFF})$ in order to minimize the objective function

$$\min_{\iota} \sum_{i=1}^{9} \omega_i \left(\frac{M_i^{model}(\iota) - M_i^{data}}{M_i^{data}} \right)^2, \tag{39}$$

in which ω_i gives a weight for each moment i.

For the moments related to the wealth and income on the household side, i.e. parameters $\beta, \eta, \underline{b}$, I use Dutch micro-data. The first three moments are calculated in the data using the DNB household survey, waves 2010 - 2020. For the discount factor β, I target the ratio of mean household financial net worth (NW) over mean net household income, which in the model is normalized to 1. Second, for the strength of the bequest motive, η, I measure the mean decay of net worth in the data as the mean net worth at age 75 over the mean worth at age 65, in order to match the ages of retirement and death in the model. Over the course of 10 years, financial net worth is almost constant, decreasing slightly from 49668 to 48683 euros. Lastly, to discipline the degree of luxurity of bequests, $\underline{b}$ I target the degree of bequest inequality. I compute the mean financial net worth in the third and sixth decile at age 75, and take the ratio as the measure of inequality.

For the fourth and the fifth moment, governing the energy expenditure share of households, I use the experimental statistics on income, consumption and wealth from Eurostat for 2015. This dataset uses data from the Household Finance and Consumption Survey. By using household level data, it calculates expenditure shares for a variety of different goods as well as total expenditures. In figure 3 the dotted gray line shows the energy expenditure share for households in each income quintile in the data. In the internal calibration, I match the average energy expenditure share of 12.56% and the degree of non-homotheticity as measured by the energy expenditure share in the first over the last quintile, equal to 1.6. I calculate the energy expenditure share over total expenditure where the latter is defined as expenditures on all HCIP items. By matching the average, and the degree of non-homotheticity, the energy expenditure per income quintile in the model results in the black line. These two parameters together pin down the behavior targeted in the data as visualized in figure 4. They seem sufficient in getting a good fit over the entire income distribution as shown in figure 3.

To discipline the productivities in the model, I use aggregate Eurostat data. I set the productivity of the green capital in electricity generation, A_{KR} to target share of electricity that is produced from renewable sources which in Europe, 2015, is 17.5%[11]. To determine the productivity of the brown capital in electricity generation, A_{KF}, I target the relative price of electricity over the price of fossil fuels. As explained above, the price of electricity is 0.0546 per kWh of fossil energy. For the electricity price, I take the DC band price

[11]Online data code: nrg_ind_ren

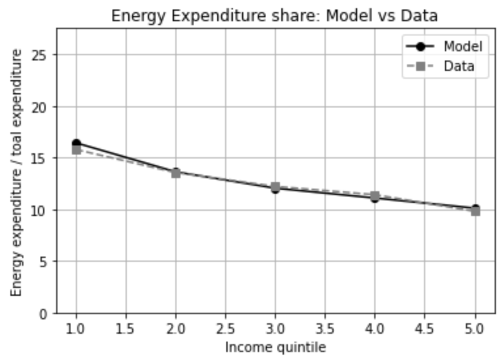

Figure 3: Energy expenditure share per income quintile in Eurostat data (2015) and in the model initial steady state

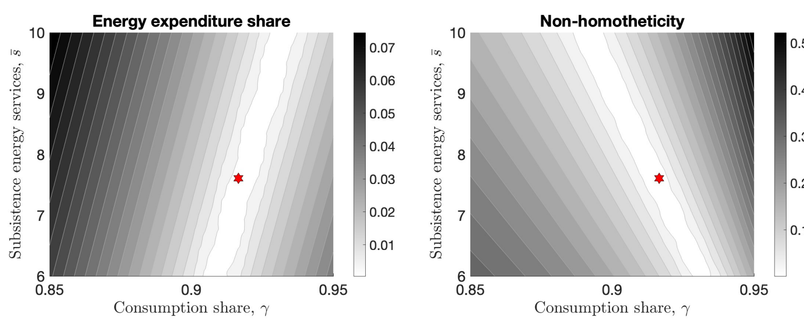

Figure 4: Absolute deviation between simulated model moment and the data target for parameters $\gamma, \bar{s}$ and A_G and their respective moments the mean energy expenditure share, degree of non-homotheticity in energy expenditures and share of households with a green durable.

for one kWh in 2015 in Europe, which is 0.131 euros, from Eurostat [12].

The productivities for both energy sources within the production of the final consumption good, A_{EC} and A_{FFC} are disciplined by matching the input share of electricity in its energy mix and the share of fossil fuels used over total fossil fuels used. Using Eurostat aggregate data for the industry excludes the electricity sector but includes all energy used by sectors that conduct other manufacturing and industrial processes. Using natural and manufactured gas, heat, oil and petroleum products, biofossils and solid fossil fuels as a measure of total fossil fuels used in the industry, this implies 34% of all energy used is electricity. To determine the amount of fossil fuels used in the industry, I follow calculates from the energy statistics report from Eurostat[13]. Taking into account all fossil fuels used in the European economy 46% was used by the industry (defined as manufacturing, storage and services). The remainder consists of fossil fuels used in electricity production (21.8%) and by households for heating and mobility (26.2%). The remaining 6% is used for among other things mining, water supply and construction.

3.2 Baseline model validation

In order to validate the model, I evaluate the baseline switching behavior in the first years of the transition, and I compare inequality in the model and data.

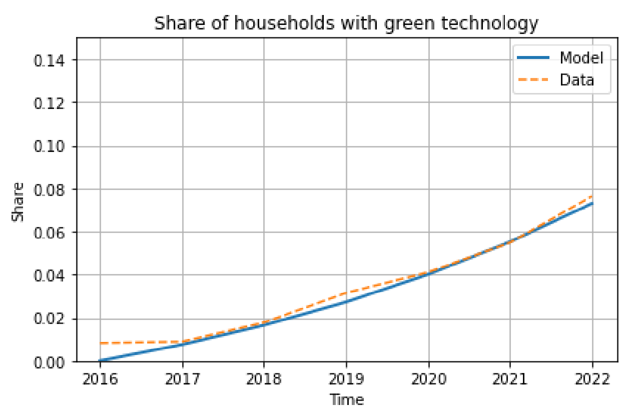

Figure 5: Baseline green technology adoption

Baseline switching behavior I use publicly available Dutch data from RDW and CBS about the share of homeowners with a heatpump, and car owners with an electrical vehicle. The take-up of electrical vehicles

[12]Online data code: nrg_pc_204

[13]Energy accounts, 2025

is slightly slower. As in the model the good is a composite of both, I take this minimum as the share to validate against. Figure shows a good fit overall.

Moment	**EU mean** (min-max)	Model
Income gini	30.8 (23.7 - 37.9)	35.0
Wealth share bottom 50%	0.03 (0.0 - 11.9)	0.19
Wealth share top 10%	0.6 (0.49-0.7)	0.28

Table 3: Inequality moments

Inequality In table 3 I show some inequality statistics in the data for the European union' countries (mean, minimum and maximum) in 2015 and the model steady state. I slightly overestimate income inequality but fall within the bounds. I do heavily underestimate wealth inequality. This is caused by a precautionary savings motive for poor households, which is not so much visible in the data.

4 Policy Experiments (first results)

The economy starts in the initial steady state, and in period 1 unexpectedly enters a transition. During the transition, the green durable good becomes available at a price premium. The productivity of producing the durable good A_G and green electricity A_{ER} increase over the course of the transition. I compare this baseline transition case to several policy experiments where I introduce a carbon tax in period 1, also unexpected to households in steady state.

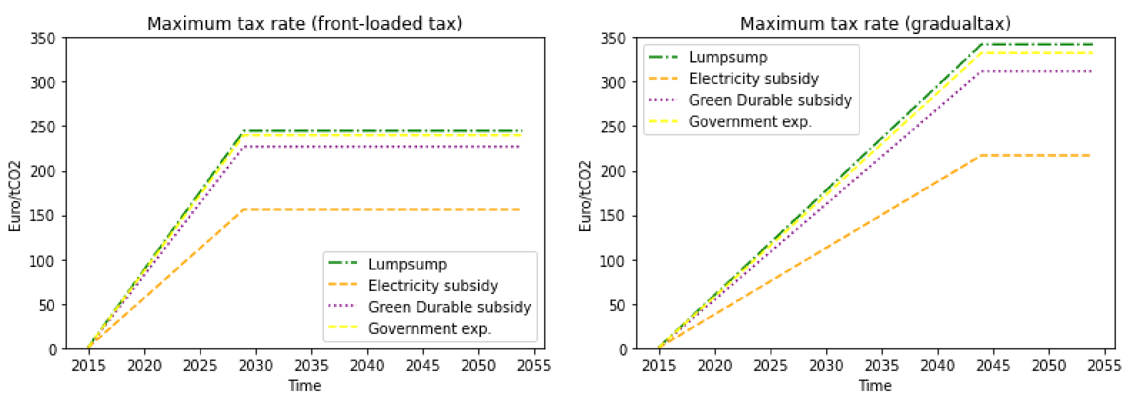

Figure 6: Carbon tax paths by implementation horizon and revenue-recycling instrument in order to meet the exogenous temperature target (2 degrees celcius)

In the policy experiments, I linearly increase the carbon tax τ_c from time $t = 1$ to $\bar{\tau}_c^{i,T}$ in $T_{\tau_c}^{gradual}$ or $T_{\tau_c}^{frontload}$ time periods. For a first iteration, I choose the exogenous time periods of $T_{\tau_c}^{gradual} = 30$ and $T_{\tau_c}^{frontload} = 15$. I then compare inequality outcomes with respect to the baseline (no tax) case by varying the instrument, i, used to recycle the tax revenue. I consider four revenue-recycling instruments: (i) government expenditure, (ii) a uniform lump-sum redistribution, (iii) a subsidy for green electricity production, (iv) a subsidy for electrification of households[14]. I start by computing the tax rate $\bar{\tau}_c^{i,T}$ that for that combination of time horizon T and instrument i achieves a maximum temperature increase of 2 degree celcius above the industrial level in 2065.[15] I then compute the distributional welfare effects through the expenditure equivalent conditional on income and age group. I analyze how much of these welfare effects is caused by the electrification friction.

Before examining these welfare effects, figure 13 shows auxiliary insight into the tax path for each horizon, instrument combination that reaches the temperature target. A fast implementation (short horizon) for the tax implies that a lower tax rate suffices in the long-run, but in the short-run tax rates are higher compared to gradual implementation. Using subsidies as recycling instrument, especially a green electricity subsidy also reduces the peak tax rate required to achieve the temperature target. The figure for temperature can be found in the appendix.

