Spatial Redistribution of Carbon Taxes

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Abstract

Policies to mitigate climate change are high on the political agenda and their distributional effects are actively discussed. This paper makes two contributions to this discussion. First, it empirically identifies the spatial dimension between rural and urban households as important for the distributional effects of carbon taxes, as rural households in Germany have a carbon footprint 2.2 tons larger than comparable urban households, about 12 percent of the average carbon footprint. Second, I build a quantitative spatial general equilibrium model to evaluate different policies of rebating carbon tax revenues in terms of their redistributive effects and their political support along the transition to clean technologies. I find that rebating carbon tax revenues as lump-sum transfers redistributes on average 8,000 Euros from rural to urban households, and thus finds a political majority only in the urban region. In contrast, place-based transfers which are set to avoid any spatial redistribution do not reduce the speed of transitioning to clean technologies and find political majorities in both regions. Finally, carbon taxes have sizeable general equilibrium effects on housing prices, mitigating the heterogeneous impact of the tax across space by a quarter as they increase urban relative to rural rents. In addition, they increase prices of non-emitting houses by 5 percent, while decreasing those of carbon-emitting houses by the same amount.

Keywords: Climate change, Inequality, Tax and Transfer policies, Spatial Economics

JEL: E21, H23, Q52, R13

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1 Introduction

Climate policies and their distributional effects are high on the political agenda of governments around the world. In particular, carbon taxes are considered a key policy instrument to reduce carbon emissions. Understanding their distributional effects is crucial for their political support, as the Yellow Vests protests in France have shown. One dimension of redistribution that has received considerable attention in the public debate, but that has not yet been studied in a rich quantitative framework, is the spatial dimension between rural and urban households. Do carbon taxes redistribute across space between rural and urban households? And if so, by how much? As the transition to clean technologies is ongoing, answering these questions requires a dynamic perspective, and the fiscal size of carbon taxes requires taking into account general equilibrium effects.[1]

This paper combines new empirical evidence with a novel and rich theoretical framework to answer these questions quantitatively. I proceed in two steps. First, I empirically document the heterogeneity of energy consumption and carbon footprints, in the German household sector in 2018, before the onset of the transition to clean technologies.[2] Focusing, on the dimensions of income and space, I provide evidence of substantial heterogeneity. Second, I build a dynamic general equilibrium, heterogeneous agent model with two regions undergoing a transition to clean technologies. I examine the impact of a carbon tax on the distributional consequences across income groups and regions along the transition. Furthermore, I compare different policies of rebating carbon tax revenues back to households and study their implications on the spatial redistribution and their political support in the overall population and within regions.

There are three main findings. First, I empirically document that rural households in Germany have a carbon footprint 2.2 tons larger than comparable urban households, about 12 percent of the average household's carbon footprint. This difference is driven entirely by emissions from gasoline and heating energy, and is robust along the income distribution. Second, based on the quantitative model, I find that rebating carbon tax revenues as lump-sum transfers redistributes on average 8,000 Euros from rural to urban households and thus finds a political majority only in the urban region. Place-based transfers, by contrast, which are set to avoid any spatial redistribution do not reduce the speed of transitioning to clean technologies and find political majorities in both regions. Third, carbon taxes have sizeable general equilibrium effects on housing prices, mitigating the heterogeneous impact of the tax across space by a quarter to 6,000 Euros as they increase urban relative to rural rents. In addition, they increase prices of non-emitting houses by 5 percent, while decreasing those of carbon-emitting houses by the same amount.

For the empirical analysis, I combine rich consumption data from the German Income and Consumption Survey (Einkommens- und Verbrauchsstichprobe, EVS) with the EXIOBASE dataset, which provides information on the amount of carbon emissions produced by different consumption goods. The consumption data shows that, relative to comparable urban households, rural households spend 60 percent more on gasoline, 10 percent more on heating energy, and are more likely to use more carbon-intensive

[1] Carbon taxes of 300 Euros per ton of carbon emissions, which is in line with what the literature forecasts the carbon tax will be in the European Union in the next years (Kalkuhl et al., 2023), on gasoline and residential heating generate tax revenues of about 60 billion Euros each year in Germany, about 1.5 percent of German GDP.

[2] Based on data from the German Federal Motor Transport Authority (*Kraftfahrtsbundesamt*) and the German Federal Association of the Energy and Water Industries (*Bundesverband der Energie- und Wasserwirtschaft*), the shares of electric cars and heat pumps in Germany in 2018 were 0.1 and 2.2 percent, respectively.

heating technologies, especially oil heating systems. These differences already control for several household characteristics, such as net household income, household size, and age of the main earner, and are economically and statistically significant. To calculate carbon emissions at the household level, I follow the literature and distinguish between direct and indirect emissions, where the former refer to emissions generated by consumption itself, such as driving a car or heating an apartment, and the latter refer to emissions generated by the production and transportation of goods (Hardadi et al., 2021). Consistent with previous findings in the literature, household carbon emissions increase with income, more than doubling from the bottom to the top third of the income distribution (Hardadi et al., 2021; Kuhn and Schlattmann, 2024; Wiedenhofer et al., 2017). For the spatial heterogeneity, I find no significant differences for indirect emissions. However, for direct emissions, rural households emit about 2.2 tons more carbon per year, about 12 (36) percent of the average household's total (direct) carbon footprint. This difference is significant and controls for net household income, household size, and age of the main earner. Furthermore, it is accounted for equally by emissions from car and heating energy and is constant along the income dimension.

Guided by this empirical evidence, I build a quantitative general equilibrium model with two regions and two types of housing and car technologies. The two regions differ in their household-specific city amenities and energy consumption requirements and are denoted *rural* and *urban*. The housing and car technologies differ in whether they emit carbon emissions and how efficiently they can convert raw energy into temperature and vehicle miles traveled, and are called *dirty* and *clean*.[3] Clean technologies emit no carbon and are more efficient. As the majority of German households are tenants and as tenants are more mobile and thus drive housing prices across regions, I model households as tenants. They can decide which region to live in and which technology to use. In addition to these discrete decisions, they decide on their continuous consumption levels of housing, heating energy, car energy, and a non-housing, non-energy good. The production of clean technologies is done by the firm sector, which consists of three firms. First, there is a construction firm that builds dirty and clean housing and converts dirty houses into clean houses. Second, there is a competitive rental firm that buys housing from the construction firm and rents them out to households. Third, there is a competitive production firm that produces cars, energy, and the non-housing, non-energy good. Finally, the government extracts the construction firm's profits, returns them back to households as lump-sum transfers within regions, and may set climate policies.

I calibrate this model to the German economy in 2018, starting in an initial stationary equilibrium without clean technologies.[4] I introduce clean technologies exogenously in 2019, which starts a transition to them, because, consistent with empirical estimates, they convert raw energy into temperature and vehicle miles traveled more efficiently. I compare a transition without any policy intervention to a transition with a carbon tax of 300 Euros per ton of carbon on energy consumption. This level is well in line with estimates of future carbon taxes under the European Union's proposed Emission Trading System 2 (ETS2), which explicitly targets emissions from heating and car energy (Kalkuhl

[3] For housing, one can think of poorly insulated houses with oil heating systems and very well insulated houses with heat pumps. For cars, one can think of traditional gasoline or diesel-powered cars and electric cars.

[4] Again, the shares of electric cars and heat pumps in all cars and heating systems were only 0.1 and 2.2 percent, respectively, which justifies this assumption.

et al., 2023).[5] I compare three ways in which the government rebates the carbon tax revenues. First, I consider lump-sum transfers, which have been shown to have important implications for redistribution along the income dimension because they turn the regressive redistribution of carbon taxes without transfers into progressive redistribution (Douenne, 2020; Kuhn and Schlattmann, 2024). This rebating scheme resembles a popular policy proposal in Germany (*Klimageld*). Second, I consider place-based transfers that are set to prevent any redistribution across regions, such that all revenues raised within a region are rebated in the same region. This policy resembles the Austrian *Klimabonus*, a policy implemented in 2022 that rebates carbon tax revenues based on whether households live in rural or urban regions. Finally, I introduce subsidies on housing renovations which aim at increasing the speed of the transition to clean houses.

I evaluate these different policy scenarios along the transition to clean technologies, which takes about 100 years. The speed of the transition to clean technologies depends strongly on whether carbon taxes are introduced. By 2050, which is when the EU wants to be carbon neutral, the share of households with clean goods is about 60 percent without, but 85 percent with carbon taxes. As a result, carbon emissions decrease by 65 percent by 2050 without policy intervention, and by 90 percent when carbon tax revenues are used for lump-sum or place-based transfers, coming close to the EU target of climate neutrality by 2050. With subsidies on housing renovations the speed of reducing emissions is even slightly increased. The speed of this transition has important implications for the level of spatial redistribution over time. Spending the tax revenue on lump-sum transfers redistributes 300 Euros annually from rural to urban households for the first years of the transition. As more households adopt clean technologies, carbon footprints and hence the level of redistribution fall and converge to a situation without spatial redistribution by 2060. The difference in the present value of net transfers between rural and urban households is around 8,000 Euros, corresponding to 25 percent of the average household's annual net income. Spending carbon tax revenues on subsidies for housing renovations leads to similar differences in the tax burden, while place-based transfers do not redistribute across space by construction. Thus, lump-sum transfers and subsidies on housing renovation result in net migration to the urban region for the first years of the transition, peaking around 2040. At that point, the urban population share increases by 1.4 percentage points, corresponding to 1.2 million individuals for Germany. Towards the end of the transition, there is net migration to the rural region as, first, the level of spatial redistribution decreases and, second, clean and energy-efficient technologies become more widespread, which is more beneficial in the rural region where energy consumption is higher.

The general equilibrium effects of carbon taxes on housing prices and rents are sizeable. Without policy intervention, the price premia for clean houses relative to the prices for dirty houses in the initial stationary equilibrium, jump, upon introducing the clean technologies, to 10 and 9 percent in rural and urban regions, respectively. The prices for dirty houses remain unchanged. As the construction firm builds new clean houses and renovates dirty houses into clean houses, the prices of clean and dirty houses converge over time. If the carbon tax revenues are spent on lump-sum transfers, the initial increase in the price premium for clean houses is 15 percent, 5 percentage points higher than without policy intervention. In addition, the prices for dirty houses fall by 5 and 2 percent, respectively, relative to the initial steady state for rural and urban regions. This decrease results from

[5] Further, I provide an extensive sensitivity analysis, including a low and high carbon tax scenario with tax levels of 100 and 500 Euros per ton of carbon, as well as a scenario with an increasing carbon tax path over the transition. I discuss these checks in Section 4.4 and provide all figures and results in Appendix C.2.

a reduction in housing demand as heating energy, a complementary good to the housing size, becomes more expensive due to the carbon tax. This reduction is larger in the rural region, first because rural households consume more heating energy and use heating technologies that emit more carbon, and second because of net migration to the urban region due to spatial redistribution. Hence, the general equilibrium effects mitigate the heterogeneous impact of the carbon tax by about a quarter as they increase urban relative to rural rents. Spending the carbon tax revenues on place-based transfers increases the rural housing price by about 1.5 percentage points, while decreasing the urban price by the same amount, relative to the scenario with lump-sum transfers, because this policy avoids spatial redistribution and thus net migration from rural to urban regions. Finally, spending the tax revenues on subsidies for renovations reduces the clean housing price premium by about 2 percentage points relative to the scenario with lump-sum transfers due to an increased supply of clean houses.

To evaluate the long-run consequences of these policies, I compare their final stationary equilibria. I find that, without any policy intervention, the share of clean cars and clean houses rises to 93 and 96 percent, respectively. Because clean technologies are more effective at converting raw energy into temperature and vehicle miles traveled, energy consumption levels in the final stationary equilibrium fall relative to the initial stationary equilibrium without clean technologies by 62 and 10 percent for heating and car energy, respectively, and household carbon emissions fall by 92 percent. Thus, without carbon taxes, there is no complete decarbonization. Since, heating energy and housing consumption are complementary, a decrease in the effective price of heating energy, caused by a more efficient heating technology, increases housing demand. As the number of newly issued land permits each period is constant, this leads to an increase in housing prices by 5 percent. Due to net migration to the rural region, this increase is 0.6 percentage points higher there. This net migration is caused by cheaper energy consumption, which is more beneficial in the rural region, where households consume more energy. Because the clean technologies are more efficient, household welfare, measured as the consumption equivalent variation (CEV) in terms of the non-housing, non-energy good, increases by 1.8 percent. When introducing a carbon tax and reimbursing households via lump-sum transfers, the share of clean technologies in the final stationary equilibrium increases to 100 and 99 percent for cars and houses, respectively. Thus, energy consumption falls by 65 and 11 percent, carbon footprints fall by 99 percent, and house prices rise by 6 percent. The distortionary effect of the tax slightly reduces the welfare gain by 0.1 percentage points. For these long-run outcomes, the results hardly change depending on what the carbon tax revenues are used for as carbon footprints and thus carbon tax revenues tend towards zero.

In a final step, I evaluate these policy scenarios based on their political support with respect to monetary and welfare outcomes. Monetary outcomes are measured by the present value of net transfers, that is, what households receive as transfers minus what they pay as carbon taxes, also including the general-equilibrium effects of rent payments. When carbon tax revenues are spent on lump-sum transfers, around 48 and 73 percent of rural and urban households have positive present values, meaning they benefit.[6] With place-based transfers the political support is 63 and 61 percent, implying that a majority of households supports this policy in both regions. In case of subsidies, there is no majority in either region in favor of the policy. The political support does not change when considering a low and high carbon tax scenario of 100 and 500 Euros per ton, as it is determined by the share of households emitting

[6] Households are classified as *rural* and *urban* based on where they live in the first year of the transition.

less than the average carbon footprint in the total population (for lump-sum transfers) or within regions (for place-based transfers). For the welfare analysis, I consider a scenario without positive externalities from reduced emissions and a scenario with these externalities. Without positive externalities, the share of households benefiting in welfare terms is smaller than the share benefiting in monetary terms because the carbon tax distorts households' consumption decisions. These distortionary effects are larger for rural households because their energy consumption and thus the share of consumption that is distorted, is larger. For lump-sum transfers the share of households benefiting is 22 and 36 percent, for place-based transfers 30 and 34 percent, and for subsidies for housing renovations 6 and 10 percent for rural and urban households, respectively. Increasing carbon taxes reduces the political support, because the marginal welfare costs of distortions increase with the level of the tax, while the marginal benefits, i.e. the transfers, remain constant. Finally, I consider the positive externalities from reducing carbon emissions on household welfare in a reduced form. Including the benefits of reducing carbon emissions in the analysis increases the political support by about 10 percentage points. All qualitative results of the welfare analysis without positive externalities from reduced emissions persist. Thus, place-based transfers find the highest political support in the overall population and among the group of households most affected by carbon taxes, i.e. rural households, regardless of whether the support is evaluated on the basis of monetary or welfare outcomes with or without positive externalities from reduced carbon emissions.