4.1 Distributional Welfare Effects Currently Alive Households

The left panels in figure 7 show the expenditure equivalence of a given policy plus redistribution instrument for the average household in a given age, productivity group for all households alive when the policy is introduced. It shows that, with the exception of a uniform lump-sum redistribution, all agents are worse off with a carbon tax in place. In the case of a lump-sum redistribution, poorer agents gain from the policy, this is due to the fact that they now receive a higher disposable income and a large part of their income is certain.

For the other cases, government expenditure and subsidy recycling, all agents are worse off, and especially poor middle-aged households suffer the largest welfare loss from a carbon tax. They cannot electrify, spend a large fraction of their income on energy and are mostly dependent on labor rather than capital income. Therefore, they see their income decrease, while their relative energy bill rises the most. Subsidies increase welfare compared to the case of wasteful government expenditure. When the subsidy is directed at renewable

[14] I cap the electrification for households at 40% as the revenue including the firms' tax payments exceeds the amount that can be given out as subsidies. This amount is in line with most taxes given out in Europe. In the default case, the remainder is spent on government expenditure.

[15] As the economy is not in net-zero at this point, the underlying assumption should be that some carbon capture technology keeps the temperature at 2 degree celcius.

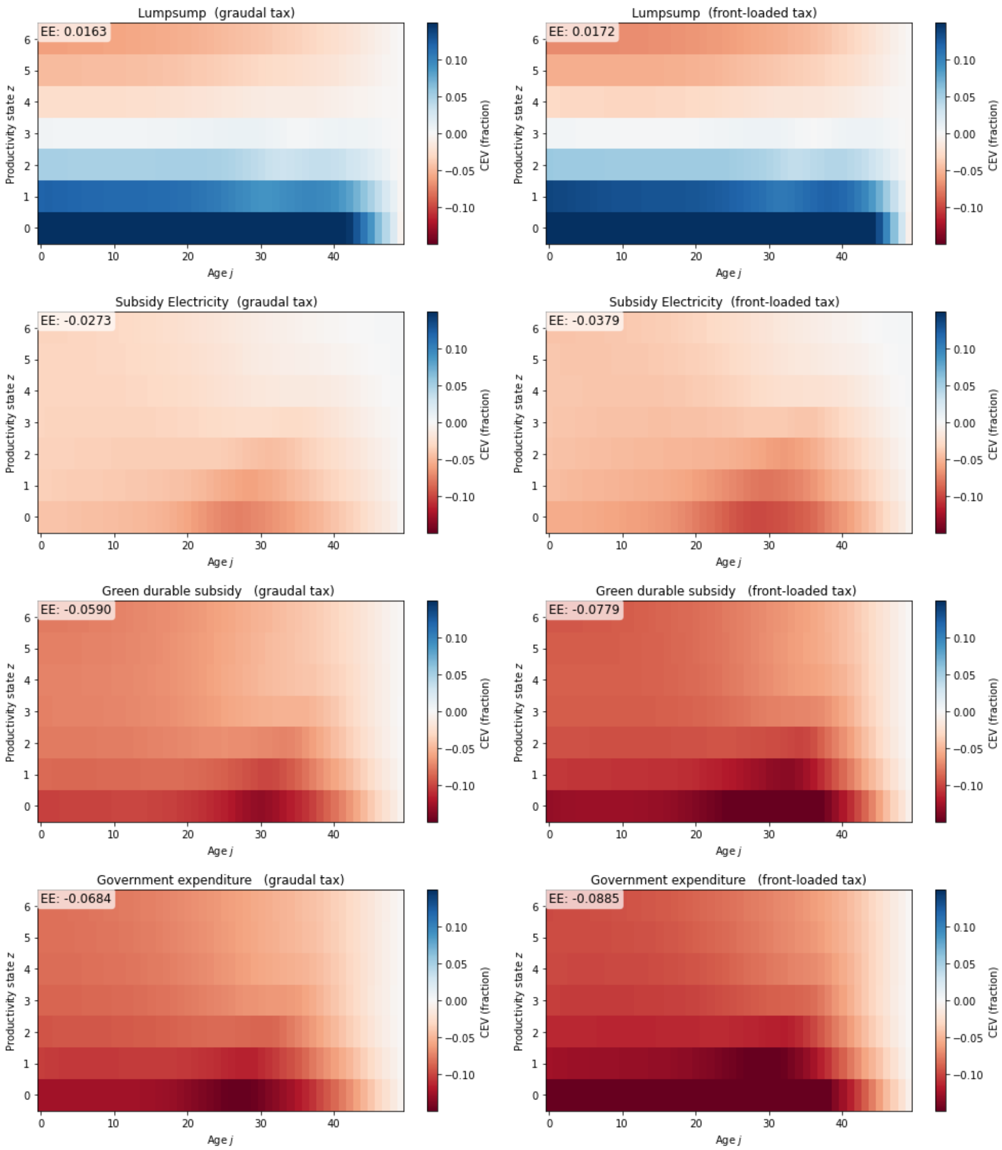

Figure 7: Expenditure equivalence for households on the age-income space for different recycling instruments, where the tax is phased in in 30 years. The percentage in expenditure required in the baseline case to be indifferent between the baseline and policy case.

electricity, the welfare losses are smaller overall compared to an electrification subsidy. The significant welfare difference between subsidy types is mostly explained by the diminished negative general equilibrium effects in the electricity subsidy case. Firstly, the carbon tax is significantly lower in this case than in the electrification subsidy case, and second, as the price of electricity is significantly lower following the subsidies, wages decrease significantly less for the same carbon tax. Overall, these two effects lead to electricity subsidies being superior over an electrification subsidy in terms of welfare effects[16].

The right panels of figure 7 show the analogous results for the case where the tax is phased-in twice as rapid. In this case compared to slow phasing in of the carbon tax, the qualitative ranking across recycling instruments is unchanged, but the welfare burden becomes markedly more front-loaded – and therefore bigger due to discounting – and more unequally distribued. Relative to the 30-year path for the carbon tax, welfare decreases for all recycling instruments except lump-sum redistribution, with the largest deterioration concentrated among low-income, middle-aged households. Quantitatively, average welfare losses become more negative in all non–lump-sum cases (electricity subsidy: from -0.0273 to 0.0379; green-durable subsidy: from 0.0590 to 0.0779; government expenditure: from 0.0684 to 0.0885; lump-sum from 0.0163 to 0.0172), and the order of magnitude differs only slightly among instruments. In the case of lump-sump, rapidly phasing in makes the agents better off. This is especially visible in table 4, and is because the increase in disposable income is front-loaded.

Instrument	CE (gradual, 30y)	CE (fast, 15y)	$CE^{\text{fast}} - CE^{\text{gradual}}$	$\left(\frac{CE^{\text{fast}} - CE^{\text{gradual}}}{\lvert CE^{\text{gradual}}\rvert}\right)$
Lump-sum transfer	0.0163	0.0172	0.0009	5.5%
Electricity subsidy	-0.0273	-0.0379	-0.0106	-38.8%
Green durable subsidy	-0.0590	-0.0779	-0.0189	-32.0%
Government expenditure	-0.0684	-0.0885	-0.0201	-29.4%

Table 4: Consumption equivalence (CE) under gradual vs. fast carbon-tax implementation. CE is measured as a fraction of consumption. Gradual corresponds to the 30-year phase-in; fast corresponds to the 15-year phase-in. Negative values indicate welfare losses.

Judging from table 4, rapid carbon-tax implementation is substantially more harmful for welfare when revenues are recycled through subsidies or wasteful government expenditure. Relative to the gradual path, average CE declines by about 38% under electricity subsidies, 32% under green-durable subsidies, and 30%

[16]The combination of a green durable subsidy and electricity subsidy does not improve welfare beyond what the electricity subsidy compared to the electrification subsidy does.

under government expenditure, while the effect is positive under lump-sum recycling (about 5.5%, from a positive base). Distributionally, figure 7 shows that these losses are concentrated among low-income, working-age households that cannot electrify quickly and rely heavily on labor income. Hence, the short-run welfare cost of fast implementation is primarily an instrument-dependent result: large under subsidy or government expenditure recycling, limited under lump-sum transfers.

4.1.1 The Role of the Electrification Adjustment Friction

The electrification margin can explain why this age heterogeneity in welfare losses at especially lower productivity level arises. It also explains why climate policy affects different age groups differently.

In order to identify the effect of the electrification friction, I compute the differential of the expenditure equivalence above with the expenditure equivalence if everyone was endowed with a green technology rather than a brown technology. Figure 8 plots the state-dependent difference in consumption-equivalent variation at $t = 1$, defined as

$$CE_{t=1}^{\text{noElec}}(j,z) - CE_{t=1}(j,z),$$

for the gradual-tax scenario.

The left panels of figure 8 show the difference between the welfare effects in absence of the electrification friction with the baseline model when the tax is phased in gradually. In all cases the electrification friction makes households significant worse off due to climate policy. Especially, the friction makes that poor, middle-aged households suffer disproportionally from climate policy. In appendix G, I show the probability that a household aged j, in income group z when the policy is introduced, switches to a green technology in its lifetime. The triangle of households who do not adopt to green technologies, overlap exactly with the darker triangles in figure 8. Together this shows that for households who do not have the financial resources or time to electrify, but life long enough to accumulate a high energy bill suffer the most from the existence of the financing frictions for electrification.

The right panel of figure 8 shows that the negative welfare effects caused by the electrification friction are substantially larger when the tax is phased-in more quickly. Overall the electrification friction affects households if the tax is phased in quickly, and the recycling instrument for tax revenue is subsidies or expenditure rather than lump-sum redistribution. On the contrary, when using lumpsump redistribution the existence of the electrification friction actually makes current, poor households a little bit better off. This is because this policy design front-loads the redistributed tax revenue, which is discounted less. Thus overall, front-loading the tax is not harmful for current generations when the tax revenue is redistributed back to households, even with the existence of the electrification friction.

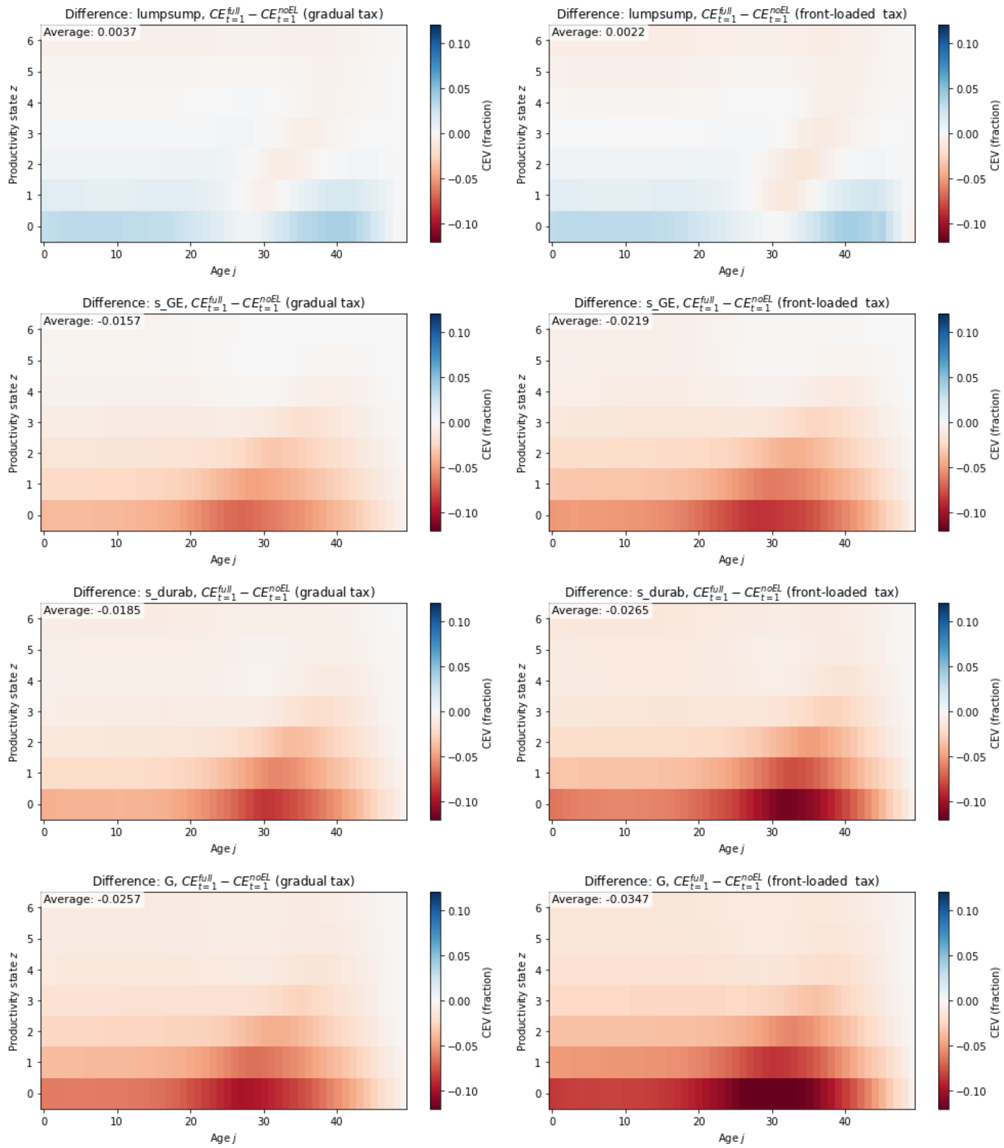

Figure 8: State-space heatmap of $CE^{\text{noEL}}_{t=1}(j,z) - CE^{\text{full}}_{t=1}(j,z)$ under a gradual (left) or rapid (right) tax implementation for different recycling instruments.

4.1.2 Further understanding the welfare effects [to include or not?]

To further investigate what exactly causes which households to be worse off due to the carbon tax, I decompose the welfare effect of a carbon tax plus redistribution instrument into three channels: (i) general equilibrium (GE), operating through changes in equilibrium factor prices (w_t, r_t) and therefore also the electricity price P_t^E; (ii) non-homothetic energy demand (NH), operating through a subsistence level for energy and hence a high energy burden for low income households; and (iii) electrification (EL), operating through durable adjustment that moves households across the state space where they are more exposed to carbon taxes ($\phi = 0$) and less exposed to carbon taxes ($\phi = 1$).

Two difficulties arise. First, GE and NH affect welfare primarily through the value function at given states, whereas EL operates importantly by shifting the distribution of households over states; a purely pointwise decomposition therefore misses EL by construction. Second, any sequential accounting of mechanisms is generally order-dependent: the measured contribution of a channel depends on which other channels are introduced first.

To address both issues, for each subset of channels $S \subseteq N \equiv \{\mathrm{GE}, \mathrm{NH}, \mathrm{EL}\}$ I define a welfare functional that combines (i) the consumption equivalence computed within the same channel configuration for each state and (ii) aggregation using the to that channel corresponding no-policy stationary distribution. Let $x = (j, z, \phi, l, m)$ denote household states and let $\mathcal{X}_{j,z}$ denote the set of states with exogenous components (j, z). Define

$$W_S(j,z) = \frac{\sum_{x \in \mathcal{X}_{j,z}} \mu_S(x) \, \mathrm{CEV}_S(x)}{\sum_{x \in \mathcal{X}_{j,z}} \mu_S(x)}, \tag{40}$$

where $\mathrm{CEV}_S(x)$ compares policy vs. no-policy within the same configuration S, and μ_S is the no-policy stationary distribution implied by S. I then apply Shapley values to the set function $S \mapsto W_S(j,z)$ to obtain an additive and order-independent decomposition of the total welfare effect into channel contributions:

$$\lambda_i(j,z) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|! \, \big(|N| - |S| - 1\big)!}{|N|!} \big(W_{S \cup \{i\}}(j,z) - W_S(j,z)\big), \qquad i \in N. \tag{41}$$

By construction,

$$W_N(j,z) = W_\emptyset(j,z) + \lambda_{\mathrm{GE}}(j,z) + \lambda_{\mathrm{NH}}(j,z) + \lambda_{\mathrm{EL}}(j,z), \tag{42}$$

such that the total welfare effect at state j, z, $W_N(j,z)$ is split up into the welfare effect absent any of the three channels, $W_\emptyset(j,z)$ and the welfare effects from the channels $\lambda_{\mathrm{GE}}(j,z), \lambda_{\mathrm{NH}}(j,z), \lambda_{\mathrm{EL}}(j,z)$. Income-dependent welfare channels

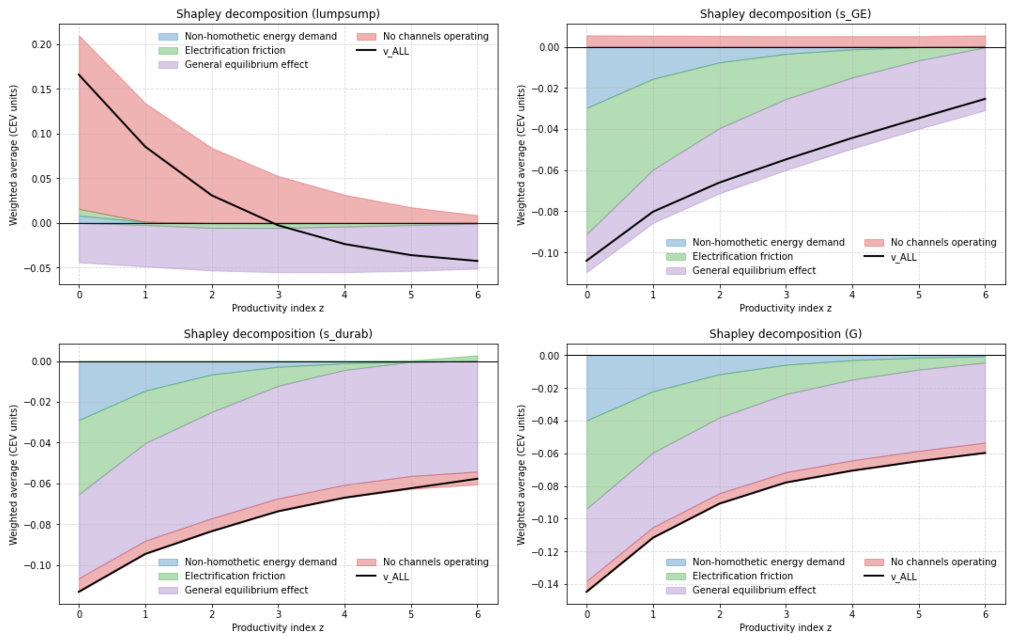

Figure 9: Decomposition of welfare effects over different states of productivity [this graph uses a phase in period of 30 years and tax rates are the same throughout all scenarios, still need to fix correct tax rate. Quantitative interpretation stays the same, qualitatively changes.]

In figure 9 I show this decomposition averaged over the income-dimension. The black line equals the total welfare effect for each group. The pink region shows $W_{\emptyset}(j,z)$, the welfare effect if all three channels are shut-off. The purple, blue and green region refer to $\lambda_{\text{GE}}(j,z), \lambda_{\text{NH}}(j,z)$ and $\lambda_{\text{EL}}(j,z)$ respectively. A first striking result is that in all cases except the lump-sum redistribution, where agents are all worse off, the three channels explain almost all the welfare effects. The decomposition for government expenditure and the electrification subsidy for the durable, show that in a world where households already electrified, there is no non-homotheticity and input prices $\{r_t, w_t\}$ are unchanged, households are only slightly worse off due to the small increase in the electricity price. When the electricity subsidy is introduced, this even becomes a positive welfare effect, as the electricity price decreases. This is caused by the carbon tax paid by the firm, which would normally cause a general equilibrium effect that decreases the wage. Furthermore, figure 9 shows that the welfare gain in the lump-sum redistribution case is completely explained by the large influx of income absent any channels. Adding the three channels has little effect on this, especially for poor households.

In all other redistribution instrument cases, the addition of channels creates the biggest difference in welfare. Figure 9 shows that welfare heterogeneity on the income dimension is primarily driven by non-homothetic energy demand and the electrification decision. Poor households with an already large relative energy bill cannot afford to electrify (directly) and have even higher energy costs, while richer households reduce their bills through earlier electrification. Therefore, the impact of non-homothetic energy demand and the electrification decision is primarily felt by the poorer households. The welfare effects operating through the general equilibrium channel, a decrease in wage and increase in interest rates, are stronger for households with a higher productivity, however this effect is small compared to the other two channels.

A green electricity subsidy reduces welfare losses from general equilibrium effects as it lowers firms' electricity costs. Therefore, input prices are less affected. An electrification subsidy, on the other hand, mitigates the welfare effects from the need to electrify. While both subsidies reduce different channels of inequality, no single subsidy is sufficient to tackle both. Using both instruments is necessary to address both the electrification friction and general equilibrium effects effectively in order to diminish the welfare effects for the poorest agents.