This paper contributes to three strands of literature. First, it contributes to the empirical literature documenting a high heterogeneity of carbon emissions in the household sector. The focus of this literature has been to study the heterogeneity along the income dimension. A key finding of this literature is that carbon emissions increase with income, which has been documented for Germany (Hardadi et al., 2021; Kuhn and Schlattmann, 2024; Miehe et al., 2016) as well as for other European (Duarte et al., 2012; Isaksen and Narbel, 2017; Kerkhof et al., 2008) and non-European countries (Perobelli et al., 2015; Wiedenhofer et al., 2017). Recently, horizontal heterogeneities of carbon footprints within income groups have received more attention, suggesting that households in rural areas have larger carbon footprints than those in urban areas (Douenne, 2020; Gill and Moeller, 2018; Tomás et al., 2020). I contribute to this literature by quantifying the heterogeneity for Germany using the most recent data available, and identifying a key role for emissions from car and heating energy.

Second, this paper contributes to the literature that studies the distributional consequences of climate policies. This literature has so far focused on redistribution along the income distribution (Douenne et al., 2023; Känzig, 2021; Kuhn and Schlattmann, 2024) and between different generations (Belfiori, 2017; Fried et al., 2018; Kotlikoff et al., 2021). Känzig (2021) shows that the poor bear higher economic costs from carbon taxes because their energy consumption share is higher and, importantly, their income falls more through general equilibrium effects in the labor market. Similarly, Kuhn and Schlattmann (2024) identify a policy trade-off between carbon emission reduction and redistribution, as policies that maximize carbon emission reduction redistribute substantially from poor to rich households. Fried et al. (2018) evaluate the distributional effects of a carbon tax on households living in a current and a future steady state in a general equilibrium life-cycle model calibrated to the U.S. economy. They find that households in the current steady state prefer uniform, lump-sum rebates, while households in the future steady state prefer reducing existing distortionary taxes. Relatedly, Kotlikoff et al. (2021) compute the optimal carbon tax path in an overlapping generations model and find that it increases the welfare of all generations by almost 5 percent, but requires major intergenerational transfers. Douenne et al. (2023) study the optimal fiscal policy to jointly address climate change and inequality and find that the revenue from carbon taxes is optimally split between reducing tax distortions and increasing transfers equally. I contribute to this literature by being the first to study the distributional consequences along the spatial dimension between rural and urban households structurally in a quantitative model with general-equilibrium effects. In doing so, I provide a novel and rich theoretical framework.

Third, this paper also relates to the recently growing literature documenting that the costs of climate change differ strongly across the globe (Carleton et al., 2022; Cruz and Rossi-Hansberg, 2024; Hassler and Krusell, 2012; Krusell and Smith Jr, 2022) but also within large countries like the United States (Bilal and Rossi-Hansberg, 2023; Fried, 2024; Hsiang et al., 2017; Rudik et al., 2022; Sun, 2024). With respect to the heterogeneous consequences of climate change across the globe, Cruz and Rossi-Hansberg (2024) find the uncertainty about the relative losses across space to be relatively small, despite a high level of uncertainty about average welfare effects. When zooming into the U.S., states in the South and West are projected to loose from higher temperatures and more storms while Northern states rather gain (Bilal and Rossi-Hansberg, 2023; Sun, 2024). Further, Bilal and Rossi-Hansberg (2023) show in a quantitative dynamic spatial assessment model that migration reduces substantially the spatial variance in the welfare impact of climate change, while increasing the losses in the value of capital at locations harmed by climate change. While this literature focuses on quantifying the spatial heterogeneity in the costs and benefits of climate change, I contribute by quantifying the spatial heterogeneity of costs and benefits from climate change mitigation policies. Understanding not only the consequences of climate change itself but also the consequences of mitigation policies is necessary to evaluate these policies thoroughly.

The remainder of this paper is structured as follows. Section 2 introduces the data used and presents the empirical results. Section 3 presents the model and explains the calibration strategy. Finally, Section 4 introduces the policy experiments and presents the results, before Section 5 concludes.

2 Empirical evidence

This section first introduces the datasets used in this paper before it empirically documents the heterogeneity in energy consumption patterns for households living in rural and urban regions. Finally, I translate these consumption patterns into carbon footprints to document the level of spatial heterogeneity along this dimension.

2.1 Data

The empirical analysis is based on two datasets. First, I use the German Income and Consumption Survey (*Einkommens- und Verbrauchsstichprobe*, EVS), which provides repeated cross-sectional data on household consumption expenditures similar to the *Consumer and Expenditure Survey* (CEX) in the U.S. The EVS provides detailed information on about 43,000 households for each wave, which corresponds to 0.1 percent of German households, and sample weights allow to construct representative statistics for the entire German population. It is conducted every 5 years and is considered to be of excellent quality as it is also used to compute the consumption basket for the German CPI. I use the most recent version from 2018. Second, I use the EXIOBASE v3.6 dataset in order to quantify the carbon emissions generated by different consumption goods. This dataset is compiled from multi-regional input-output tables and distinguishes between 44 countries and five rest of the world regions, 163 industries, and 200 products.[7] I bridge the two datasets based on the bridging strategy developed in Hardadi et al. (2021). To calibrate the model, I additionally use data from the German Socio-Economic Panel (SOEP).[8]

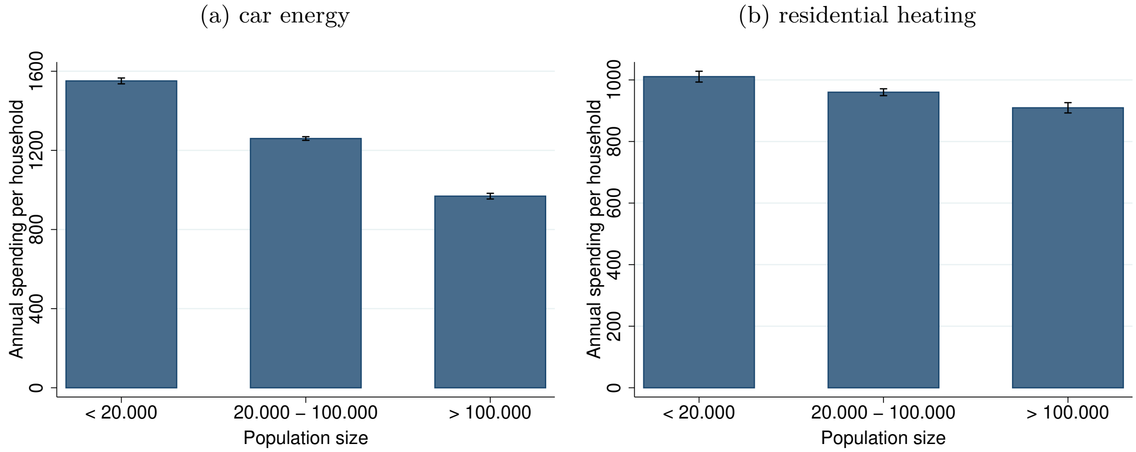
2.2 Spatial heterogeneity in energy consumption

To analyze the heterogeneity in energy consumption patterns of households living in rural and urban regions, I focus on car energy and residential heating consumption. These two consumption goods are not only considered to be of key importance for carbon footprints, as they account for about a third of total household carbon emissions (Kuhn and Schlattmann, 2024), but they are also key for understanding the heterogeneity in carbon footprints across regions, as I will document. I distinguish between three levels of city size: small villages with less than 20,000 inhabitants, small cities with population sizes between 20,000 and 100,000 inhabitants and large cities with more than 100,000 inhabitants. Based on this definition, around one-third of the total population is allocated to each city size category. In order to identify the differences in energy consumption for comparable households living in cities of different sizes, I regress annual household expenditures for car energy and residential heating not only on the city size category but also on the age of the main earner, household net disposable income, and the household size.[9] For residential heating expenditures, I further control for the heating technology to isolate the level of expenditures from the heating technology. In a second step, I compute the predicted values of household expenditures on car energy and residential heating for a household with average levels of net income, age, and household size (and heating technology for residential heating) living in each of the three regions. Note, that these averages are based on the total sample, such that I compare households with the same net household income, household size and age of the main earner.

Figure 1 shows the resulting predicted annual expenditures for comparable households depending on where they live. Figure 1a shows that an average household with respect to age, net household income, and the household size living in a village of less than 20,000 inhabitants spends about 1,550 Euros per year on car energy, while a comparable household living in a large city spends only about 970 Euros. Thus, rural households spend around 60 percent more on car energy than urban households with the same average characteristics. Similarly, Figure 1b shows that rural households spend around 1010 Euros on residential heating, while urban households spend 900 Euros. Thus, rural households spend around 10 percent more on residential heating than comparable urban households. These differences are statistically significant as indicated by the black bootstrapped confidence intervals.

[7]For more information see Stadler et al. (2018).
[8]For more information see Goebel et al. (2019).
[9]All regression specifications and results are shown in Appendix A.1.

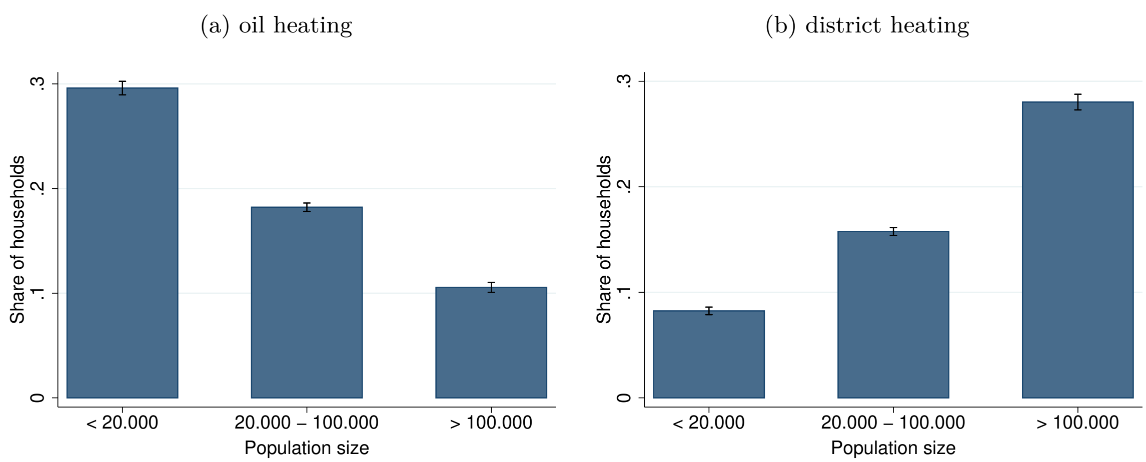
Figure 1: Annual energy expenditures across regions (in Euro)



Notes: Panel (a) shows the predicted annual household expenditures in Euro for car energy for an average household with respect to age, net disposable income, and household size living in a region of one of the three city sizes. Panel (b) shows the same statistic on residential heating, where the household additionally has an average heating technology. All regression specifications and results are shown in Appendix A.1.

In addition to the level of energy consumption, rural and urban households also differ in the way they heat. While in both regions around half of the population heats with natural gas, Figure 2 shows that the share of households using oil and district heating differs significantly. Figure 2a indicates that 30 percent of rural households use oil heating, while only around 11 percent of urban households use this technology. Figure 2b shows the opposite for district heating. While close to 30 percent of urban households use district heating, only about 8 percent of rural households do so. These shares are again calculated for an average household with respect to the age of the main earner, the net disposable

Figure 2: Heating technologies across regions



Notes: Panel (a) shows the predicted share of households heating with oil for an average household with respect to age, net disposable income and household size living in regions with different cities sizes. Similarly, Panel (b) shows the same statistic on the share of households using district heating. All regression specifications and outputs are shown in Appendix A.1.

income of the household, and its size. Importantly, heating with oil generates substantially more carbon emissions than district heating. According to the most recent estimates by the International Institute for Sustainability Analysis and Strategy based on the Global Emission Model for Integrated Systems (GEMIS) version 5.0, producing one kWh with oil and district heating in Germany in 2015 generated 315 and 237 grams of carbon emissions, respectively. Note that district heating is based on multiple heat sources, including fossil fuels and renewables. As the share of renewable energy in district heating increases, while the level of carbon emissions from burning oil remains constant, this difference can be considered a lower bound along the transition to clean technologies.

2.3 Spatial heterogeneity in carbon footprints

As a final step in the empirical analysis, I calculate the annual level of carbon emissions on the household level. Following the literature, I distinguish between direct and indirect emissions (Hardadi et al., 2021). The former refer to emissions generated directly by household consumption, such as driving a car or heating an apartment, and account for around 30 percent of total household emissions. The latter refer to emissions generated by the production and transportation of goods and services, such as transporting a banana from South America to Europe. Emissions from public transportation, such as bus travel, are also included in indirect emissions.