Age-dependent welfare channels Figure 10 shows the same decomposition but then averaged over the income dimension. The directions in which channels operate is the same in both cases, however figure 10 shows that welfare inequality along the age dimension arises mainly from general equilibrium effects (wage and interest rate changes) and the electrification decision. Middle-aged agents suffer disproportionately from not being able to electrify while still accumulating a high energy bill. Younger agents suffer from the permanent decrease in wages caused by the policy. In this picture, the same conclusion can be drawn about the effectiveness of different subsidy schemes on the different channels operating, however when averaging out the income dimension, the difference between the total welfare effects in the combined subsidy case and the subsidy for green electricity become very small. This implies that the combined subsidy helps mostly the poorest agents, but not necessarily the middle-aged group.

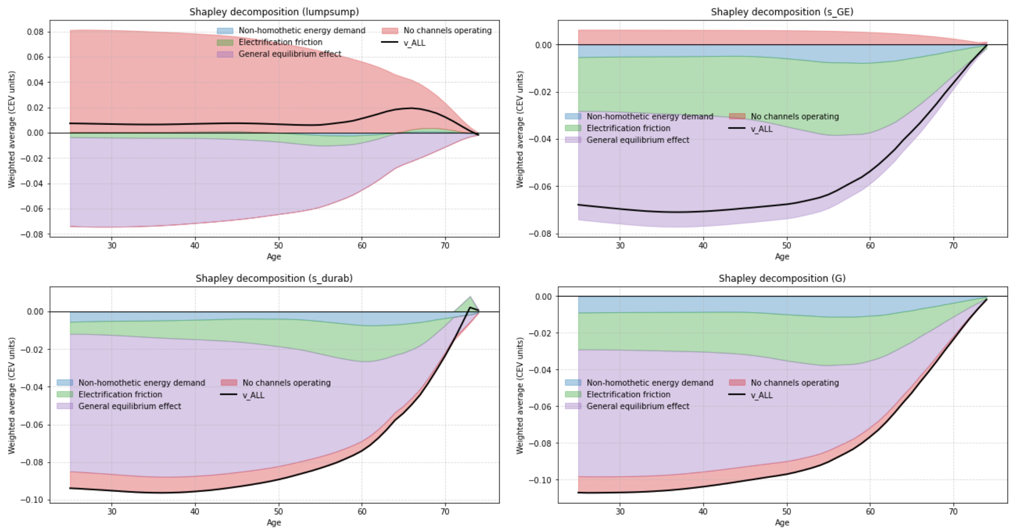

Figure 10: Decomposition of welfare effects over different states of age [this graph uses a phase in period of 30 years and tax rates are the same throughout all scenarios, still need to fix correct tax rate. Quantitative interpretation stays the same, qualitatively changes.]

4.2 Long-run efficiency

Figure 11 shows that a front-loaded carbon-tax path is associated with a sharper short-run contraction, but a faster medium- to long-run recovery in output. In both panels, GDP initially declines after the policy introduction because higher fossil fuel costs raise firms' production costs before the productivity of renewable capital has risen to its maximum level. This short-run dip is deeper under the rapid implementation path (left panel), consistent with the mechanism that taxes rise sharper in the short-run while renewable capital productivity is still low. As a result, the economy experiences a stronger temporary cost push and wage compression early in the transition.

Over time, however, the ranking reverses in efficiency terms: the rapid path closes the gap to baseline sooner and stabilizes at a higher GDP level than the gradual path for a given date in the transition. Due to the lower long-run tax rate, production becomes less exposed to higher energy costs and can move more closely to the non-tax baseline scenario. This dynamic is visible across all recycling schemes, implying that long-run efficiency gains from faster implementation are relatively robust to the redistribution instrument. The instrument mainly affects the level of GDP along the transition. Electricity subsidies consistently dominate the other recycling schemes by dampening general-equilibrium effects. On the other hand, the speed of the tax phase-in primarily governs the speed of recovery.

Taken together, faster implementation worsens short-run efficiency outcomes but improves long-run GDP recovery, whereas slower implementation smooths the transition at the cost of delayed macroeconomic recovery.

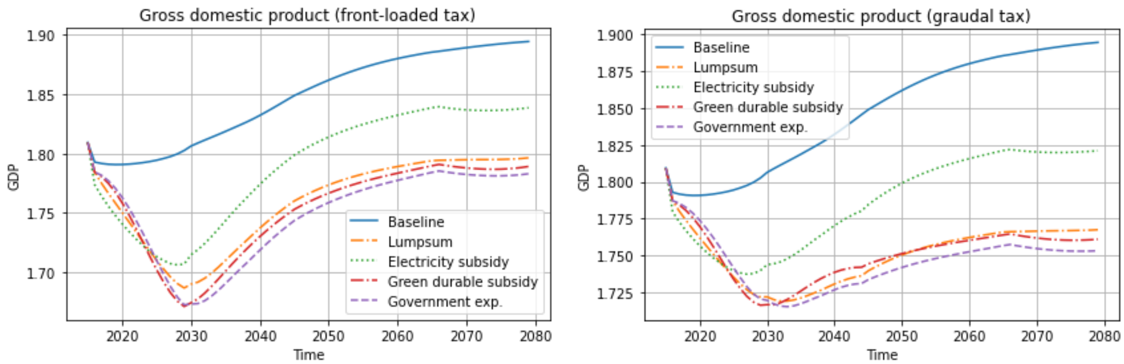

Figure 11: GDP over the course of the transition for a rapid transition (left) or slow transition (right)

These findings are broadly in line with the findings in the analyses of the effect of front-versus-back loading a tax and on short-,medium- and long-run GDP Coenen et al. (2024). They are also supportive evidence of reduced economic activity, as in Kaldorf & Rottner (2024). However, in their paper reduced economic activity caused by climate policy reduces the interest rate, which increases the possibility of a financial crisis. This last fact does not hold true in the economy in this paper due to the existence of a shift to the capital-intensive electricity sector.

4.3 Welfare of Future-Born generations

The analysis so far focused on households alive when the policy is introduced. I now consider future cohorts, i.e., households born in cohort $t > 1$. Because the carbon tax increases over the first years before reaching its peak, these cohorts typically face higher average carbon tax rates over their lifetimes than those already alive at $t = 0$. At the same time, as electrification progresses, later born households are increasingly likely to be born with a green durable, which mechanically changes the incidence of the policy across cohorts.

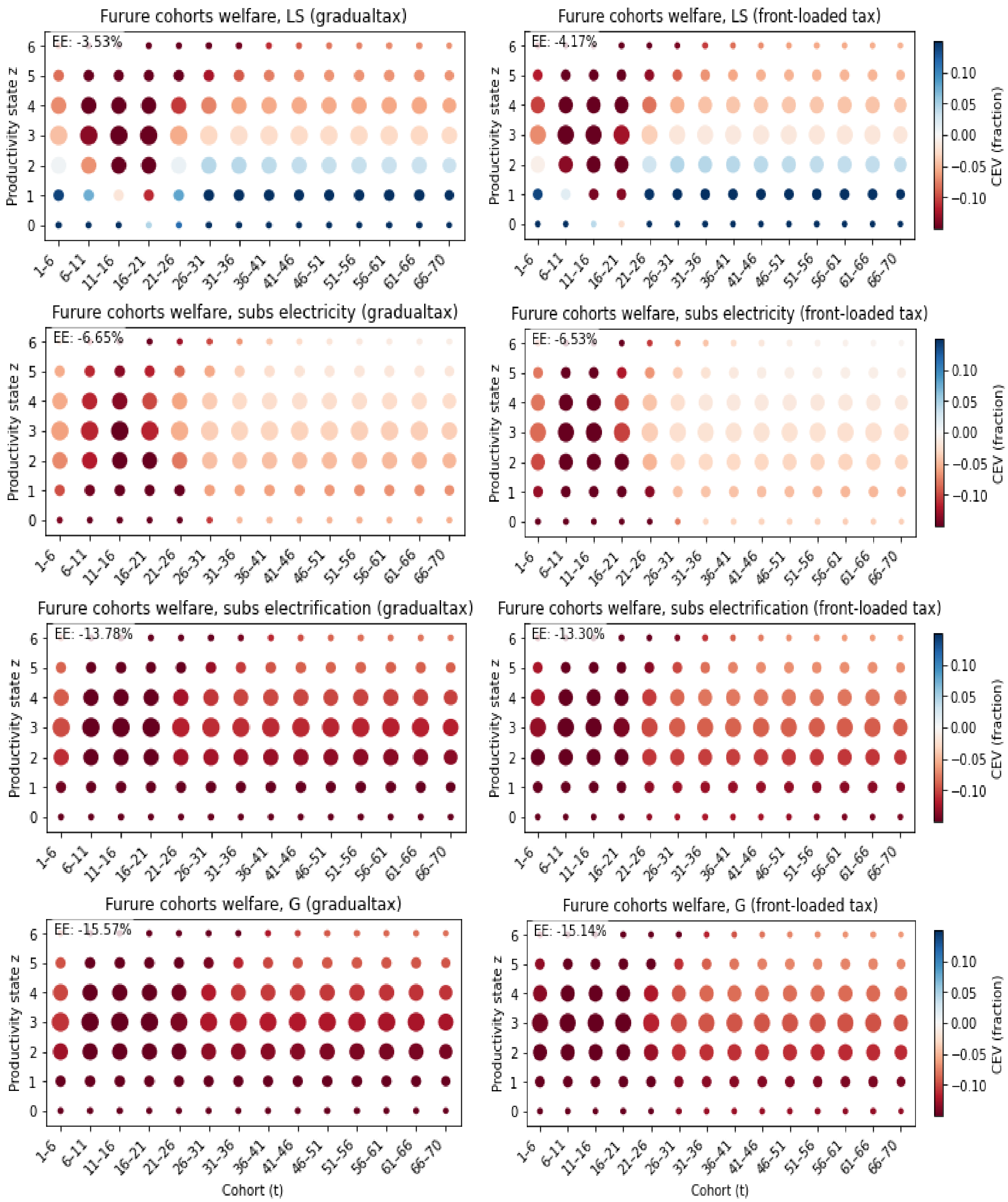

Figure 12: The expenditure equivalence for generations born in cohort t (x-axis), productivity level z (y-axis). Size denotes the size of this group.

Figure 12 reports expenditure-equivalence welfare changes by cohort t, productivity z. Future generations suffer less from the carbon tax if revenues are recycled using a lump-sum redistribution instrument, and to some sense from the electricity subsidy. Conditional on t and z households born with a green durable experience substantially smaller welfare losses than those born with a brown durable, as can be seen in the appendix. The differential between the two groups depends on the redistribution instrument used: an electricity subsidy mitigates the welfare losses for households born with a green durable most. Therefore when the electricity subsidy is included, welfare inequality between the two groups is largest. The timing of the carbon tax shifts the main burden of the tax slightly between cohorts, but does not affect aggregate future welfare effects.

5 Conclusion

This paper studied the effects of a carbon tax on inequality in an economy containing both sides of the energy transition: electrification and decarbonization of electricity. It examined these effects under multiple revenue redistribution instruments, and different horizons at which the tax is phased in. I show that while carbon taxation robustly accelerates emission reduction, its effectiveness and welfare effects are highly dependent on the tax path and revenue recycling instrument. I also show that welfare effects are potentially unequal and shaped by three mechanisms: non-homothetic energy demand, heterogeneous carbon intensity across households caused by an electrification choice, and general-equilibrium wage and interest rate responses. These three channels cause the biggest welfare costs to be borne by middle-aged, poor households.

A wasteful carbon tax or a carbon tax redistributed using subsidies poses a timing trade-off, where rapid phasing in comes at a larger current welfare burden and GDP dip, but larger and faster future GDP recovery and benefits future generations more. This trade-off vanishes with lump-sum redistribution. Rapid implementation of a carbon tax attenuates both a small current welfare increase, as well as faster and larger GDP recovery in future periods. It is the one instrument that does not materialize in choosing between the two.

If subsidies are chosen as a redistribution instrument, subsidizing the electricity sector has a clear preference over subsidizing electrification. An electricity subsidy decreases the price of electricity, which stimulates electrification – especially in the firm – which allows for a lower carbon tax for the same temperature target. The combined effect of a lower tax rate and lower electricity prices account for smaller general equilibrium effects. Furthermore they benefit households who have electrified. This however increases the unequal welfare burden between households who can versus those who cannot electrify, especially at a rapid tax implementation.

Overall, the electrification margin for households created distributional effects via heterogeneous carbon intensity of energy demand, that are significant. When policy-makers are inclined on reducing emissions, it would best balance this objective with an equity objective through the use of lump-sum redistribution rather than targetted subsidies, and phase the tax in quickly to diminish future costs of the carbon tax. These results underscore that the design of revenue recycling determines who wins and who loses from climate policy. By quantifying the relative importance of the underlying inequality channels, the paper offers guidance for policymakers seeking to balance equity and decarbonization efficiency objectives along the green transition.

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Appendix

Appendix A: Solving the household problem

The value function is given by

$$V_j(a,\phi;y,P,\mathcal{T}) = \max\{V_j^{NA}(a,\phi;y,P,\mathcal{T}), V_j^{A}(a,\phi;y,P,\mathcal{T})\} \tag{43}$$

I individually solve for the intermediate functions, which I can do for the last living period given the bequest value.

I start by solving the non-adjuster problem. I first solve for the static problem analytically. The dynamic problem then becomes

$$V_j^{NA}(a,\phi,m;y,P,\mathcal{T}) = \max_{a'} \tilde{u}(\tilde{c}) + \beta\mathbb{E}[V_{j+1}(a',\phi',m';y,P,\mathcal{T})] \tag{44}$$

subject to

$$\tilde{w} = y + (1+r)a + \mathcal{T} - \delta_\phi - f(j)m - a' \tag{45}$$

$$e = (1-\gamma)\frac{\tilde{w}}{\phi P^E + (1-\phi)(P^{FF}+\tau_c)} + \gamma(\phi\rho + (1-\phi)\chi)\bar{s} \tag{46}$$

$$c = \gamma\big(\tilde{w} - (\phi\rho + (1-\phi)\chi)(\phi P^E + (1-\phi)(P^{FF}+\tau_c))\bar{s}\big) \tag{47}$$

$$\tilde{c} = c^{1-\gamma}\big(\frac{e}{\phi\rho + (1-\phi)\chi} - \bar{s}\big) \tag{48}$$

$$\tilde{u}(\tilde{c}) = \frac{\tilde{c}^{1-\sigma}}{1-\sigma} \tag{49}$$

$$m' = (1 - f(j) + r)m, \quad \phi' = \phi \tag{50}$$

$$a' \geq 0 \tag{51}$$

Given value function $V_j^{NA}(a,\phi,m;y,P,\mathcal{T})$ and policy functions $a'_j(a,\phi,m;y,P,\mathcal{T})$, $c_j(a,\phi,m;y,P,\mathcal{T})$, $e_j(a,\phi,m;y,P,\mathcal{T})$, I continue by solving for the adjuster value function, by recognizing that this is an interpolation of the non-adjuster problem

$$V_j^A(a,\phi;y,P,\mathcal{T}) = \max_{m'} V_j^{NA}(\tilde{a},\phi'=1,m';y,P,\mathcal{T}) \tag{52}$$

$$\tilde{a} = a - (P^G - \varphi P^B) + m' \tag{53}$$

$$m' \leq \lambda P^G \tag{54}$$

Which gives policy function $\phi'_j(a,\phi,m;y,P,\mathcal{T})$,$m'_j(a,\phi,m;y,P,\mathcal{T})$ and value function $V_j^A(a,\phi,m;y,P,\mathcal{T})$

Appendix B: Solving the Production side

There are three production sectors. One for the final output good, one for the two durable goods and one for electricity.

Appendix B1: Output-good-producing firm

A representative firm produces output goods which can be used for production or converted in durable goods. Inputs are capital, labor and electricity. The technology is a constant returns to scale CES

$$Y^C(K_C,L_C,E_C,FF_C) = \Big[(1-\psi)\big(A_{KC}K_C^{\alpha_c}L_C^{1-\alpha_c}\big)^{\frac{\nu-1}{\nu}} + \psi A_{MC}M^{\frac{\nu-1}{\nu}}\Big]^{\frac{\nu}{\nu-1}} \tag{55}$$

Gives first order conditions

$$r+\delta = \Big[(1-\psi)B^{\frac{\nu-1}{\nu}} + \psi M^{\frac{\nu-1}{\nu}}\Big]^{\frac{1}{\nu-1}}(1-\psi)\,B^{\frac{\nu-1}{\nu}-1}\,A_{KC}\alpha_c\,K_C^{\alpha_c-1}L_C^{1-\alpha_c} \tag{56}$$

$$w = \Big[(1-\psi)B^{\frac{\nu-1}{\nu}} + \psi M^{\frac{\nu-1}{\nu}}\Big]^{\frac{1}{\nu-1}}(1-\psi)\,B^{\frac{\nu-1}{\nu}-1}\,A_{KC}(1-\alpha_c)\,K_C^{\alpha_c}L_C^{-\alpha_c} \tag{57}$$

$$P^E = \Big[(1-\psi)B^{\frac{\nu-1}{\nu}} + \psi M^{\frac{\nu-1}{\nu}}\Big]^{\frac{1}{\nu-1}}\psi\,M^{\frac{\nu-1}{\nu}-1}\Big(M^{\frac{1}{\iota}}\kappa E_C^{\frac{\iota-1}{\iota}-1}\Big) \tag{58}$$

$$P^{FF}+\tau_c = \Big[(1-\psi)B^{\frac{\nu-1}{\nu}} + \psi M^{\frac{\nu-1}{\nu}}\Big]^{\frac{1}{\nu-1}}\psi\,M^{\frac{\nu-1}{\nu}-1}\Big(M^{\frac{1}{\iota}}(1-\kappa)FF_C^{\frac{\iota-1}{\iota}-1}\Big) \tag{59}$$

where

$$B = A_{KC}K_C^{\alpha_c}L_C^{1-\alpha_c} \tag{60}$$

$$M = \Big(\kappa E_C^{\frac{\iota-1}{\iota}} + (1-\kappa)FF_C^{\frac{\iota-1}{\iota}}\Big)^{\frac{\iota}{\iota-1}}. \tag{61}$$

Appendix B2: Durable good producers

In this economy, the durable goods can be produced by converting the consumption good (with cost 1, as its the numeraire) at some rate A_G, A_B, such that production functions are given as

$$Y^{D_G}(C_G) = A_G C_G \tag{62}$$

$$Y^{D_B}(C_B) = A_B C_B \tag{63}$$

These imply input demand functions

$$C_G = \frac{1}{A_G} Y^{D_G} \tag{64}$$

$$C_B = \frac{1}{A_B} Y^{D_B} \tag{65}$$

and prices $P^G = \frac{1}{A_G}$, $P^B = \frac{1}{A_B}$

Appendix B3: Electricity firm

The profits of the electricity firm are given as follows

$$\begin{aligned}\Pi(K_{E_R}, K_{E_F}, FF_E) = P_E\big(\alpha_R^{\frac{1}{\lambda}}(A_R K_R)^{\frac{\lambda-1}{\lambda}} + \alpha_F^{\frac{1}{\lambda}}(A_F[\zeta K_F^{\frac{\omega-1}{\omega}} + (1-\zeta)FF^{\frac{\omega-1}{\omega}}]^{\frac{\omega}{\omega-1}})^{\frac{\lambda-1}{\lambda}}\big)^{\frac{\lambda}{\lambda-1}} \\ - (r+\delta)K_{E_R} - (r+\delta)K_{E_F} - (P^{FF} + \tau_c)FF_E\end{aligned} \tag{66}$$

Equivalently, I can write the problem as follows

$$\Pi = P_E\big(\alpha_R^{\frac{1}{\lambda}} E_R^{\frac{\lambda-1}{\lambda}} + \alpha_F^{\frac{1}{\lambda}} E_F^{\frac{\lambda-1}{\lambda}}\big)^{\frac{\lambda}{\lambda-1}} - P_{E_R}E_R - P_{E_F}E_F \tag{67}$$

subject to the technology constraints

$$E_R = A_R K_R \tag{68}$$

$$E_F = A_F[\zeta^{\frac{1}{\omega}}(A_{KF}K_F)^{\frac{\omega-1}{\omega}} + (1-\zeta)^{\frac{1}{\omega}} FF^{\frac{\omega-1}{\omega}}]^{\frac{\omega}{\omega-1}} \tag{69}$$

Which implies I can split up the problem in two parts. First the problem where I minimize cost by choosing K_{E_R} (K_{E_R}, FF_E) subject to the constraint that production needs to equal some amount E_R (E_F). This problem gives me input demand functions for K_{E_R} (K_{E_R}, FF_E) in terms of E_R (E_F) as well as a price for E_R (E_F), namely P_{E_R} (P_{E_F}).

With these prices I can solve the problem in equation 67, to get the input demand functions for E_F and E_R in terms of some output level Y^E. Combining these with the input functions derived from the other two problems, I get input demand functions: $K_{E_R}(Y^E, r, P^F F, \tau_c)$ $K_{E_R}(Y^E, r, P^F F, \tau_c), FF_E(Y^E, r, P^F F, \tau_c)$, as functions of total output and input prices.