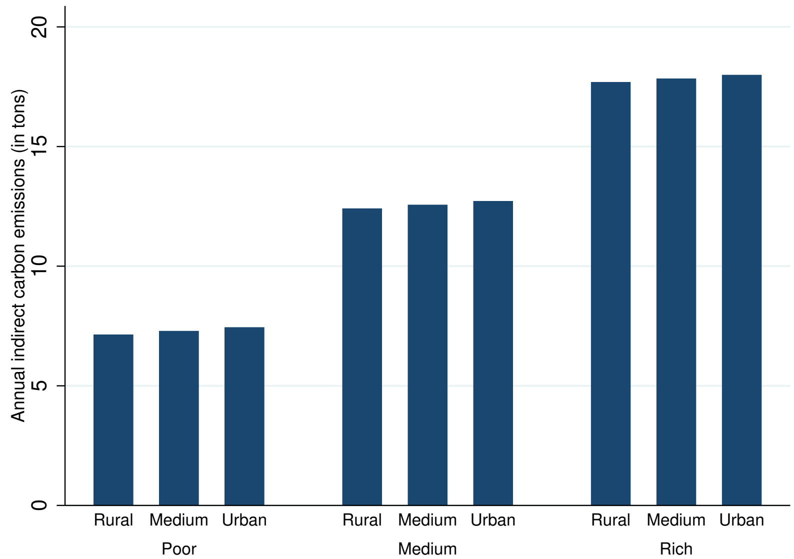
To calculate indirect emissions, I bridge the EXIOBASE dataset on carbon intensities for a large set of consumption goods with the EVS dataset. For this procedure, I follow the bridging strategy developed in Hardadi et al. (2021) but depart from their analysis in two ways. First, while they estimate carbon footprints for an average household and for eleven income groups, I impute carbon emissions at the household level. This is crucial for my empirical analysis as it allows me to distinguish between carbon footprints of households in rural and urban regions.[10] Second, they correct for expenditure underreporting in the EVS data. I also compute results corrected for expenditure underreporting as a robustness check but find differences to be negligible for my analysis. Therefore, I abstain from this adjustment. To calculate direct emissions, I also follow Hardadi et al. (2021) and take estimates for total direct emissions in Germany from the German Federal Statistical Office and allocate them to households based on their expenditures.[11] I compute indirect and direct carbon footprints at the household level and group households into three equally sized income categories based on their net household income. I regress the annual carbon footprints on the city size and household income categories, as well as on the household size and the age of the main earner. I compute the predicted carbon footprints for an household with the average age and household size, and for each combination of the three city size and income categories.

[10] The same empirical approach was also used in Kuhn and Schlattmann (2024).

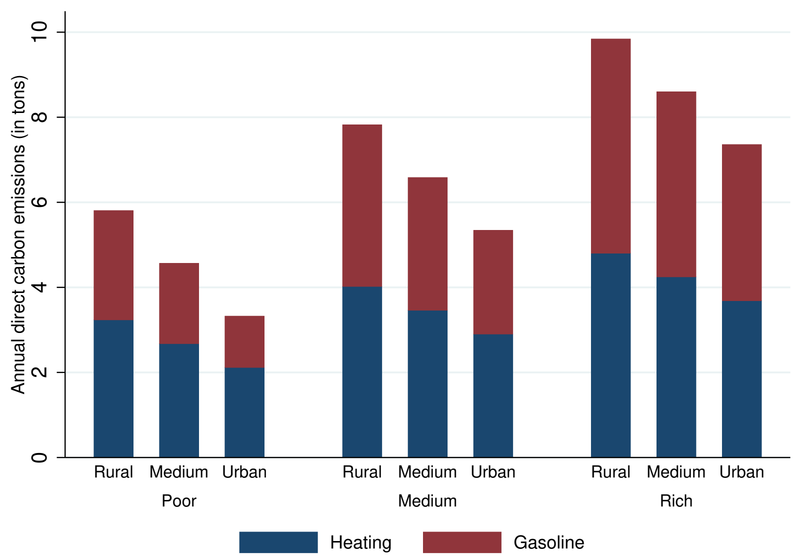
[11] An alternative approach is to divide household expenditures for each of the different items, such as gasoline or oil, by the respective annual average price to get the quantities. As the German Federal Cartel Office did not find significant price differences for gasoline between urban and rural regions (Bundeskartellamt, 2020), one can assume identical prices for households in both regions. In a second step, one can use estimates from the natural science literature on the level of emissions generated by the consumption of these quantities to calculate the level of direct emissions at the household level. I find very similar results for both approaches.

Figure 3: Household carbon footprints across regions and income

(a) indirect emissions



(b) direct emissions



Notes: This figure shows the predicted indirect and direct carbon emissions for households of different income and city size groups with average age and household size. The three income categories *Poor*, *Medium*, and *Rich* are based on three equally sized net household income categories. The three city size categories *Rural*, *Medium*, and *Urban* refer to city sizes of less than 20,000, 20,000 to 100,000 and more than 100,000 inhabitants. All regression specifications and outputs are shown in Appendix A.2.

Figure 3 shows the results for indirect and direct emissions.[12] First, for both types of emissions, I corroborate the finding in the literature that carbon emissions increase with income (Hardadi et al., 2021; Kuhn and Schlattmann, 2024; Wiedenhofer et al., 2017). Moving from the bottom to the top

[12]More details on the estimation and all regression results can be found in Appendix A.2.

third of the net income distribution increases indirect and direct carbon footprints by a factor of 2.5 and 2, respectively. Second, Figure 3a shows that indirect emissions vary hardly by city size within income groups. Direct emissions, on the other hand, fall substantially with the city size within income groups, as Figure 3b documents. Rural households emit around 2.2 tons more carbon than comparable urban households. This difference is equivalent to around 12 (36) percent of the total (direct) carbon emissions of an average household in Germany, and stems from emissions generated by residential heating and car energy in equal parts. Interestingly, this difference in carbon footprints is constant along the income dimension which is remarkable given that emissions increase substantially with income. Thus, direct carbon emissions vary substantially by city size, while indirect emissions do not. Therefore, I focus in the quantitative model on direct emissions by introducing a carbon tax on polluting car and residential heating energy. Focusing on direct emissions also makes sense from a policy perspective as the ETS2 will target direct emissions from car energy and residential heating.

3 Model

This section develops a quantitative general equilibrium model with two regions and two types of technologies for cars and housing units, one is clean and does not emit carbon, the other one is dirty and emits carbon. In addition to a household sector, there is a firm sector constructing and renovating housing, renting out housing and producing final consumption goods. Finally, there is a government which extracts the profits of the firms, redistributes them to households via lump-sum transfers within regions, and may introduce climate policies.

3.1 Household sector

The economy is populated by a continuum of measure one of infinitely lived tenants. I focus on tenants because they make up the majority of German households and because they are more mobile and thus drive prices in housing markets across space.[13] Households can migrate between a rural region, denoted by r, and an urban region, denoted by u. In each region, there is a housing stock of clean and dirty housing, denoted by $H^{r,cl}$, $H^{r,di}$ and $H^{u,cl}$, $H^{u,di}$, respectively. Time is discrete.

3.1.1 Preferences

Household's per period utility follows a CRRA specification over a Cobb-Douglas aggregate of non-housing and housing consumption. If the household lives in the urban region, denoted by $l = 1$, it additionally receives household-specific city amenities κ that are constant over time. Both, housing and non-housing are modeled as composite goods. Housing consists of the housing size h and effective heating energy $(1+\phi^{h,j})e^h$, while non-housing consumption consists of effective car energy consumption $\left(1 + \phi^{c,j}\right)(e^c - \underline{e^{c,l}})$ and non-housing, non-car energy consumption x. The parameters $\phi^{c,j}$ and $\phi^{h,j}$ describe the efficiency of converting raw car and heating energy into effective car and heating energy, that is vehicle miles traveled and temperature. Note, that these production efficiencies depend on

[13]Figures A6 and A5 in Appendix A.2 show that the empirical results hardly change when only including tenants.

whether the housing stock or the car is dirty, denoted by $j = di$ or clean, denoted by $j = cl$.[14] To capture the empirical observation that households in rural regions consume more car energy, there is a location-specific subsistence level of car energy consumption $\underline{e^{c,l}}$. This level can be thought of as car energy for commuting from which households derive no utility.

Hence, the per-period utility function of households reads[15]

$$
\begin{aligned}
u(x, h, e^h, e^c, l) &= \frac{1}{1-\sigma}\left(\tilde{x}^{\gamma}\tilde{h}^{1-\gamma}\right)^{1-\sigma} + l\kappa \\
\tilde{x} &= \left(\mu_x x^{\frac{\nu_x - 1}{\nu_x}} + (1-\mu_x)\left[\left(1+\phi^{c,j}\right)\left(e^c - \underline{e^{c,l}}\right)\right]^{\frac{\nu_x-1}{\nu_x}}\right)^{\frac{\nu_x}{\nu_x-1}} \\
\tilde{h} &= \left(\mu_h h^{\frac{\nu_h - 1}{\nu_h}} + (1-\mu_h)\left[(1+\phi^{h,j})e^h\right]^{\frac{\nu_h-1}{\nu_h}}\right)^{\frac{\nu_h}{\nu_h-1}}
\end{aligned}
$$

where γ, μ_x, and μ_h measure the relative preferences for non-housing consumption, non-housing non-car energy consumption, and the housing size, respectively. The parameters ν_x and ν_h describe the elasticities of substitution between non-housing, non-car energy consumption and car energy consumption as well as between the housing size and heating energy consumption, respectively. Furthermore, $1/\sigma$ characterizes the intertemporal elasticity of substitution.

3.1.2 Labor Income

Household labor income consists of the economy-wide wage $w_{i,t}$ and an idiosyncratic productivity shock $\nu_{i,t}$, that follows an AR(1)-process. Thus, it evolves according to

$$
\begin{aligned}
\log y_{i,t} &= \log w_{i,t} + \nu_{i,t} \\
\nu_{i,t} &= \rho \nu_{i,t-1} + \eta_{i,t} \\
\eta_{i,t} &\sim \mathcal{N}\left(0, \sigma_\eta^2\right) \qquad \text{i.i.d.},
\end{aligned}
$$

where $p \in (0, 1)$ describes the persistence of the idiosyncratic component and σ_η^2 the variance of the innovations. Note, that this process is the same for households in rural and urban regions which is consistent with very similar income paths for them in the EVS dataset.[16]

3.1.3 Budget constraint

Besides their labor income y, households may receive two types of government transfers. First, the government extracts the firm's profits from constructing and renovating housing which it returns to households within regions as lump-sum transfers T^{π}. Second, if the government imposes carbon taxes,

[14] I calibrate these parameters according to empirical estimates in the literature as described in more detail in Section 3.4.5.

[15] For readability, I omit the subscripts for the year of the transition. When I turn to the recursive formulation of the dynamic household problem, I will introduce them.

[16] I further checked whether income levels of rural and urban households might be heterogeneously affected by carbon taxes. Känzig (2021) finds that the impact of carbon taxes on household income is strongest in sectors with a high sensitivity to changes in aggregate demand, such as retail or hospitality. Based on his classification, I grouped sectors into those with lower and higher demand sensitivity, but found no significant differences in employment shares for rural and urban households.

the resulting tax revenues may be returned to households as transfers T^τ, depending on the policy. They can spend this total income on four consumption goods, the housing size h, car energy e^c, heating energy e^h and non-car energy, non-housing consumption x (the numeraire). The price of renting one housing unit is given by the location and housing type-specific rent $\rho(l, \lambda^h)$. The variable λ^h takes on values of 1 and 0 if the household lives in a house with a clean and dirty technology, respectively. The rent is endogenous and is determined on one of the four segmented rental markets. If a household lives in a clean house, it pays the exogenous price p^{eh} per unit of heat consumption. This price is constant over time and the same for households in rural and urban regions.[17] If a household lives in a dirty house, it has to pay the carbon tax τ on each ton of carbon emissions, where ξ_l^h translates heating energy consumption into carbon emissions. Because, as shown in the empirical section of this paper, rural households use heating technologies that emit more carbon, ξ_l^h is location-specific. The cost for car energy is modeled analogously. If a household drives a clean car, denoted by $\lambda^c = 1$, it pays the economy-wide and constant exogenous price p^{ec}. Households driving a dirty car must pay the carbon tax τ, where ξ^c converts car energy consumption into carbon emissions. Finally, households may decide to buy a new car. The costs associated with this adjustment are denoted E^j and depend on whether the household buys a car with a clean ($j = cl$) or dirty technology ($j = di$). Hence, the household's budget constraint reads

$$x = y + T^\pi + T^\tau - \rho(l, \lambda^h)h - [p^{eh} + (1 - \lambda^h)\xi_l^h \tau]e^h - [p^{ec} + (1 - \lambda^c)\xi^c \tau]e^c - E^j$$

where $E^j = p^{c,cl}$, $E^j = p^{c,di}$, or $E^j = 0$ in case the household buys a clean, dirty, or no new car, respectively. The prices for new cars $p^{c,cl}$ and $p^{c,di}$ are further specified in Section 3.2.3.

3.1.4 Recursive formulation of the dynamic decision problem

In addition to their continuous choices for the four consumption goods, housing size h, heating energy e^h, car energy e^c and non-car energy non-housing consumption x, households have to take four discrete decisions in each period. They have to decide whether they want to change their location, whether they want to move to a house with a different technology, whether they to buy a new car, and if so, whether to buy a car with a dirty or clean technology. In total, there are 12 different combinations of these decisions. For each of the four discrete decisions, there is a type-1 extreme value shock to smooth them. The timing is as follows. First, households enter the period with their state variables from the previous period and observe their income shock. Second, they make contingent consumption plans for each of the 12 combinations of discrete decisions. Third, they receive the extreme value shocks. Specifically, they first receive the car type shock, then the car adjustment, the housing type and moving shocks. Thus, households take their car type decision contingent on the car adjustment, the housing type and the moving decision. Similarly, they take the car adjustment decision contingent on the housing type and the moving decision and finally the housing type decision contingent on their moving decision. These decisions take effect immediately. In the last stage consumption takes place and households transition to the next period.

[17]Even though, as shown in the empirical section, rural and urban households use different heating technologies, the prices per unit of heating energy are very similar.