The first step to solving the firm problem for the supply function, is to choose E_F, E_R to minimize cost subject to the constraint of producing some level of electricity $\bar{E}$. The Lagrangian reads

$$\mathcal{L} = P_{E_R} E_R + P_{E_F} E_R + \Lambda(\bar{E} - \big(\alpha_R^{\frac{1}{\lambda}} E_R^{\frac{\lambda-1}{\lambda}} + \alpha_F^{\frac{1}{\lambda}} E_F^{\frac{\lambda-1}{\lambda}}\big)^{\frac{\lambda}{\lambda-1}})$$

The first order conditions are

$$\frac{d\mathcal{L}}{dE_R} \implies \Lambda \alpha_R^{\frac{1}{\lambda}} (E_R)^{\frac{\lambda-1}{\lambda}-1} \big(\alpha_R^{\frac{1}{\lambda}} E_R^{\frac{\lambda-1}{\lambda}} + \alpha_F^{\frac{1}{\lambda}} E_F^{\frac{\lambda-1}{\lambda}}\big)^{\frac{\lambda}{\lambda-1}-1} = P_{E_R} \tag{70}$$

$$\frac{d\mathcal{L}}{dE_F} \implies \Lambda \alpha_F^{\frac{1}{\lambda}} (E_F)^{\frac{\lambda-1}{\lambda}-1} \big(\alpha_R^{\frac{1}{\lambda}} E_R^{\frac{\lambda-1}{\lambda}} + \alpha_F^{\frac{1}{\lambda}} E_F^{\frac{\lambda-1}{\lambda}}\big)^{\frac{\lambda}{\lambda-1}-1} = P_{E_F} \tag{71}$$

$$\frac{d\mathcal{L}}{d\Lambda} \implies \bar{E} = \big(\alpha_R^{\frac{1}{\lambda}} E_R^{\frac{\lambda-1}{\lambda}} + \alpha_F^{\frac{1}{\lambda}} E_F^{\frac{\lambda-1}{\lambda}}\big)^{\frac{\lambda}{\lambda-1}} \tag{72}$$

Dividing through

$$\frac{P_{E_R}}{P_{E_F}} = \frac{\alpha_R^{\frac{1}{\lambda}} (E_R)^{\frac{\lambda-1}{\lambda}-1}}{\alpha_F^{\frac{1}{\lambda}} (E_F)^{\frac{\lambda-1}{\lambda}-1}} \tag{73}$$

Solve for E_R and plug in

$$(\frac{P_{E_R}}{P_{E_F}})^{-\lambda} \frac{\alpha_R}{\alpha_F} E_F = E_R \implies \bar{E} = \big(\alpha_R^{\frac{1}{\lambda}} ((\frac{P_{E_R}}{P_{E_F}})^{-\lambda} \frac{\alpha_R}{\alpha_F} E_F)^{\frac{\lambda-1}{\lambda}} + \alpha_F^{\frac{1}{\lambda}} E_F^{\frac{\lambda-1}{\lambda}}\big)^{\frac{\lambda}{\lambda-1}}$$

Rewriting:

$$\bar{E} = \big(\alpha_R^{\frac{1}{\lambda}} ((\frac{P_{E_R}}{P_{E_F}})^{-\lambda} \frac{\alpha_R}{\alpha_F})^{\frac{\lambda-1}{\lambda}} + \alpha_F^{\frac{1}{\lambda}}\big)^{\frac{\lambda}{\lambda-1}} E_F \tag{74}$$

such that

$$E_F = \frac{\bar{E}}{\big(\alpha_R^{\frac{1}{\lambda}} ((\frac{P_{E_R}}{P_{E_F}})^{-\lambda} \frac{\alpha_R}{\alpha_F})^{\frac{\lambda-1}{\lambda}} + \alpha_F^{\frac{1}{\lambda}}\big)^{\frac{\lambda}{\lambda-1}}} \tag{75}$$

where input demand scales linearly in the amount produced $\bar{E}$, taking all prices as given.

This implies that for any output $\bar{E}$, input demand is given by

$$E_F = \alpha_F \left(\frac{P_{E_F}}{P_E}\right)^{-\lambda} \bar{E} \tag{76}$$

$$E_R = \alpha_R \left(\frac{P_{E_R}}{P_E}\right)^{-\lambda} \bar{E} \tag{77}$$

and the natural price index for E is

$$P_E = (\alpha_R P_{E_R}^{1-\lambda} + \alpha_F P_{E_F}^{1-\lambda})^{\frac{1}{1-\lambda}} \tag{78}$$

Similarly, for the intermediate electricity from renewable and fossil, from the first order conditions, prices for these are given by marginal costs

$$P_{E_R} = \frac{r+\delta}{A_R} \tag{79}$$

$$P_{E_F} = \frac{1}{A_F}(\zeta((r+\delta)/A_{KF})^{1-\omega} + (1-\zeta)(P_{FF}+\tau_c)^{1-\omega})^{\frac{1}{1-\omega}} \tag{80}$$

and input demands are

$$K_R = \frac{1}{A_R} E_R \tag{81}$$

$$K_F = \zeta\left(\frac{r+\delta}{A_{KF}P_{E_F}}\right)^{-\omega} E_F \tag{82}$$

$$FF = (1-\zeta)\left(\frac{P_{FF}+\tau_c}{P_{E_F}}\right)^{-\omega} E_F \tag{83}$$

Appendix C: Equilibrium algorithm

Appendix C1: No tax, stationary equilibrium

Given exogenous fossil fuel price $P^F F$

1. **Initialization.**

   (a) Guess an interest rate r

   (b) Compute the implied price of electricity and the prices of durables as marginal costs:

$$P^E = \left[\alpha_R \left(\frac{r}{A_R}\right)^{1-\lambda} + \alpha_F \left(\frac{1}{A_F}\left(\zeta r^{1-\omega} + (1-\zeta)(P_{FF}+\tau_c)^{1-\omega}\right)^{\frac{1}{1-\omega}}\right)^{1-\lambda}\right]^{\frac{1}{1-\lambda}} \tag{84}$$

$$P^G = \frac{1}{A_G}, \quad P^B = \frac{1}{A_B} \tag{85}$$

2. **Firm Problem.**

   (a) Using a non-linear solver, solve for (K_C, E_C, FF_C, w) such that the labor market clears and the firm's first-order conditions are satisfied:

$$r+\delta = \left[(1-\psi)B^{\frac{\nu-1}{\nu}} + \psi M^{\frac{\nu-1}{\nu}}\right]^{\frac{1}{\nu-1}} (1-\psi)\, B^{\frac{\nu-1}{\nu}-1}\, A_{KC}\alpha_c\, K_C^{\alpha_c-1} L_C^{1-\alpha_c} \tag{86}$$

$$w = \left[(1-\psi)B^{\frac{\nu-1}{\nu}} + \psi M^{\frac{\nu-1}{\nu}}\right]^{\frac{1}{\nu-1}} (1-\psi)\, B^{\frac{\nu-1}{\nu}-1}\, A_{KC}(1-\alpha_c)\, K_C^{\alpha_c} L_C^{-\alpha_c} \tag{87}$$

$$P^E = \left[(1-\psi)B^{\frac{\nu-1}{\nu}} + \psi M^{\frac{\nu-1}{\nu}}\right]^{\frac{1}{\nu-1}} \psi\, M^{\frac{\nu-1}{\nu}-1} \left(M^{\frac{1}{\iota}} \kappa E_C^{\frac{\iota-1}{\iota}-1}\right) \tag{88}$$

$$P^{FF}+\tau_c = \left[(1-\psi)B^{\frac{\nu-1}{\nu}} + \psi M^{\frac{\nu-1}{\nu}}\right]^{\frac{1}{\nu-1}} \psi\, M^{\frac{\nu-1}{\nu}-1} \left(M^{\frac{1}{\iota}} (1-\kappa) FF_C^{\frac{\iota-1}{\iota}-1}\right) \tag{89}$$

3. **Household Problem.**

   (a) Given the price vector $P=(P^{FF},P^G,P^B,P^E,r,w)$, compute the value and policy functions:

   $$V_j^{NA}(a,\phi;Y,P,\mathcal{T}),\quad V_j^{A}(a,\phi;Y,P,\mathcal{T}),$$
   $$\phi_j'(a,\phi;Y,P,\mathcal{T}),\quad a'j(a,\phi;Y,P,\mathcal{T}),\quad c_j(a,\phi;Y,P,\mathcal{T}),\quad e_j(a,\phi;Y,P,\mathcal{T})$$

   (b) Compute the stationary distribution μ such that the bequest condition holds:

   $$\int a'(\mathbf{x})d\mu_J = \int \frac{a}{1+r}, d\mu{-}1 \tag{90}$$

4. **Aggregation.**

   (a) Compute household aggregates:

   $$A_{hh} = \sum^{J-1} \int a(\mathbf{x}), d\mu_j, \qquad C_{hh} = \sum^{J-1} \int c, d\mu_j, \tag{91}$$

   $$E_{hh} = \sum^{J-1} \int \phi e, d\mu_j, \qquad FF_{hh} = \sum^{J-1} \int (1-\phi)e, d\mu_j \tag{92}$$

   (b) Compute net durable demands:

   $$D_{hh}^G = \sum_{j=0}^{J-1} \int [\phi\delta_G + (\phi'-\phi)], d\mu_j \tag{93}$$

   $$D_{hh}^B = \sum_{j=0}^{J-1} \int [(1-\phi)\delta_B - (\phi'-\phi)], d\mu_j \tag{94}$$

5. **Sectoral Output and Input Demands.**

   (a) Use market clearing for electricity:

   $$Y^E = E_{hh} + E_C \tag{95}$$

(b) Compute input demands for electricity production:

$$K_{E_R} = \frac{1}{A_R}\alpha_R\left(\frac{P^{E_R}}{P^E}\right)^{-\lambda}Y^E, \tag{96}$$

$$K_{E_F} = \zeta\left(\frac{r}{P^{E_F}}\right)^{-\omega}\alpha_F\left(\frac{P^{E_F}}{P^E}\right)^{-\lambda}Y^E \tag{97}$$

$$FF_E = (1-\zeta)\left(\frac{P^{FF}+\tau_c}{P^{E_F}}\right)^{-\omega}\alpha_F\left(\frac{P^{E_F}}{P^E}\right)^{-\lambda}Y^E \tag{98}$$

(c) Prices of intermediate inputs:

$$P_{E_R} = \frac{r}{A_R}, \qquad P_{E_F} = \frac{1}{A_F}\left(\zeta^\omega r^{1-\omega} + (1-\zeta)^\omega(P_{FF}+\tau_c)^{1-\omega}\right)^{\frac{1}{1-\omega}} \tag{99}$$

6. **Durable Goods Sectors.**

(a) Use market clearing for durables:

$$Y^{D_G} = D^G_{hh}, \qquad Y^{D_B} = D^B_{hh} \tag{100}$$

(b) Compute input demands:

$$C_G = \frac{Y^{D_G}}{A_G}, \qquad C_B = \frac{Y^{D_B}}{A_B} \tag{101}$$

7. **Equilibrium Conditions.**

(a) Check capital market clearing:

$$A = K_C + K_{E_R} + K_{E_F} \tag{102}$$

(b) Check aggregate resource constraint:

$$Y = C_{hh} + C_B + C_G + I_{E_R} + I_{E_F} + I_C + P^{FF}(FF_{hh} + F_E) + \int \phi f(j)M - (\phi' - \phi)M', d\mu \tag{103}$$

If either condition fails, update r and return to Step 1(b).

Appendix C2: Transition

1. **Initialization.**

(a) Fix a time horizon $t = 0, \ldots, T$, tolerance levels $\varepsilon_r > 0$, and a damping parameter $\eta_r \in (0,1)$.

(b) Choose an initial guess for the interest-rate path $\{r_t^{(i=0)}\}_{t=0}^T$.

(c) Specify path for productivity gains $\{A_t\}_{t=0}^T$ and taxes $\{\tau_{c_t}\}_{t=0}^T$, and calculate the implied sequences for $\{P_t^E\}_{t=0}^T$ and $\{w_t\}_{t=0}^T$ from the firm problem.

2. **Outer iteration** $i = 0, 1, 2, \ldots$ (until convergence):

   (a) Compute the value function of the stationary equilibrium in the final period T, $V_j^T(a, \phi; Y, P, \mathcal{T})$. By backward induction, taking the price sequences as given, compute the value function $V_j^t(a, \phi; Y, P, \mathcal{T})$ for $t = T-1, ..., 0$. Using the policy functions, simulate the distribution forward for T periods starting from the initial distribution μ_0, being the initial cross-sectional distribution of households μ_0 as the steady state at $t = 0$

   (b) From the distribution, for each time period t calculate aggregate capital holdings $\int a(r_i) d\mu_t$ and aggregate electricity demand from households $E_{hh} = \int \phi e d\mu_t$

   (c) **Inner iteration,** $j = 0, 1, 2, \ldots$ (until convergence): solve the static production problem to clear the market. For each time period t:

      i. Guess an interest rate r_j, calculate $P_j^E(r_j)$.

      ii. Given r_j, $P_j^E(r_j)$ calculate K_C and E_C from the first order conditions of the final consumption good firm.

      iii. Given E_{hh}, E_C and r_j calculate K^{E_R} and K_{E_F}

      iv. Check if $\int a(r_i) d\mu_t = K_C(r_j) + K^{E_R}(r_j) + K_{E_F}(r_j)$. If not, update r_j and go back to ii.

   (d) Check if $\{r_t^{(i)}\}_{t=0}^T = \{r_t^{(j)}\}_{t=0}^T$, if not update

   $$\{r_t^{(i+1)}\}_{t=0}^T = \eta_r \{r_t^{(i)}\}_{t=0}^T + (1 - \eta_r)\{r_t^{(j)}\}_{t=0}^T$$

   and continue with step 1.c.

Appendix D: Deriving the aggregate resource constraint

Given production functions for durable goods, consumption and electricity

$$D_G: \quad Y^{D_G}(C_G) = A_G C_G \tag{104}$$

$$D_B: \quad Y^{D_B}(C_B) = A_B C_B \tag{105}$$

$$C: \quad Y^C(K_C, L_C, E_C, FF_C) = F^C(K_C, L_C, E_C, FF_C) \tag{106}$$

$$E: \quad Y^E(K_{E_F}, K_{E_R}, FF_E) = F^E(K_{E_F}, K_{E_R}, FF_E) \tag{107}$$

and the fact that fossil fuels are imported, the following markets need to clear[17]:

$$\text{Capital:} \qquad \sum^{J-1} \int a_t d\mu_j = K_{C,t} + K_{E_R,t} + K_{E_F,t} \tag{108}$$

$$\text{Labor:} \qquad \sum^{J-1} \int y d\mu_j \; = L_C (= \bar{L}) \tag{109}$$

$$\text{Green Durable:} \quad Y^{D_G} = \sum^{J-1} \int [(\phi' - \phi) + \delta_G \phi] d\mu_j \tag{110}$$

$$\text{Brown Durable:} \quad Y^{D_B} = \sum^{J-1} \int [\delta_B (1-\phi) - \varphi(\phi' - \phi)] d\mu_j \tag{111}$$

$$\text{Fossil Fuel:} \qquad FF = \sum^{J-1} \int e(1-\phi') d\mu_j + FF_E \tag{112}$$

$$\text{Electricity:} \qquad Y^E = \sum^{J-1} \int e\phi' d\mu_j + E_C \tag{113}$$

the government budget constraint needs to hold

$$G + \mathcal{T} + s_{E_R} K_{E_R}(r+\delta) + s_{electr} P^G \sum_{j=0}^{J-1} \int (\phi' - \phi) d\mu_j = \tau_c [\sum_{j=0}^{J-1} \int e(1-\phi') d\mu_j + FF_E] \tag{114}$$

such that the aggregate resource constraint can be derived. Without loss of generation, I here only derive the case of lump-sump redistribution.

Starting from the household budget constraint (note that households with $\phi = 1$ are not allowed choose to switch back after electrification, such that the budget constraint can be written as):

$$\begin{aligned} wy + (1+r)a + \mathcal{T} = c + a' + \phi' e P^E + (1-\phi') e (P^{FF} + \tau_c) + \phi \delta_G P^{D_G} + (1-\phi)\delta_B P^{D_B} \\ + (\phi' - \phi)(P^{D_G} - \varphi P^{D_B}) + \underbrace{\phi f(j) M - (\phi' - \phi) M'}_{=m(\phi', \phi)} \end{aligned} \tag{115}$$

where $(\phi' - \phi)(P^{D_G} - \varphi P^{D_B})$ is the cost of electrification. Furthermore $m(\phi', \phi)$ is the loan installment payment in case of staying (having previously electrified) or receiving the loan in case of electrifying.

[17] The conditions read as follows. Total saving must equal total capital demand. Total labor supply must equal labor demand. Production of the green durable must be equal to newly bought green durables plus depreciation (bequests don't go on the market but are passed through as the durable itself), production of brown durable equals depreciation minus what comes on the market (can be negative?). Total fossil fuel equals household usage and fossil fuels used in electricity production, lastly electricity production is equal to household demand plus final consumption good electricity input demand

In the first step I integrate both sides of the budget constraint

$$wL_C + \int (1+r)ad\mu + \mathcal{T} = C_{hh} + \int a'd\mu + \int \phi' e P^E d\mu + \int (1-\phi')e(P^{FF}+\tau_c)d\mu + \int \phi\delta_G P^{D_G}d\mu + \int (1-\phi)\delta_B P^{D_B}d\mu \tag{116}$$

$$+ \int (\phi'-\phi)(P^{D_G} - \varphi P^{D_B})d\mu + \int m(\phi',\phi)d\mu$$

Starting with the the two durable goods, in the budget constraint, rearrange terms to get these:

$$P^{D_B}\left[\int (1-\phi)\delta_B - (\phi'-\phi)d\mu\right] \quad \text{and} \quad P^{D_G}\left[\int \phi\delta_G + (\phi'-\phi)d\mu\right] \tag{117}$$

which are exactly as in market clearing conditions (7) and (8), such that I can write

$$P^{D_B}\left[\int (1-\phi)\delta_B - (\phi'-\phi)d\mu\right] = P^{D_B}Y^{D_B} \quad \text{and} \quad P^{D_G}\left[\int \phi\delta_G + (\phi'-\phi)d\mu\right] = P^{D_G}Y^{D_G} \tag{118}$$

Furthermore, plugging the production functions for $Y^{D_B} = A_G C_G$and $Y^{D_G} = A_G C_G$, and noting that in this linear technology, and with price for C equal to one, I get $P^{D_G} = \frac{1}{A_G}$ and $P^{D_B} = \frac{1}{A_B}$ these expressions simply become

$$P^{D_B}\left[\int (1-\phi)\delta_B - \varphi(\phi'-\phi)d\mu\right] = C_B \quad \text{and} \quad P^{D_G}\left[\int \phi\delta_G + (\phi'-\phi)d\mu\right] = C_G \tag{119}$$

which I can substitute in equation 116 to get

$$wL_C + \int (1+r)ad\mu + \mathcal{T} = C_{hh} + C_B + C_G + \int a'd\mu + \int \phi' e P^E d\mu + \int (1-\phi')e(P^{FF}+\tau_c)d\mu \tag{120}$$

$$+ \int m(\phi',\phi)d\mu$$

Next, I rewrite the market clearing condition for electricity,

$$\sum^{J-1} \int e\phi' d\mu_j = Y^E - E_C \tag{121}$$

and substitute the RHS in the new aggregate budget constraint. I also take $(1+r)a$ to the right hand side, to get

$$wL_C + \mathcal{T} = C_{hh} + C_B + C_G + \int [a' - (1+r)a]d\mu + (Y^E - E_C)P^E + \int (1-\phi')e(P^{FF}+\tau_c)d\mu \tag{122}$$

$$+ \int m(\phi',\phi)d\mu$$

Using the capital market clearing condition, I rewrite $\int [a' - (1+r)a]d\mu$ as follows:

$$[a' - (1+r)a]d\mu = K_{t+1} - (1+r)K_t \tag{123}$$

Noting that $K_t = K_{C,t} + K_{E_R,t} + K_{E_F,t}$, I split up aggregate capital to get:

$$K_{t+1} - (1+r)K_t = K_{C,t+1} - K_{C,t} + K_{E_R,t+1} - K_{E_R,t} + K_{E_F,t+1} - K_{E_F,t} - rK_{C,t} - rK_{E_R,t} - rK_{E_F,t} \tag{124}$$

$$= I_{C,t} + I_{E_R,t} + I_{E_F,t} - rK_{C,t} - rK_{E_R,t} - rK_{E_F,t} \tag{125}$$

which I substitute in the aggregate budget constraint

$$\begin{aligned} wL_C + \mathcal{T} = {} & C_{hh} + C_B + C_G + I_C + I_{E_R} + I_{E_F} - rK_{C,t} - rK_{E_R,t} - rK_{E_F,t} + (Y^E - E_C)P^E \\ & + \int (1-\phi')e(P^{FF} + \tau_c)d\mu + \int m(\phi', \phi)d\mu \end{aligned} \tag{126}$$