For brevity, I focus on the discrete decision of whether households buy a dirty or a clean car, conditional on buying a new car and neither changing the housing technology nor the region in which they live. The recursive formulations of the other discrete choices are analogous and are shown in the Appendix B.1. The value functions of buying a dirty car (DCA) and a clean car (CCA) conditional on not moving (NM) and not changing the housing type (NHA) are given by

$$\begin{aligned} V_t^{\text{NM,NHA,DCA}}(l_t, y_t, \kappa, \lambda_t^c, \lambda_t^h) \quad &= \max_{\{h_t, e_t^c, e_t^h\}} \quad u(x_t, h_t, e_t^h, e_t^c, l_{t+1}) + \beta\,\mathbb{E}\left[V_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda_{t+1}^c, \lambda_{t+1}^h) \mid y_t\right] \\ s.t. \qquad x_t &= y_t + T_t^{\pi} + T_t^{\tau} - \rho(l_{t+1}, \lambda_{t+1}^h)h_t - [p_t^{eh} + (1-\lambda_{t+1}^h)\xi_l^h \tau]e_t^h - [p^{ec} + (1-\lambda_{t+1}^c)\xi^c \tau]e_t^c - p_t^{c,di} \\ l_{t+1} &= l_t, \quad \lambda_{t+1}^c = 0, \quad \lambda_{t+1}^h = \lambda_t^h \end{aligned}$$

$$\begin{aligned} V_t^{\text{NM,NHA,CCA}}(l_t, y_t, \kappa, \lambda_t^c, \lambda_t^h) \quad &= \max_{\{h_t, e_t^c, e_t^h\}} \quad u(x_t, h_t, e_t^h, e_t^c, l_{t+1}) + \beta\,\mathbb{E}\left[V_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda_{t+1}^c, \lambda_{t+1}^h) \mid y_t\right] \\ s.t. \qquad x_t &= y_t + T_t^{\pi} + T_t^{\tau} - \rho(l_{t+1}, \lambda_{t+1}^h)h_t - [p_t^{eh} + (1-\lambda_{t+1}^h)\xi_l^h \tau]e_t^h - [p^{ec} + (1-\lambda_{t+1}^c)\xi^c \tau]e_t^c - p_t^{c,cl} \\ l_{t+1} &= l_t, \quad \lambda_{t+1}^c = 1, \quad \lambda_{t+1}^h = \lambda_t^h \end{aligned}$$

respectively. The expected value function is further specified in Appendix B.1, too.

3.2 Firm sector and production

There are three representative firms in the economy. First, a construction firm that builds dirty and clean housing and converts dirty housing into clean housing. Second, a rental firm that buys the housing stock from the construction firm and rents it out to households. Finally, a production firm that produces cars, energy, and the non-housing, non-energy good.

3.2.1 Construction Sector

The construction firm builds houses of both technologies and renovates dirty houses into clean ones. For the housing construction function, I follow Kaplan et al. (2020) and assume that the firm uses land permits and labor services as inputs. Thus, the firm's problem for constructing housing of type j in region l in time period t, reads

$$\max_{I_{l,t}^{h,j}} q_{l,t}^j I_{l,t}^{h,j} - w_{l,t}^j N_{l,t}^j \quad \text{s.t} \quad I_{l,t}^{h,j} = \psi_{l,t}^{h,j} \left(N_{l,t}^j\right)^{\alpha_l^h} \overline{L_l}^{1-\alpha_l^h} \quad \text{with} \quad \psi_{l,t}^{h,cl} = \Omega_{l,t}^h \psi^{h,di}$$

where $q_{l,t}^j$ and $I_{l,t}^{h,j}$ are the housing price and the number of housing units built for housing type j in location l in time period t. Further, $w_{l,t}^j$ is the wage for one unit of labor services, $N_{l,t}^j$ is the quantity of labor services employed, and $\overline{L_l}$ is the number of new permits for buildable land in region l.[18] Following Favilukis et al. (2017), I assume that these permits are sold competitively by the government to the

[18] In equilibrium all wages in this economy are equal to one, as discussed in Section 3.2.3.

construction firm and that their number is exogenous and constant over time. Hence, in equilibrium, all rents from housing construction accrue to the government and the construction firm makes no profit by building houses. Next, α_l^h and $\psi_{l,t}^{h,j}$ describe the relative share of labor services in the construction of housing and the total factor productivity of constructing housing, respectively. Based on empirical estimates from the literature, I assume that clean housing construction is initially more costly but that, due to exogenous technological process, its productivity converges to that of dirty housing construction which is assumed to be constant over time. The parameter $\Omega_{l,t}^h$, which describes this convergence of productivities over the transition period, is specified when calibrating the model in Section 3.4.5.

Solving the firm's problem yields the optimal level of housing construction of type j of[19]

$$I_{l,t}^{h,j} = \left(\alpha_l^h \frac{q_{l,t}^j}{w_{l,t}^j}\right)^{\frac{\alpha_l^h}{1-\alpha_l^h}} \left(\psi_{l,t}^{h,j}\right)^{\frac{1}{1-\alpha_l^h}} \overline{L_l}.$$

Hence, the number of new houses built increases one-to-one with the number of new land permits issued. Note also that the housing supply elasticity, i.e. how strongly housing construction responds to changes in housing prices, is given by $\frac{\alpha_l^h}{1-\alpha_l^h}$ and thus depends only on α_l^h.

After deriving the optimal levels for dirty and clean housing construction, the construction firm needs to decide which housing type to build on the newly permitted land. Comparing both profit functions[20] shows that the construction firm builds clean housing if the selling price of one unit of clean housing is higher than the selling price of one unit of dirty housing, adjusted for the relative productivity of constructing clean housing, formally

$$q_{l,t}^{h,cl} > \frac{q_{l,t}^{h,di}}{\Omega_{l,t}^h}.$$

In addition to constructing new houses, the construction firm can also renovate dirty houses into clean ones. For this renovation process, the firm solves

$$\max_{I_{l,t}^{ren}} q_{l,t}^{cl} I_{l,t}^{ren} - w_{l,t}^{ren} N_{l,t}^{ren} - q_{l,t}^{di} h_{l,t}^{di} \quad \text{s.t} \quad I_{l,t}^{ren} = \Omega_{l,t}^{ren} \min\left\{\left(N_{l,t}^{ren}\right)^{\alpha^{ren}}, h_{l,t}^{di}\right\}.$$

Thus, the construction firm uses dirty houses, which it buys from the rental firm at the market price $q_{l,t}^{di}$, and labor services, for which it pays wage $w_{l,t}^{ren}$, to produce clean housing of size $I_{l,t}^{ren}$, which it can sell to the rental firm for the market price $q_{l,t}^{cl}$. I assume a Leontief production function with a TFP-parameter of $\Omega_{l,t}^{ren}$, for which I assume the same speed of the technological process as for the TFP-parameter for the construction of clean houses $\Omega_{l,t}^h$. Solving this problem, the optimal level of renovations is given by[21]

$$I_{l,t}^{ren} = \Omega_{l,t}^{ren}\left[\frac{\alpha^{ren}}{w_{l,t}^{ren}}\left(\Omega_{l,t}^{ren} q_{l,t}^{cl} - q_{l,t}^{di}\right)\right]^{\frac{\alpha^{ren}}{1-\alpha^{ren}}}.$$

[19]The full derivation is provided in Appendix B.2.1.
[20]Again, full derivations are provided in Appendix B.2.1.
[21]Full derivations are provided in Appendix B.2.2.

Hence, the Leontief specification of the production function ensures that the elasticity of renovating dirty housing with respect to the effective renovation price $\Omega^{ren}_{l,t} q^{cl}_{l,t} - q^{di}_{l,t}$ is $\frac{\alpha^{ren}}{1-\alpha^{ren}}$, which I calibrate to match the overall housing supply elasticity. The construction firm renovates dirty housing as long as it yields positive profits, i.e. $\Omega^{ren}_{l,t} q^{cl}_{l,t} > q^{di}_{l,t}$, and there is still dirty housing, i.e. $H^{di}_{l,t} > 0$. I assume that the government accrues all profits from the renovation process.

3.2.2 Rental Firm

The competitive, representative rental firm decides how much dirty and clean housing to buy and how much dirty housing to renovate in each location. Hence, it maximizes

$$\begin{aligned}
V(H^{di}_{l,t}, H^{cl}_{l,t}) \quad &= \max_{h^{cl}_{l,t}, h^{di}_{l,t}, h^{ren}_{l,t}} \rho^{cl}_{l,t}(H^{cl}_{l,t} + h^{cl}_{l,t} + h^{ren}_{l,t}) + \rho^{di}_{l,t}(H^{di}_{l,t} + h^{di}_{l,t} - h^{ren}_{l,t}/\Omega^{ren}_{l,t}) \\
&- \quad q^{cl}_{l,t} h^{cl}_{l,t} - q^{di}_{l,t} h^{di}_{l,t} - q^{ren}_{l,t} h^{ren}_{l,t} + \frac{1}{1+r} E[V(H^{di}_{l,t+1}, H^{cl}_{l,t+1})] \\
\text{s.t} \quad H^{cl}_{l,t+1} \quad &= (1-\delta^h)(H^{cl}_{l,t} + h^{cl}_{l,t} + h^{ren}_{l,t}) \\
H^{di}_{l,t+1} \quad &= (1-\delta^h)(H^{di}_{l,t} + h^{di}_{l,t} - h^{ren}_{l,t}/\Omega^{ren}_{l,t}) \\
H^{cl}_{l,t+1}, H^{di}_{l,t+1} \quad &\geq 0.
\end{aligned}$$

where $h^{cl}_{l,t}$, $h^{di}_{l,t}$, and $h^{ren}_{l,t}$ are the number of clean, dirty, and renovated houses bought, $q^{cl}_{l,t}$, $q^{di}_{l,t}$, and $q^{ren}_{l,t}$ are the respective prices, and $\rho^{cl}_{l,t}$ and $\rho^{di}_{l,t}$ are the rents for clean and dirty housing. Finally, $H^{di}_{l,t}$ and $H^{cl}_{l,t}$ are the stocks of both types of housing, which must be non-negative and depreciate at the rate δ^h each period. Solving this problem yields a one-to-one mapping between rents and housing prices, where the latter are given by the infinitely, discounted and depreciated sum of the former[22]

$$q^{cl}_{l,t} = \rho^{cl}_{l,t} + \sum_{j=1}^{\infty} \left(\frac{1-\delta}{1+r}\right)^j E\left[\rho^{cl}_{l,t+j}\right], \quad q^{di}_{l,t} = \rho^{di}_{l,t} + \sum_{j=1}^{\infty} \left(\frac{1-\delta}{1+r}\right)^j E\left[\rho^{di}_{l,t+j}\right].$$

3.2.3 Car, energy, and non-housing, non-energy production

Finally, there is a representative and competitive firm that produces cars, energy, and the non-housing, non-energy good for both regions. All three goods are produced with a constant returns to scale technology, implying that the production firm makes no profits. For the non-housing, non-energy good, the production function reads

$$X_t = N^x_t,$$

where N^x_t is the number of labor units employed. As the price of the non-housing, non-energy good is the numeraire in this economy, the competitive wage is given by $w^x_t = 1$. Since labor is assumed to be perfectly mobile across sectors, all wages in this economy are equal to one.

[22] This relationship can be easily rewritten into the user-cost formula, i.e. $\rho^{cl}_{l,t} = q^{cl}_{l,t} - \frac{1-\delta}{1+r} E\left[q^{cl}_{l,t+1}\right]$ and $\rho^{di}_{l,t} = q^{di}_{l,t} - \frac{1-\delta}{1+r} E\left[q^{di}_{l,t+1}\right]$.

The production function for cars of technology j is given by

$$C_t^j = \psi_t^{c,j} N_t^{c,j}, \quad \text{with} \quad \psi_t^{c,cl} = \Omega_t^c \psi^{c,di}$$

where Ω_t^c describes the productivity differences between producing clean and dirty cars. Analogous to the construction of housing, I assume exogenous technological improvements for the production of clean cars, while the productivity of producing dirty cars is assumed to be constant. Thus, the price of cars of technology j is given by $p_t^{c,j} = \frac{1}{\psi_t^{c,j}}$.

The production functions of cars and heating energy also follow a constant returns to scale technology and read

$$E_{l,t}^c = \psi^{ec} N_t^{ec} \quad \text{and} \quad E_t^h = \psi^{eh} N_t^{eh},$$

which implies prices of $p^{ec} = \frac{1}{\psi^{ec}}$ and $p^{eh} = \frac{1}{\psi^{eh}}$. For energy production, I assume no technological process, such that these prices remain constant over the transition period.

3.3 Government

In the baseline scenario without carbon taxation, the government collects revenue from two sources. First, it owns the land permits in both regions and thus extracts all profits from the construction of housing by selling these permits to the representative housing construction firm. Second, it also extracts all profits from the renovation of dirty houses. These revenues are transferred back to households within regions in as lump-sum transfers such that the government budget is balanced each period. Hence, the government budget constraints are

$$\pi_{u,t}^{h,cl} + \pi_{u,t}^{h,di} + \pi_{u,t}^{ren} = \int_0^1 T_{l,t}^{\pi} l_{i,t} di$$

$$\text{with} \quad \pi_{u,t}^{h,cl} = q_{u,t}^{cl} I_{u,t}^{h,cl} - w_{u,t}^{cl} N_{u,t}^{cl}, \quad \pi_{u,t}^{h,di} = q_{u,t}^{di} I_{u,t}^{h,di} - w_{u,t}^{di} N_{u,t}^{di} \quad \text{and} \quad \pi_{u,t}^{ren} = q_{u,t}^{cl} I_{u,t}^{ren} - w_{u,t}^{ren} N_{u,t}^{ren} - q_{u,t}^{di} h_{u,t}^{di}$$

and

$$\pi_{h,r,t}^{cl} + \pi_{r,t}^{h,di} + \pi_{r,t}^{ren} = \int_0^1 T_{l,t}^{\pi} (1 - l_{i,t}) di$$

$$\text{with} \quad \pi_{r,t}^{h,cl} = q_{r,t}^{cl} I_{r,t}^{h,cl} - w_{r,t}^{cl} N_{r,t}^{cl}, \quad \pi_{r,t}^{h,di} = q_{r,t}^{di} I_{r,t}^{h,di} - w_{r,t}^{di} N_{r,t}^{di} \quad \text{and} \quad \pi_{r,t}^{ren} = q_{r,t}^{cl} I_{r,t}^{ren} - w_{r,t}^{ren} N_{r,t}^{ren} - q_{r,t}^{di} h_{r,t}^{di}$$

for both regions, where $l_{i,t}$ indicates whether household i lives in the urban region in year t.

3.4 Calibration

I calibrate the initial stationary equilibrium of this model, in which clean technologies are assumed to be absent, to the German economy in 2018. I use 2018 as the starting point for two reasons. First, the main dataset for the calibration, the EVS dataset, is from 2018. Second, in 2018, the shares of electric cars and heat pumps relative to all cars and heating systems were only 0.1 and 2.2 percent, respectively, according to the German Federal Motor Transport Authority (*Kraftfahrtsbundesamt*) and the German Federal Association of the Energy and Water Industries (*Bundesverband der Energie- und Wasserwirtschaft*), which allows me to interpret 2018 as a steady state without these goods. Further, I calibrate the share of urban households to the share of tenants living in cities with at least 100,000 inhabitants, which is around 47.1 percent.

My calibration strategy follows a three-step procedure. First, I take a set of parameters from the literature and directly from the data. A second set of parameters is calibrated in closed form, directly matching the empirical moments. Finally, I calibrate the remaining parameters using a simulated method of moments. In the following, I describe this procedure in more detail.

3.4.1 Utility Function

One period in the model corresponds to one year in the data. The discount rate and the coefficient of relative risk aversion are set to standard values of $\beta = 0.98$ and $\sigma = 2.0$, respectively. Exploiting the nested CES structure of the utility function, I can calibrate the weights in the utility function on the non-housing composite γ, the non-housing non-car energy consumption μ_c, and the housing size μ_h in closed form to the respective empirical expenditure shares using the first-order conditions. This procedure gives me values of $\gamma = 0.78$, $\mu_c = 0.99$, and $\mu_h = 0.91$. The mean of the city amenities is set to match the share of households in the urban region, resulting in a value of $\mu_\kappa = 0.0000011$. The elasticity of substitution between non-car energy non-housing consumption and car energy consumption, denoted by ν_x, is calibrated to match the own price elasticity of car energy consumption. An increase in the price of car energy leads to a greater decrease in car energy consumption if both goods are substitutes than if they are complements. As target, I take the own-price elasticity for gasoline of -0.35 estimated by Frondel and Vance (2009) for Germany, resulting in a value of $\nu_x = 0.45$. For the elasticity of substitution between the housing size and heating energy, I proceed analogously. I target the own-price elasticity of heating energy of -0.2 estimated by Auffhammer and Rubin (2018) and get a value of $\nu_h = 0.1$. Both targets are well in line with other estimates in the literature (Bastos et al., 2015; Brons et al., 2008; Davis and Muehlegger, 2010; Goetzke and Vance, 2021; Ruhnau et al., 2023). Finally, I need to calibrate the subsistence level of car-energy consumption in both regions. For the rural region, I take the difference in car-energy consumption in both regions, which is $\underline{e^{c,r}} = 4.5$, and for the urban region, I use $\underline{e^{c,u}} = 0$ as normalization because I already match the overall car-energy consumption by calibrating the utility weights.

3.4.2 Preference Shocks

For each of the four discrete decisions, there is a location and scale parameter to calibrate. To calibrate the migration shock, I use data from the German Socio-Economic Panel (SOEP). The SOEP is a longitudinal survey of around 40,000 individuals in Germany from 1984 to 2021. It contains information on many socioeconomic variables and on the county in which an individual lives. Based on the classification of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), I group these 401 counties into rural and urban regions. Finally, I compute the share of households in the SOEP that move between these two regions each period, which is

0.79%. I calibrate the location parameter of the mobility shock to match this share and get a value of $\mu_{\epsilon,l} = -0.00036$. I calibrate the scale parameter of the moving shock, denoted by $\sigma_{\epsilon,l}$, to match the moving semi-elasticity with respect to income shocks, which indicates by how many percentage points net migration rates increase if wages increase by one percent. The implicit assumption is that households respond to expenditure shocks resulting from carbon prices in the same way as they respond to income shocks. As target, I take 0.2 estimated by Monras (2018), which gives me a value of $\sigma_{\epsilon,l} = 0.0001$. Next, I calibrate the location and scale parameters of the housing-type shock to match the level and curvature of the adoption rates of clean houses. I use the data from the German Federal Association of the Energy and Water Industries (*Bundesverband der Energie- und Wasserwirtschaft*) and obtain values of $\mu_{\epsilon,h} = -0.00004$ and $\sigma_{\epsilon,h} = 0.000014$, respectively. For the car adjustment shock, I calibrate the location and scale parameters to match the share of households buying a car and the price elasticity of cars, yielding $\mu_{\epsilon,c} = -0.00008$ and $\sigma_{\epsilon,c} = 0.00003$. Finally, for the car-type shock, I normalize the location parameter to 0, as the adoption rates of clean cars is matched by the price premium of clean cars. The scale parameter is set to match the price elasticity of clean cars and yields $\sigma_{\epsilon,ct} = 0.0003$. As empirical targets, I take estimates from Fridstrøm and Østli (2021) for Norway of -1.27.

3.4.3 Labor Income

The average annual household income in the model provides a normalization and is set to 30,821 Euros in line with the EVS data for tenants. For the idiosyncratic shock process, I use estimates from Fehr et al. (2013) for the persistence parameter ρ and calibrate the variance of the income shock σ^2_η to match the Gini index for net household income in Germany in 2018. According to the German Federal Statistical Office the Gini index was 0.311, resulting in values of $\rho = 0.957$ and $\sigma^2_\eta = 0.031$.

3.4.4 Housing Construction

The labor intensity parameter in the housing construction function is a key parameter in the model as it determines the housing supply elasticity in region l, which is given by $\alpha^h_l/(1-\alpha^h_l)$. Exploiting this direct mapping, I calibrate α^h_l to estimates of the housing supply elasticity in both regions. As targets, I take estimates from Beze (2023) for Germany who finds values of 0.285 and 0.204 for rural and urban regions, respectively.[23] These estimates are well in line with other estimates in the literature (Baum-Snow and Han, 2024; Lerbs, 2014) and imply values of $\alpha^h_r = 0.3986$ and $\alpha^h_u = 0.2563$. For the housing renovation elasticity, I target the overall housing supply elasticity in Beze (2023), giving me a value of $\alpha^h_{ren} = 0.333$. The number of land permits issued is calibrated to match the initial steady state rent in both regions, yielding $\overline{L_r} = 362$ and $\overline{L_u} = 154$. Since in the initial steady state housing construction and the total housing supply are directly linked through the depreciation rate, the number of land permits also determines the number of housing units constructed and the TFP parameter for dirty housing construction, denoted $\psi^{h,di}$, can be normalized to 1. For the initial productivity of clean housing construction relative to dirty housing construction, I take estimates from the Bavarian Construction Association, which estimates that the construction of clean housing was

[23]These estimates of urban and rural housing supply elasticities refer to the estimates of the 25th and 75th percentiles of the land development intensity distribution.

147 Euros per square meter more expensive in 2018, resulting in an initial productivity discount of 5.77 percent. For its convergence over the transition period, I take estimates from LCP Delta, which forecasts that the price of heat pumps, a key component of clean housing, will fall by 40 percent over 10 years (Delta, 2021). I then extrapolate this convergence rate over the entire transition period.[24] The TFP parameters for housing renovations at the beginning of the transition are calibrated to match the number of renovations. According to Cischinsky and Diefenbach (2018), the renovation rate, which characterizes the share of housing renovations in a given year relative to the total housing stock, was 0.99% in Germany in 2016, yielding initial values of $\Omega^{ren}_{r,2019} = 0.955$ and $\Omega^{ren}_{u,2019} = 0.939$. For the productivity improvements of housing renovation, captured by the path of Ω^{ren}_{l}, I assume the same rate as for housing construction.[25] I calibrate the depreciation rate for housing by matching the share of new housing units relative to the total housing stock. According to the German Federal Statistical Office these numbers were 287,400 and 42,400,000, respectively, in 2018, giving in a depreciation rate for housing of $\delta_h = 0.0068$. Finally, I calibrate the interest rate to match the housing-price-to-rent ratio. According to the German Bundesbank, the ratio was 28 in 2018, resulting in an interest rate of $r = 0.03$.

3.4.5 Technical Parameters

To calibrate the parameters that translate heating energy consumption into carbon emissions, I use estimates from International Institute for Sustainability Analysis and Strategy based on the Global Emission Model for Integrated Systems (GEMIS) version 5.0 (IINAS and Strategy, 2021). I weight their estimates of carbon emissions for different heating systems by the empirical shares of rural and urban households using these heating systems. I get estimates of $\xi^h_r = 0.247$ and $\xi^h_u = 0.232$ tons of carbon emissions per MWh of heating consumption. To translate the car energy consumption into carbon emissions, I take estimates from the Helmholtz Institute for diesel and gasoline, weight them with their respective empirical shares and get a value of $\xi^c = 0.251$ tons of carbon emissions per 100 liters of gasoline. I calibrate the productivity parameters for the production of heating and car energy by matching their prices in 2018, which I get from the German Federal Statistical Office. For car energy, I weight the average prices of diesel and gasoline with their respective shares in 2018, resulting in a price of $p^{ec} = 0.0045$ and a productivity of $\psi^{ec} = 222$. Analogously, I also weight the different heating sources by their respective empirical shares and get a price of heating energy of $p^{eh} = 0.0023$ and a productivity of $\psi^{eh} = 435$. The productivity of producing dirty cars is calibrated to match the expenditure share of new car purchases and is $\psi^{c,di} = 61.6$. For the production of clean cars, I calibrate the productivity difference relative to dirty cars and its convergence over time by matching the observed share of electric vehicles purchased in Germany until 2023. I then again extrapolate this convergence rate over the entire transition period. Finally, I calibrate the parameters governing the efficiency differences in converting raw car and heating energy into vehicle miles traveled and temperature between clean and dirty technologies. For cars, Lévay et al. (2017) estimate for Germany that the cost of fossil fuels are 25 percent higher than for electric fuels, resulting in a value of $\phi^{c,cl} = 0.33$. For heating energy, Taruttis and Weber (2022) estimate for Germany that the average energy consumption in for houses with heat pumps and all other houses are 51 kWh/m^2a and 174

[24]Figure A7b in the Appendix shows the technological process of clean housing construction along the transition.
[25]Figure A7c in the Appendix shows the technological process of housing renovations along the transition.

Table 1: List of parameters

Parameter	Description	Value	Source/Target	Method
Utility function				
β	Discount rate	0.98	Standard value	Literature
σ	CRRA-coefficient	2.0	Standard value	Literature
γ	Weight non-housing composite good	0.78	Expenditure share of non-housing	Closed form
μ_c	Weight non-housing, non-car energy consump.	0.99	Average exp. non-housing non-car energy	Closed form
μ_h	Weight housing size	0.91	Average expenditures rent	Closed form
μ_κ	Mean city amenities	0.0000011	Share of HHs in urban region	SMM
ν_x	Elasticity of substitution x vs. e^c	0.45	Own price elasticity of car energy	SMM
ν_h	Elasticity of substitution h vs. e^h	0.1	Own price elasticity of heating energy	SMM
$\underline{e^{c,r}}$	Min. car energy consumption - rural	4.5	Diff. car energy consump. urban vs. rural	Closed form
$\underline{e^{c,u}}$	Min. car energy consumption - urban	0.0	Normalization	-
Preference shocks				
$\mu_{\epsilon,l}$	Location parameter of location pref. shock	-0.00036	Share of households moving across regions	SMM
$\mu_{\epsilon,h}$	Location parameter of housing type pref. shock	-0.00004	Level of clean housing adoption rate	SMM
$\mu_{\epsilon,c}$	Location parameter of car pref. shock	-0.00008	Share of households buying dirty cars	SMM
$\mu_{\epsilon,ct}$	Location parameter of car techn. pref. shock	0.0	Normalization	-
$\sigma^2_{\epsilon,l}$	Scale parameter of location pref. shock	0.0001	Elasticity of moving	SMM
$\sigma^2_{\epsilon,h}$	Scale parameter of housing type pref. shock	0.000014	Curvature of clean housing adoption rate	SMM
$\sigma^2_{\epsilon,c}$	Scale parameter of car pref. shock	0.00003	Elasticity of dirty car purchases	SMM
$\sigma^2_{\epsilon,ct}$	Scale parameter of car technology pref. shock	0.0003	Elasticity of clean car purchases	SMM
Labor income				
ρ	Persistence of income shock	0.957	Fehr et al. (2013)	Literature
σ^2_η	Variance of income shock	0.031	Gini index	SMM
Housing construction				
α^h_r	Labor intensity housing construction - rural	0.3986	Rural housing supply elast. in Beze (2023)	Closed form
α^h_u	Labor intensity housing construction - urban	0.2563	Urban housing supply elast. in Beze (2023)	Closed form
α^{ren}	Labor intensity housing renovations	0.333	Overall housing supply elast. in Beze (2023)	Closed form
$\overline{L_r}$	Number of issued land permits - rural	362	Initial steady state rent - rural	SMM
$\overline{L_u}$	Number of issued land permits - urban	154	Initial steady state rent - urban	SMM
$\psi^{h,di}$	Productivity dirty housing construction	1.0	Normalization	-
Ω^h_r	Techn. progress clean housing constr. - rural	see A7b	See text	Literature
Ω^h_u	Techn. progress clean housing constr. - urban	see A7b	See text	Literature
Ω^{ren}_r	Techn. progress housing renov. - rural	see A7c	see text	Literature
Ω^{ren}_u	Techn. progress housing renov. - urban	see A7c	see text	Literature
δ	Depreciation rate for housing	0.0068	Housing construction rate	Closed form
r	Interest rate	0.03	Housing price-to-rent ratio	Closed form
Technical parameters				
ξ^h_r	Heating energy to emissions translation - rural	0.247	See text	Literature
ξ^h_u	Heating energy to emissions translation - urban	0.232	See text	Literature
ξ^c	Car energy to emissions translation	0.251	See text	Literature
ψ^{ec}	Inverse of price car energy per liter	222	German Federal Statistical Office	Literature
ψ^{eh}	Inverse of price gas per MWh	435	German Federal Statistical Office	Literature
ψ^c	Productivity dirty car production	61.6	Average exp. car purchases	Literature
Ω^c	Technological progress clean car production	see A7a	See text	SMM
$\phi^{c,cl}$	Additional car energy efficiency clean cars	0.33	Lévay et al. (2017)	Literature
$\phi^{c,di}$	Additional car energy efficiency dirty cars	0.0	Normalization	-
$\phi^{h,cl}$	Additional heating energy efficiency clean houses	2.412	Taruttis and Weber (2022)	Literature
$\phi^{h,di}$	Additional heating energy efficiency dirty houses	0.0	Normalization	-

Notes: This table lists the parameters of the model with their values, calibration targets, and the calibration method.

kWh/m^2a, respectively. Thus, the efficiency premium for clean houses is $\phi^{h,cl} = 2.412$. The values for the dirty technologies, $\phi^{c,di}$ and $\phi^{h,di}$ are normalized to 0. All parameters, their values, targets and the calibration method are summarized in Table 1.