Take $-rK_{C,t}$ and $-P^E E_C$ to the other side to get

$$\begin{aligned} wL_C + rK_{C,t} + P^E E_C + \mathcal{T} = {} & C_{hh} + C_B + C_G + I_{C,t} + I_{E_R,t} + I_{E_F,t} - rK_{E_R} - rK_{E_F} + Y^E P^E \\ & + \int (1-\phi')e(P^{FF} + \tau_c)d\mu + \int m(\phi', \phi)d\mu \end{aligned} \tag{127}$$

and since standard FOC for the final production good imply that marginal products are equalized with input prices, Eulers theorem implies that $Y^C = wL_C + (\delta + r)K_{C,t} + P^E E_C + (P^{FF} + \tau_c)FF_C$:

$$\begin{aligned} Y^C + \mathcal{T} = {} & (P^{FF} + \tau_c)FF_C + C_{hh} + C_B + C_G + I_C + I_{E_R} + I_{E_F} - rK_{E_R} - rK_{E_F} + Y^E P^E + \delta K_C \\ & + \int (1-\phi')e(P^{FF} + \tau_c)d\mu + \int m(\phi', \phi)d\mu \end{aligned} \tag{128}$$

There is a zero-profit condition in the market for electricity which reads that

$$Y^E P^E - (\delta + r)K_{E_R,t} - (\delta + r)K_{E_F,t} - FF_E(P^{FF} + \tau_c) = 0 \tag{129}$$

So I can substitute for $Y^E P^E - rK_{E_R,t} - rK_{E_F,t}$ in the aggregate budget constraint

$$\begin{aligned} Y^C + \mathcal{T} = {} & C_{hh} + C_B + C_G + I_{C,t} + I_{E_R,t} + I_{E_F,t} + (P^{FF} + \tau_c)FF_C + FF_E(P^{FF} + \tau_c) \\ & + \delta(K_C + K_{ER} + K_{EF}) + \int (1-\phi')e(P^{FF} + \tau_c)d\mu + \int m(\phi', \phi)d\mu \end{aligned} \tag{130}$$

Next I impose the government budget constraint such that $\mathcal{T}$ cancels with $\tau_c \int e(1-\phi')d\mu + \tau_c FF_E + \tau_c FF_C$

$$\begin{aligned} Y^C = {} & C_{hh} + C_B + C_G + I_{C,t} + I_{E_R,t} + I_{E_F,t} + P^{FF} FF_C + FF_E P^{FF} \\ & + \delta(K_C + K_{ER} + K_{EF}) + P^{FF} \int (1-\phi')ed\mu + \int m(\phi', \phi)d\mu \end{aligned} \tag{131}$$

Impose market clearing for fossil fuels (with abroad) $FF = FF_C + FF_E + \int (1-\phi')ed\mu$

$$Y^C = C_{hh} + C_B + C_G + I_{C,t} + I_{E_R,t} + I_{E_F,t} + P^{FF} FF + \int m(\phi', \phi)d\mu + \delta(K_C + K_{ER} + K_{EF}) \tag{132}$$

Substitute in

$$\int m(\phi', \phi) d\mu = \int \phi f(j) M - (\phi' - \phi) M' d\mu \tag{133}$$

And rewrite capital investment

$$Y_t^C = C_{hh,t} + C_{B,t} + C_{G,t} + K_{t+1} - K_t + P^{FF} FF_t + \int \phi f(j) M_t - (\phi' - \phi) M_{t+1}] d\mu \tag{134}$$

Which reads as follows. Total production can either be used for consumption of the household directly, can be converted in brown or durable goods, can be invested in capital, can be spend on fossil fuels or spend on repaying the loan. In steady state,

$$Y^C = C_{hh} + C_B + C_G + \delta K + P^{FF} FF + M(r + r_m) \tag{135}$$

Appendix E: Calibration data

DNB household survey

The DNB household survey consists of longtidunal data following about 2000 households. The survey contains multiple topics, such as work, pensions, mortgages, income, assets, liabilities and others. I use information about income, assets and liabilities from the AGI (Aggregated data on income) and AGW (Aggregated data on assets, liabilities and mortgages) datasets. These datasets contain information about for example total assets or income, as a sum of individual components that were asked in the surveys. The data I use is from the years 2010 to 2020.
To estimate the income process, I constrain the sample to the ages 25-65. I delete observations with a negative net labor income or net labor income that exceeds 300.000 euros per year, to not include outliers. For the wealth moments, I treat negative wealth levels as zero-wealth in order to match the models no unsecured borrowing constraint. Net worth is calculated as the sum of checking account, savings, bond holdings, stock holdings and mutual funds, and non-mortgage debt is subtracted.

Appendix F: Climate Model

Appendix F1: The Climate Model

The climate module is exactly taken from Douenne et al. (2025). The temperature is given as

$$Z_{t+1} = Z_t + \epsilon \left(\zeta \mathcal{E}_t - Z_t \right), \tag{136}$$

where cumulative emissions evolve according to

$$\mathcal{E}_{t+1} = \mathcal{E}_t + E_t^M + E_t^{\text{ex}}. \tag{137}$$

I set Z_0, ϵ, ζ, $\mathcal{E}_0$, and the exogenous emissions path $\{E_t^{\text{ex}}\}_{t\geq 0}$ externally, and take all values from Douenne et al. (2025).

*Appendix F1.1: Mapping model outcomes to emissions In the model, I explicitly track fossil fuel demand, FF_t, as the sum of direct household and firm fossil fuel demand and indirect fossil fuel demand in electricity production:

$$FF_t = FF_{E,t} + FF_{C,t} + FF_{HH,t}. \tag{138}$$

The exogenous price of fossil fuels is calibrated as the price of 1000 kWh of energy, where 67% stems from gasoline and 33% from natural gas. The 670 kWh gasoline component corresponds to

$$\frac{670}{8.9} = 75.2 \text{ liters of gasoline,} \tag{139}$$

and the 330 kWh natural gas component corresponds to

$$\frac{330}{10} = 33 \text{ m}^3 \text{ of natural gas.} \tag{140}$$

Using emission factors of 2.3 kg CO_2 per liter of gasoline and 1.9 kg CO_2 per m^3 of natural gas, one unit of fossil fuel in the model produces

$$75.2 \cdot 2.3 + 33 \cdot 1.9 = 235.66 \text{ kg CO}_2. \tag{141}$$

Hence, model emissions implied by fossil fuel demand are given by

$$E_t^M = 235.66 \cdot FF_t, \tag{142}$$

with E_t^M measured in kg CO_2.

Appendix F1: Temperature outcomes

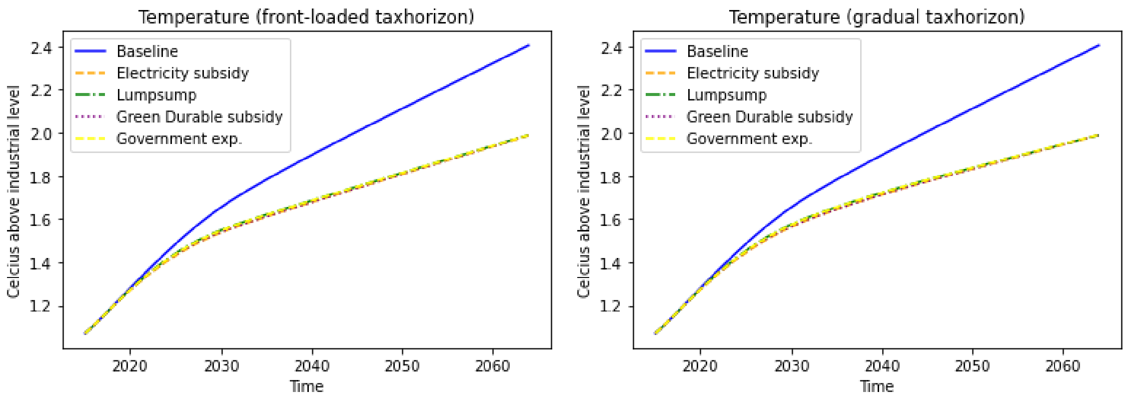

Figure 13: Temperature paths by implementation horizon and revenue-recycling instrument in order to meet the exogenous temperature target (2 degrees celcius)

Appendix G: Lifetime probability of electrification

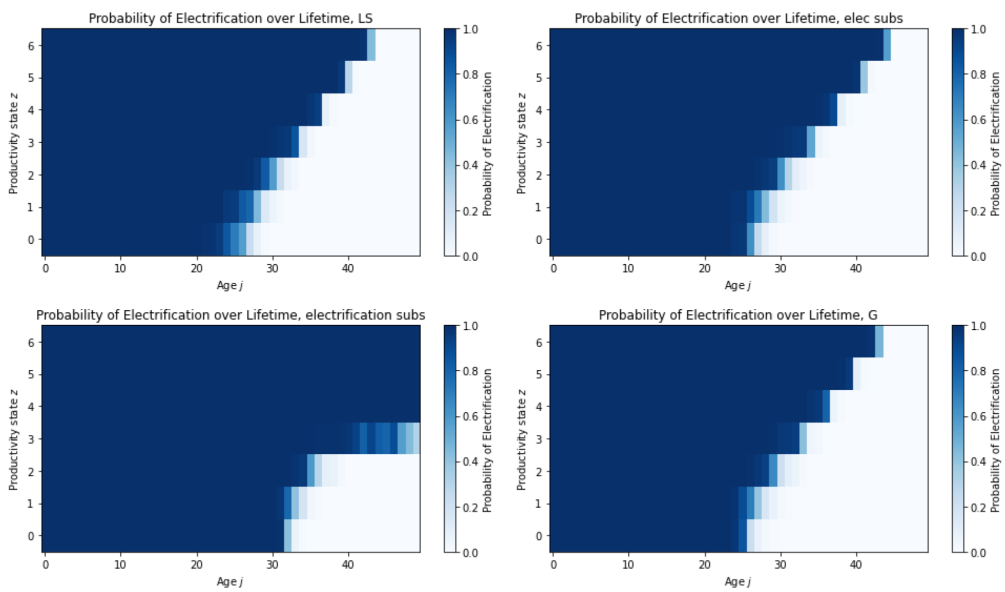

Figure 14: The probability that a household electrifies during its lifetime, where white is 0 and dark blue is 1.