3.4.6 Model fit

I asses the model fit based on the data in the initial steady state of 2018 and the first years of the transition from 2019 to 2023. Overall, the model is able to match key data moments very well. The model moments of the parameters that are calibrated in closed form, such as the weights in the utility function, match their empirical targets exactly. Table 2 shows the model fit for the parameters that are calibrated with a simulated method of moments.

Table 2: Model fit

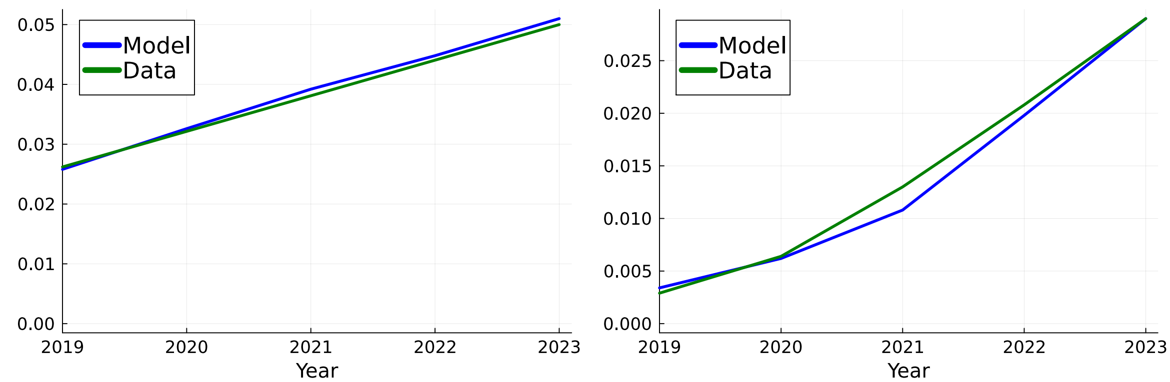
Moment	Model	Data	Parameter	Source
Utility function				
Urban population share	47.1	47.1	μ_κ	Own calculations based on EVS
Own price elasticity e_c	-0.34	-0.35	ν_x	Frondel and Vance (2009)
Own price elasticity e_h	-0.19	-0.2	ν_h	Auffhammer and Rubin (2018)
Preference shocks				
Share of HHs moving across regions (%)	0.78	0.79	$\mu_{\epsilon,l}$	Own calculations based on SOEP
Share of overall car purchases (%)	8.3	8.3	$\mu_{\epsilon,c}$	Federal Motor Transport Authority
Level of clean housing adoption	see Figure 4a		$\mu_{\epsilon,h}$	Federal Assoc. of Energy & Water Industry
Semi-elasticity of moving	0.21	0.2	$\sigma^2_{\epsilon,l}$	Monras (2018)
Elasticity overall car purchases	-0.92	-0.99	$\sigma^2_{\epsilon,c}$	Fridstrøm and Østli (2021)
Elasticity electric car purchases	-1.25	-1.27	$\sigma^2_{\epsilon,ct}$	Fridstrøm and Østli (2021)
Curvature of clean housing adoption	see Figure 4a		$\sigma^2_{\epsilon,h}$	Federal Assoc. of Energy & Water Industry
Labor income				
Gini index	0.31	0.31	σ^2_η	German Federal Statistical Office
Housing construction				
Initial steady state rent - rural	6.87	6.87	$\overline{L_r}$	Own calculations based on EVS
Initial steady state rent - urban	8.45	8.45	$\overline{L_u}$	Own calculations based on EVS
Technical parameters				
Adoption rate of clean cars	see Figure 4b		Ω_c	Federal Motor Transport Authority

Notes: This table shows the model fit of the parameters that are calibrated with a simulated method of moments.

The model matches the urban population share exactly and the own price elasticities of car and heating energy very well. For the preference shocks, the model is able to match the moments for the location parameters of the shocks very well and also the elasticities for the discrete choices only deviate slightly from their empirical targets. Finally, it matches the Gini index and the initial rents in both regions exactly. For calibrating the parameters of the housing adjustment shock and the technological improvements, I target the adoption rates of clean houses and cars, respectively. Figure 4 plots the share of households with clean goods in the model, without carbon taxes, and in the data. The levels and the speed of adjustments are matched very well.

Figure 4: Model fit technology adjustments

(a) Housing (b) Cars



Notes: Panel (a) compares the shares of households with clean housing technologies in the model and in the data. The data points are weighted equally by the share of households with heat pumps and those living in apartments of energy class A+ or A. Panel (b) shows the corresponding values for cars. The empirical values show the share of households with electric vehicles, not including hybrids.

4 Policy experiments

I now use the calibrated model to study the consequences of introducing carbon taxes on the level of redistribution across income groups and space, on the speed of transitioning to clean technologies and on their political support depending on how the carbon tax revenues are rebated back to households. I start in an initial stationary equilibrium in which only dirty technologies exist and introduce clean technologies exogenously. Since clean technologies are more efficient at converting raw car and heating energy into vehicle miles traveled and temperature, this starts a transition to clean technologies, even without any policy intervention. I compare this transition without policy to one in which I introduce a carbon tax of 300 Euros per ton of carbon. This level is well in line with estimates of future carbon taxes under the Emission Trading System 2 (ETS2) proposed by the European Union (Kalkuhl et al., 2023). I compare three ways of recycling back the carbon tax revenues. First, since carbon taxes have been shown to be regressive because poor households spend a higher share of their total expenditures on carbon intensive goods, such as energy, the literature has identified lump-sum transfers as a way to avoid this regressive redistribution. In general, compensating households with lump-sum transfers has been found to be even progressive as household carbon footprints increase with income (Douenne, 2020; Kuhn and Schlattmann, 2024). This rebate scheme resembles a popular policy proposal in Germany (*Klimageld*). If households are compensated with lump-sum transfers[26], the government budget constraint, which needs to balance each period, reads in period t

[26] The level of transfers along the transition is shown in Figure A8 in the Appendix.

$$\int_0^1 \left[e_{i,t}^h(1-\lambda_{i,t}^h)(l_{i,t}\xi_u^h + (1-l_{i,t})\xi_r^h) + e_{i,t}^c(1-\lambda_{i,t}^c)\xi^c\right]\tau di = T_t^\tau.$$

Second, as shown in the empirical part of this paper, carbon footprints differ substantially across space between rural and urban regions. Thus, lump-sum transfers redistribute from rural to urban households. Therefore, I consider place-based transfers, where transfers are set such that there is no redistribution between regions. This policy resembles the Austrian *Klimabonus*, a policy that was implemented in 2022 and reimburses carbon tax revenues based on whether households live in rural or urban regions. The government budget constraints for both regions read

$$\int_0^1 \left[e_{i,t}^h(1-\lambda_{i,t}^h)(1-l_{i,t})\xi_r^h + e_{i,t}^c(1-\lambda_{i,t}^c)(1-l_{i,t})\xi^c\right]\tau di = \int_0^1 (1-l_{i,t})T_{r,t}^\tau di$$

and

$$\int_0^1 \left[e_{i,t}^h(1-\lambda_{i,t}^h)l_{i,t}\xi_u^h + e_{i,t}^c(1-\lambda_{i,t}^c)l_{i,t}\xi^c\right]\tau di = \int_0^1 l_{i,t}T_{u,t}^\tau di,$$

for the rural and urban region, respectively.

Finally, I use the carbon tax revenue to finance subsidies for clean housing renovations, where the subsidies are paid on the labor costs. Thus, the government budget reads

$$\int_0^1 \left[e_{i,t}^h(1-\lambda_{i,t}^h)(l_{i,t}\xi_u^h + (1-l_{i,t})\xi_r^h) + e_{i,t}^c(1-\lambda_{i,t}^c)\xi^c\right]\tau di = \left[w_{l,t}N_{r,t}^{ren} + w_{l,t}N_{u,t}^{ren}\right]\psi_t,$$

where ψ_t characterizes the percentage subsidy in period t. While the first two policies are concerned with redistribution across income groups and space, the third policy aims to increase the speed of the transition to clean technologies and implicitly redistributes between early and late clean housing type adopters.

I first document the transitional dynamics of key household variables and the housing sector. Thereafter, I compare the long-run consequences of these different policies by comparing their stationary equilibria. Finally, I evaluate the political support for these policies in monetary and welfare terms.

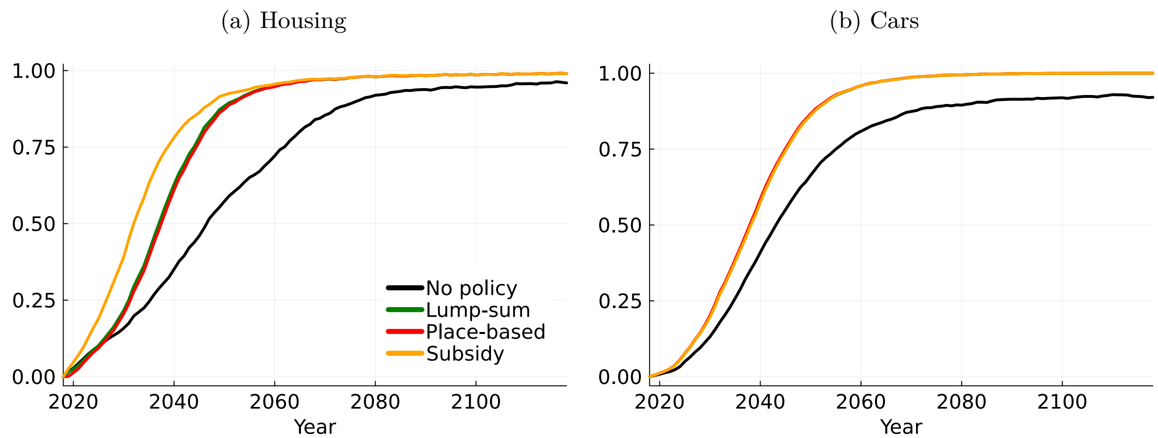
4.1 Results along the transition

I begin by documenting how key household variables, such as technology types, consumption levels, carbon footprints, and the level of spatial redistribution, evolve during the transition. I then show how the endogenous housing prices change and how housing construction and renovation respond to the different policy scenarios.

4.1.1 Consumption and spatial redistribution

Figure 5 shows the share of households with clean houses and cars along the transition. Without any policy intervention, the share of households with clean houses rises steadily over the transition to around 35 and 73 percent in 2040 and 2060, respectively, before converging to the new equilibrium at around 96 percent in 2085. Introducing a carbon tax of 300 Euros per ton accelerates the transition significantly. When the tax revenue is spent on transfers to households, the share of clean houses is 61 and 91 percent in 2040 and 2060, respectively, before it converges to the new equilibrium at 99 percent in 2080. When spending the carbon tax revenues on subsidies for renovations, the transition is further accelerated, so that 77 and 92 percent of the housing stock is clean in 2040 and 2060, respectively. Note that the subsidy on renovations is initially around 60 percent before it declines at the same rate as carbon emissions.[27] For cars, the transitions are similar. Without policy intervention, the share of clean cars is 40 and 81 percent in 2040 and 2060, respectively, before converging to the new equilibrium at 93 percent. With carbon taxes, the shares are 56 and 95 percent in 2040 and 2060, respectively, and converge to 100 percent. Complete decarbonization is thus only possible with carbon taxes. The share of clean cars does not depend on how the carbon tax revenues are spent.

Figure 5: Share of clean technologies along the transition



Notes: Panel (a) shows the share of households with clean houses along the transition period for the different policy scenarios considered. Panel (b) shows the corresponding share of households with clean cars along the transition.

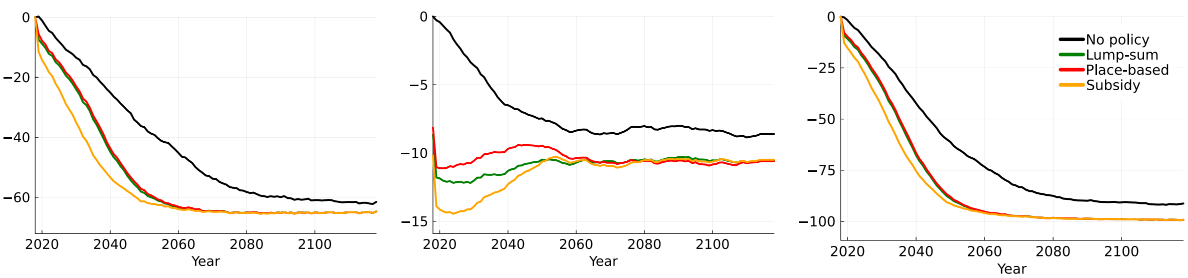
As households adopt clean and more efficient technologies, their raw energy consumption decreases. Figure 6 shows the percentage changes in energy consumption and carbon footprints relative to the initial steady state. First, note that car and heating energy consumption fall by around 10 to 15 percent after introducing carbon taxes due to a price effect, as a carbon tax of 300 Euros per ton increases the price of car and heating energy by around 60 and 100 percent, respectively. Since urban households have lower car energy consumption and lump-sum transfers redistribute to urban households, leading to an increase in the urban population share, the reduction in car energy consumption is one percentage points larger with lump-sum than with place-based transfers.[28] If the carbon tax revenues are spent on subsidies for renovations, the reduction is another two percentage points larger due to the negative income effect of smaller direct transfers. As households move into clean houses heating energy consumption steadily falls until it converges the new equilibrium around 63 percent lower than the initial equilibrium. When introducing carbon taxes, car energy consumption stays at the level of the initial drop around 11 percent lower than in the initial equilibrium. Without carbon

[27] Figure A10 in the Appendix shows the level of the subsidy along the transition period.
[28] These results on migration are shown next.

taxes, fewer households adopt clean cars and hence car energy consumption falls by only 9 percent. The resulting carbon footprints fall faster with carbon taxes. With carbon taxes they fall by about 70 to 75 percent and by 95 percent until 2040 and 2060, respectively, without them they fall by 45 and 74 percent, respectively. Note again that there is no complete decarbonization without carbon taxes.

Figure 6: Percentage changes over the transition

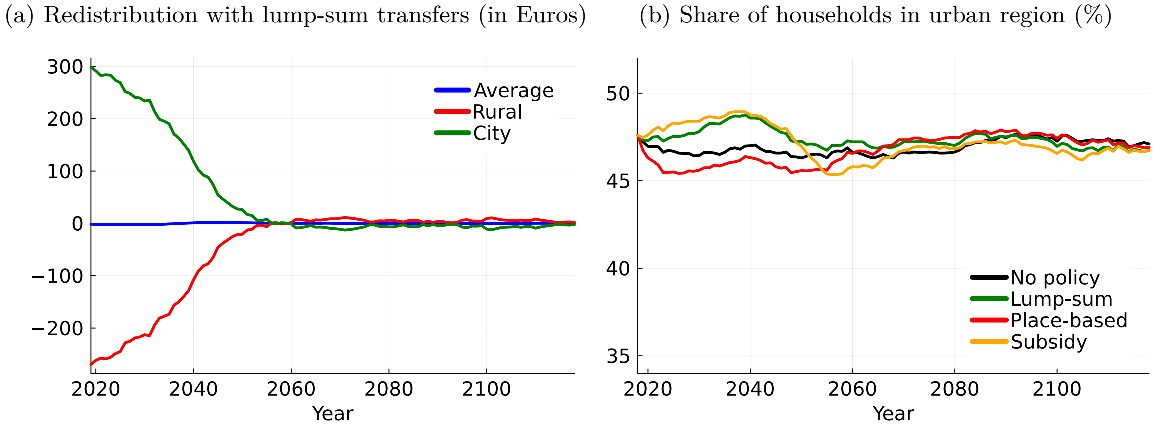
(a) Heating energy (b) Cars energy (c) Carbon footprints



Notes: Panel (a) and Panel (b) show the percentage change in heating and car energy along the transition for the considered policy scenarios. Panel (c) depicts the resulting path of carbon footprints.

Finally, Figure 7 shows the resulting level of spatial redistribution and the urban population share along the transition. For readability, I focus on the redistribution with lump-sum transfers, all other policies are shown in Figure A11 in the Appendix. Upon introducing the carbon tax with lump-sum transfers, an average urban household receives an annual net transfer of 300 Euros, whereas an average rural household have net payments of 270 Euros. As households adopt clean technologies over time, the level of redistribution declines until there is no more spatial redistribution after 2055. The present value of this difference in net transfers between rural and urban households is around 8,000 Euros, around 25 percent of the average household annual net income. This spatial redistribution has implications for the location choice of households. During the first years of the transition, the urban population share increases with lump-sum transfers from initially 47.1 percent to around 48.5 percent in the year 2040. This net migration of about 3 percent of the urban population corresponds to around 1.2 million individuals for Germany. This finding is consistent with empirical studies finding net migration to urban regions after gasoline price increases (Molloy and Shan, 2013). The increase in the urban population share over 20 years corresponds to an increase in the annual net migration rate to the urban region by 0.15 percent of the urban population, slightly less than the migration flow to the rural region during COVID, which was around 0.2 (Stawarz et al., 2022). Over time, this share falls again and converges to the new stationary equilibrium at around 46.3 percent. When spending the carbon tax revenues on subsidies for renovations, the initial increase in the urban population share is similar to the one with lump-sum transfers, as the level of spatial redistribution is similar, too, as shown in Figure A11 in the Appendix. If spending the carbon tax revenues on place-based transfers and without any carbon taxes, there is no such net migration to the urban region but only the net migration to the rural regions along the transition.

Figure 7: Location choices and redistribution over the transition



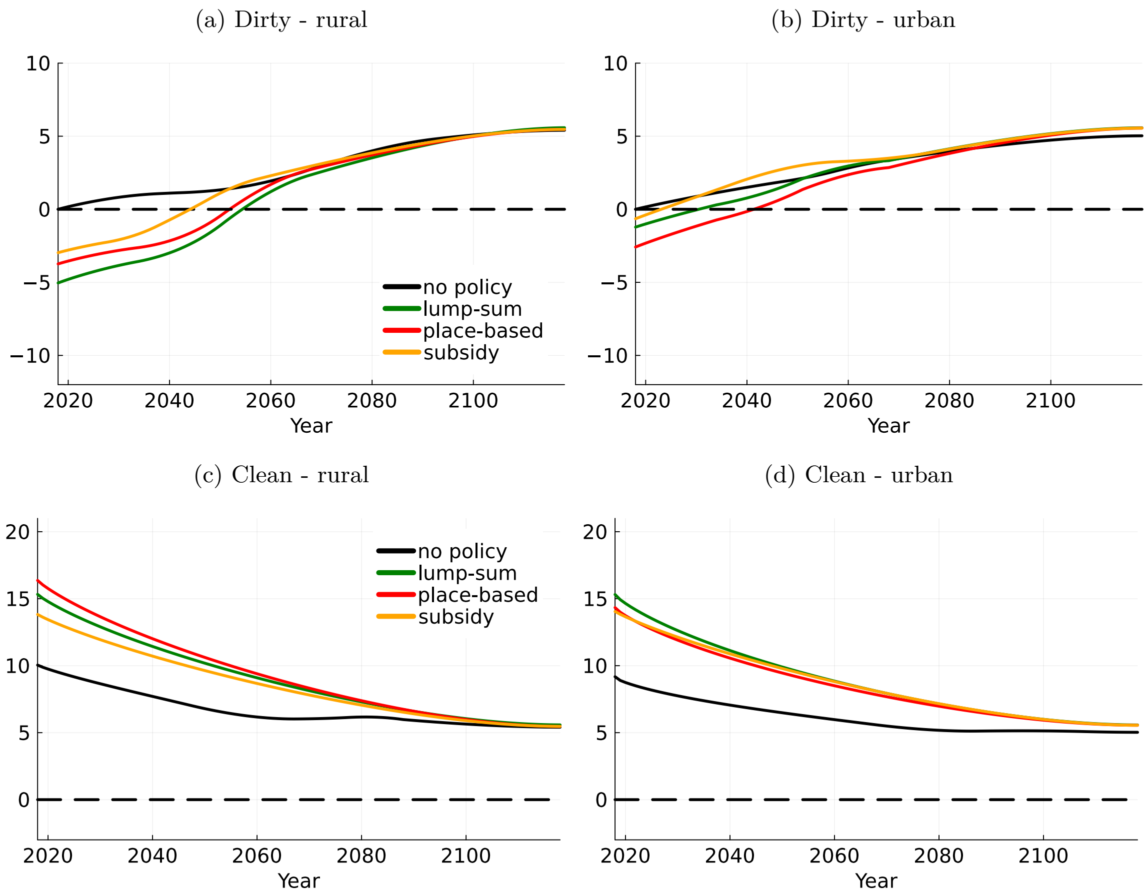
Notes: Panel (a) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers. Figure A11 in the Appendix shows the level of spatial redistribution for all policy scenarios. Panel (b) shows the share of the population living in the urban region along the transition for the different policy scenarios.

4.1.2 Housing sector

This subsection documents how housing prices and housing construction and renovation change over the transition. Figure 8 shows the percentage changes for the four endogenous housing prices relative to the initial stationary equilibrium in the same region. Without any policy intervention, the endogenous price premium for clean houses jumps to 10 and 9 percent for rural and urban regions, respectively, upon introducing clean technologies, while the prices of dirty houses remain unchanged. This price increase is slightly higher in the rural region because of higher carbon tax payments and thus higher demand for clean houses. As the construction firm builds new clean houses and renovates dirty houses into clean ones, prices for clean and dirty houses converge and stabilize around 6 percent higher than in the initial stationary equilibrium after around 100 years.

If introducing a carbon tax of 300 Euros per ton of carbon emissions and transferring the collected tax revenues back to households as lump-sum transfers, the initial increase in the price premium for clean houses is 15 percent, 5 percentage points higher than in the scenario without carbon tax. This increase in the price premium results from a higher demand for clean houses as carbon taxes increase the price of heating dirty houses. Prices for dirty houses fall by 5 and 2 percent for rural and urban regions, respectively, relative to the initial steady state. This decrease is due to a reduction in housing demand as heating energy, a complementary good to the housing size, becomes more expensive due to the carbon tax. Since rural households consume more heating energy and use heating technologies that emit more carbon, this effect is stronger for them. In addition, there is net migration to the urban region which reduces housing demand and thus prices in the rural region. Thus, the general equilibrium effects mitigate the heterogeneous impact of the carbon tax as they increase urban relative to rural rents. Quantitatively, this effect reduces the level of spatial redistribution by a 25 percent from 8,000 Euros to 6,000 Euros. When carbon tax revenues are spent on place-based transfers, housing prices are about 1 to 2 percent higher (lower) in the rural (urban) region compared to the scenario with lump-sum transfers. This difference is due to higher transfers to rural households. When the carbon tax revenues are spent on subsidies for renovating dirty into clean houses, the initial price premium for clean houses is around 2 and 1 percentage point lower than with lump-sum transfers in rural and urban regions, respectively. This is because the subsidy increases the supply of clean housing, which reduces prices in equilibrium.

Figure 8: Housing price changes over the transition



Notes: Panel (a) shows the percentage change of the housing price of dirty houses in the rural region relative to the price in the initial stationary equilibrium for dirty housing along the transition for the different policy scenarios. Panels (b) - (d) show the corresponding paths for dirty houses in the urban region and for clean houses in the dirty and clean region, respectively.

Next, I document how the supply of housing, which is determined by the construction and renovation of houses, responds to the different policy scenarios. Figure 9 shows the construction and renovation rates, defined as the share of newly constructed and renovated houses in a given period relative to the total housing stock in the initial steady state in the same region.[29] Since the prices for clean houses are higher with carbon taxes, the housing construction rate is around 0.02 percentage points higher. Housing construction rates rise to around 0.71 percent in 2050 before they slightly fall to the final stationary equilibrium due to falling prices of clean houses. Subfigure 9b shows that the renovation rate

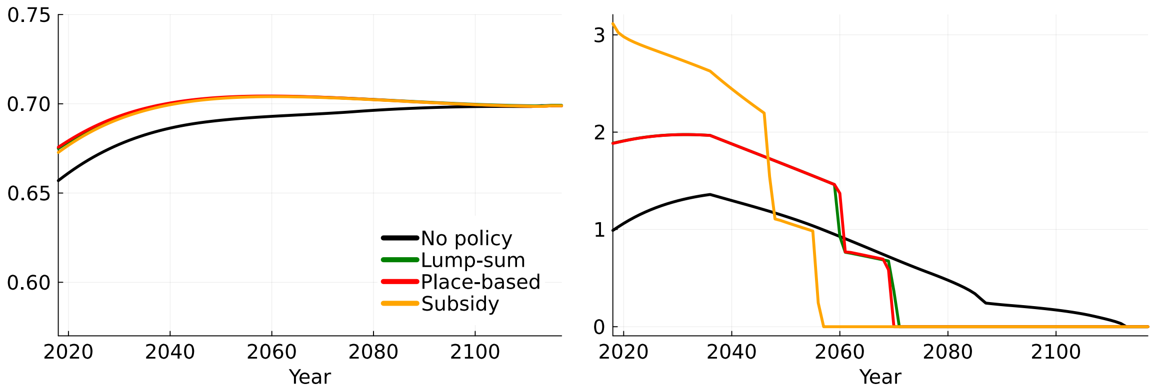
[29]Subfigure 9a shows the total level of newly constructed housing regardless of the technology. Figure A12 in the Appendix shows the construction rates of both technology types along the transition.

strongly varies with the policy scenario. Without any policy intervention, the renovation rate initially increases from around 1 percent to 1.3 percent in 2035 due to technological progress. But over time, the prices of clean and dirty houses converge, making renovations less profitable and thus reducing the renovation rate until there are no more renovations after 2115. With carbon taxes, the price difference between clean and dirty houses is larger, leading to a renovation rate of around 2 percent until 2040, before it declines. Finally, with subsidies on renovations the rate increases to around 3 percent before falling to zero in 2058. The initial subsidy on renovations is about 60 percent and its path over the transition is shown in Figure A10 in the Appendix.

Figure 9: Housing construction and renovations over the transition

(a) Housing construction rate (%)

(b) Housing renovation rate (%)



Notes: Panel (a) shows the share of newly constructed housing relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition. Panel (b) shows the share of housing renovations relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition.

4.2 Long-run consequences of carbon taxes

To assess the long-run consequences of the different policy scenarios, I compare their stationary equilibria. Since the prices of clean and dirty houses have converged in the long-run, housing renovations are no longer profitable. Therefore, for this long-run analysis, I focus on reimbursing households through lump-sum and place-based transfers. Table 3 shows the percentage changes in key variables for the different policy scenarios relative to the initial stationary equilibrium without clean technologies. Because clean technologies are more efficient in converting raw energy into temperature and vehicle miles traveled, the vast majority of households use clean technologies in the final steady states. In the scenario without carbon taxes this is true for 92 to 97 percent of households and when introducing carbon taxes, this number even increases to 99 to 100 percent. As the share of clean, energy-efficient technologies increases, energy consumption decreases. Without policy intervention, the reductions are around 10 and 62 percent for car and heating energy, respectively. With carbon taxes these numbers increase in absolute terms to 11 and 65 percent. While there are no sizeable spatial differences in heating energy consumption, the reductions in car energy consumption are about 5 percentage points higher in the urban region. This difference is due to a higher subsistence level and thus a higher marginal utility for a given level of consumption, which results in a lower price elasticity of car energy consumption in the rural region, in line with empirical findings (Santos and Catchesides, 2005; Wadud et al., 2010). As a result of this shift to clean technologies, carbon footprints decrease by about 92 percent without and by 99 percent with carbon taxes. Thus, (almost) complete decarbonization can only be achieved with carbon taxes. Since heating energy and housing size are complementary goods, a higher efficiency in the heating technology also increases the demand for housing. Thus, the average housing size increases by about 2.3 percent without policy intervention and by 2.4 percent with carbon taxes. The larger increase with carbon taxes results from a higher share of clean houses and thus more efficient heating technologies. This increase in housing demand leads to an increase in the rent by around 5 to 6 percent, as the housing supply exhibits decreasing returns to scale due to the constant number of land permits issued each period. Consumption of the non-housing, non-energy good increases slightly, and there is almost no spatial redistribution from carbon taxes as carbon footprints and thus carbon tax payments and transfers tend to zero.

Table 3: Changes from initial to final stationary equilibrium

	No policy		Lump-sum		Place-based	
	Rural	Urban	Rural	Urban	Rural	Urban
Clean cars (ppts.)	92.5	93.5	100	100	100	100
Clean housing (ppts.)	97.4	95.1	99.4	98.9	99.4	98.9
Car energy (%)	-7.6	-12.0	-8.7	-13.3	-8.8	-13.4
Heating energy (%)	-63.4	-60.9	-65.4	-64.7	-65.4	-64.7
Carbon emissions (%)	-93.0	-90.7	-99.6	-98.9	-99.6	-98.9
Housing size (%)	2.3	2.3	2.4	2.5	2.3	2.5
Rent (%)	5.9	5.3	6.1	5.8	6.0	5.8
Further consumption (%)	0.1	0.9	0.2	1.6	0.3	1.5
Net transfers (Euro)	0	0	2.58	-2.99	0.02	-0.02
Population share (ppts.)	1.23	-1.23	1.34	-1.34	1.35	-1.35
Welfare (CEV)	1.93	1.76	1.82	1.71	1.82	1.70

Notes: This table shows the changes of key outcomes from the initial stationary equilibrium to the final stationary equilibrium for the different policy scenarios.

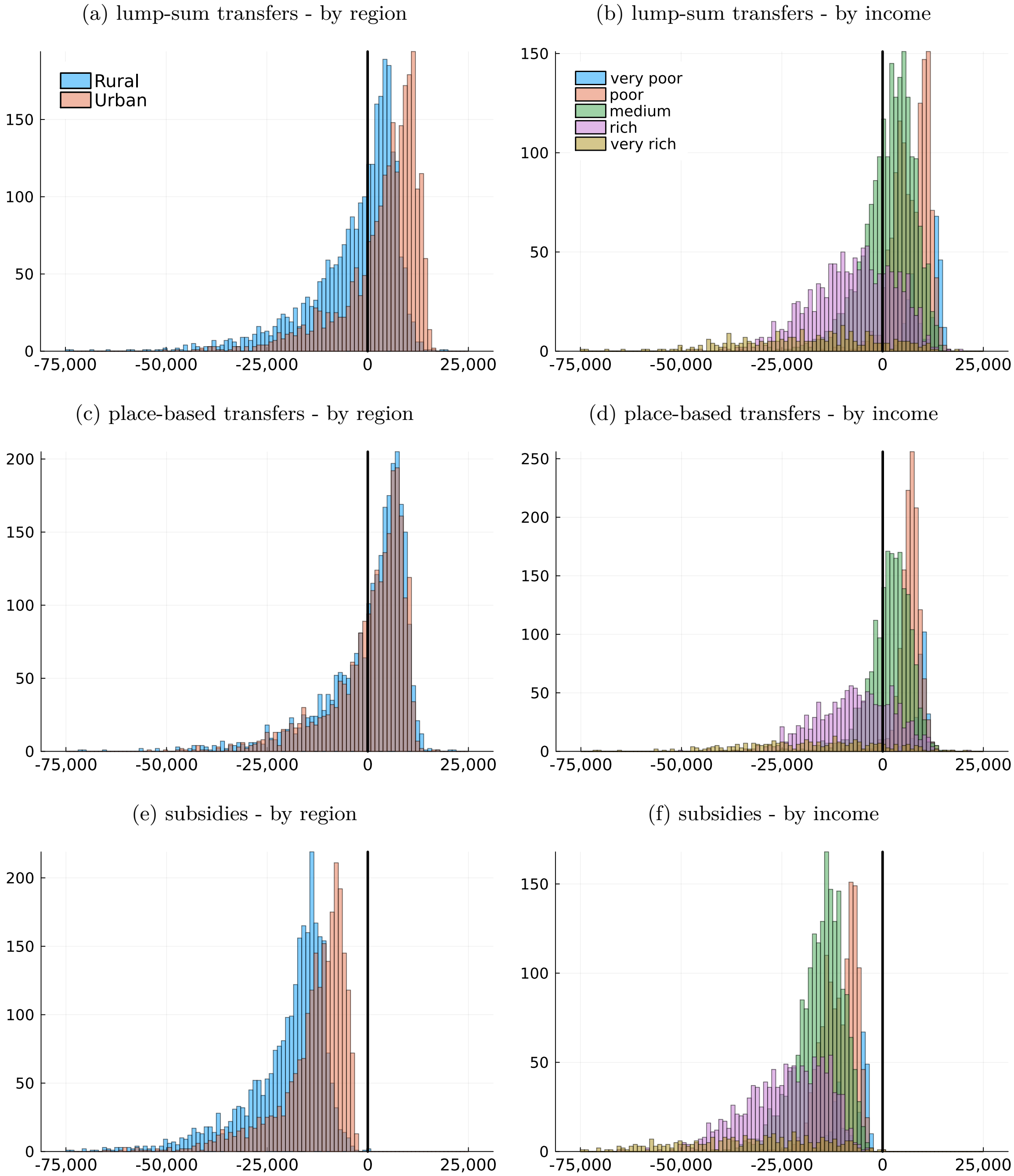
As more efficient technologies lead to a lower price of effective energy in the final steady state, there is a net migration to the rural region where households consume more energy. Without carbon taxes, the rural population share increases by 1.23 percentage points, corresponding to around one million individuals. With carbon taxes the share of clean technologies is higher and consequently the rural population share increases by around 1.34 percent. Finally, household welfare, measured as the consumption equivalent variation (CEV) in terms of the non-housing, non-energy good, increases without carbon taxes by 1.93 and 1.76 percent for rural and urban households, respectively, relative to the initial stationary equilibrium without clean technologies. This welfare gain results from the use of more efficient technologies, which allow for a reduction in raw energy consumption and more spending on the other consumption goods. The welfare gain is higher for rural households as they consume more energy and thus benefit more from clean, more efficient technologies. With carbon taxes, the distortionary effects of the tax reduce the welfare gain by 0.11 and 0.15 percentage points for rural and urban households, respectively.

4.3 Distributional consequences and political support of carbon taxes

Having documented the average paths of key economic variables along the transition and in the final stationary equilibria, the next step is to zoom in on the distributional effects of the different policy scenarios across income groups and regions in order to assess their political support. I evaluate these policies based on their monetary and welfare consequences for households. For the monetary effects, I calculate for each household and year, their net transfers, defined as the direct transfers they receive, including government transfers from firm's profits, minus their carbon tax payments. I then compute the present value of these net transfers for each household. Figure 10 plots the distributions of these present values conditional on the region and household income of households in the first period of the transition for the different policy scenarios. First, observe that the distributions are skewed to the left for all three policy scenarios. Subfigures 10b, 10d, and 10f show that this results from the left-skewed income distribution. If carbon tax revenues are spent on transfers, there are many households with positive present values of up to 15,000 Euros, while some households lose up to 50,000 Euros. For lump-sum transfers, urban households on average have higher present values than rural households, implying a redistribution from rural to urban regions. With place-based transfers, this spatial redistribution disappears by construction, and households in both regions have very similar distributions of present values. When spending the carbon tax revenues on subsidies for renovations, the net transfers are always negative, as the transfers from the firm's profits are lower than households' carbon tax payments.

Table 4 shows the resulting shares of the population that benefit, i.e. have a positive present value, for the different policy scenarios. Besides the baseline carbon tax of 300 Euros per ton, I evaluate a low and a high carbon tax scenario with tax levels of 100 Euros and 500 Euros per ton, respectively. The reason is that, even though a carbon tax of 300 Euros per ton is well in line with empirical estimates for the expected carbon tax under the European ETS2, there is still a high degree of uncertainty about its exact level and path. This uncertainty stems from the fact that the European Union does not set a price for carbon, but rather determines the number of certificates issued to firms that emit carbon. Hence, the price of these certificates, which will constitute the carbon tax, will be determined by the market depending on their supply and demand. Appendix C provides all results for the low and high carbon tax scenarios. The share of households benefiting from a given policy hardly changes with the level of the carbon tax. It depends only on the share of households that emit less than the population average (for lump-sum transfers) or the region-specific average (for place-based transfers). However, there are sizeable differences between the different recycling schemes. For lump-sum transfers, the share of households who benefit is about 48 and 73 percent in rural and urban regions, respectively, while for place-based transfers it is around 63 and 61 percent, respectively. Thus, if these policies are evaluated solely on the basis of their monetary impact on households, place-based transfers find a majority in both regions, while lump-sum transfers do not. In case of subsidies, there is no household benefiting.

Figure 10: Distributions of present values of net transfers



Notes: Panels (a), (c), and (e) show the distributions of present value of net transfers depending on the location in which households lives in the first period of the transition for the different policy scenarios. Panels (b), (d), and (f) show the same distributions for different income groups.

Table 4: Political support for climate policies - monetary decision

	Lump-sum			Place-based			Subsidy		
$\tau =$	100	300	500	100	300	500	100	300	500
All	60.1	59.9	60.1	62.2	62.4	62.1	0.0	0.0	0.0
Rural	48.2	48.1	48.1	63.3	63.2	63.0	0.0	0.0	0.0
Urban	73.3	73.1	73.2	61.0	61.3	61.1	0.0	0.0	0.0

Notes: This table shows the share of households who benefit from a given policy in monetary terms. I consider different rebating schemes and different carbon taxes levels.

As a final step in this analysis, I assess the welfare consequences of these policies. In doing so, I consider not only their monetary consequences for households, but also their distortionary effects. In order to also take into account the benefits of reducing carbon emissions, I calculate a second scenario in which I model these benefits in reduced form based on estimates from the literature. It is important to note that there is a high degree of uncertainty in these estimates, especially with respect to the damages from climate change and their impact on household welfare. Consequently, the level of benefits is also highly uncertain, which means that this final subsection is subject to a higher degree of uncertainty. I need to make three assumptions. First, I assume that the social cost of carbon is 500 Euros per ton of carbon, which is on the high end of what the literature traditionally uses, but within the range of recent estimates (Bilal and Känzig, 2024; Rennert et al., 2022). Second, I assume that this tax is set for the European Union, and that households within the Union do not care about households in other regions. Third, I assume that the positive externalities of reduced emissions are homogeneous across income groups and regions.

Table 5 presents the main results on the political support for the different policies with and without benefits from reducing carbon emissions.[30] First, note that the political support for carbon taxes is lower when evaluated based on welfare effects than when evaluated based on monetary outcomes. This is because the carbon tax distorts households' consumption decisions and thus reduces their welfare. Because the marginal welfare costs of the distortions increase with the level of the tax, while the marginal benefits (transfers + reduced form benefits) are constant, the political support decreases with the level of the carbon tax. This decline is stronger for rural households because they consume more energy, implying that a larger share of their consumption is distorted. Spending carbon taxes on subsidies for housing renovations only finds little support among the electorate. The support for spending the carbon tax revenues on place-based transfers is higher than for spending them on lump-sum transfers, especially for rural households, as this policy avoids spatial redistribution from rural to urban households. Thus, place-based transfers allow to set carbon taxes higher subject to the constraint that the policy must find support in both regions.[31] When the positive externalities of reducing carbon emissions are taken into account, the overall support for carbon taxes increases by around 10 percentage points. The qualitative results remain unchanged.

[30] Figure A13 in the Appendix plots the distributions of welfare effects.

[31] Again, because of the high degree of uncertainty about climate benefits, the exact numbers are less important than the qualitative differences.

Table 5: Political support for climate policies - welfare decision

	Lump-sum			Place-based			Subsidy		
$\tau =$	100	300	500	100	300	500	100	300	500
Baseline									
All	36.3	29.1	17.3	40.2	32.4	18.0	14.1	8.1	4.0
Rural	31.1	22.3	11.0	38.8	30.2	15.0	11.7	6.1	2.0
Urban	42.5	36.1	23.8	41.4	34.1	21.2	16.6	10.1	6.0
Positive ext.									
All	46.2	38.9	23.3	50.1	41.9	23.1	25.1	16.3	11.0
Rural	41.2	30.6	16.1	48.9	40.0	19.1	22.5	13.2	7.1
Urban	52.1	46.8	31.0	51.4	43.6	26.8	27.1	19.3	15.0

Notes: This table shows the share of households who benefit from a given policy in welfare terms. I consider different rebating schemes, different levels of carbon taxes, and specification with and without positive externalities of reduced emissions.

4.4 Sensitivity Analysis

The current analysis already considers a variety of different policy scenarios, which are evaluated in terms of their consequences for the spatial redistribution and their political support. For the main analysis, I assume a constant carbon tax of 300 Euros per ton of carbon emissions. Although this tax is well in line with empirical estimates for the expected carbon tax under the European ETS2, which will explicitly target emissions from heating and car energy, there is still a high degree of uncertainty on its exact level and path. This uncertainty stems from the fact that the European Union does not set a carbon price but rather determines the number of certificates issued to carbon emitting firms. Hence, the price of these certificates, which will constitute the carbon tax, will be determined by the market, depending on their supply and demand. Thus, C.2 provides an extensive sensitivity analysis with respect to the level and path of the carbon tax, as well as for extreme ways of recycling carbon tax revenues, where either only rural or only urban households receive transfers. First, consistent with the scenarios considered for the political support of the policies, I show the results for a lower carbon tax scenario of 100 Euros per ton and a higher tax scenario of 500 Euros per ton. The sensitivity analysis shows that all qualitative results remain unchanged. For the quantitative results, I find, not surprisingly, that lower (higher) carbon taxes reduce (increase) the size of the effects. Lower (higher) carbon taxes reduce (increase) the speed of the transition and lead to less (more) spatial redistribution when being used for lump-sum transfers. While in the baseline scenario with a carbon tax of 300 Euros per ton, the share of households with clean cars and houses in 2050 is around 87 and 90 percent, respectively, these numbers fall with taxes of 100 Euros per ton (increase with taxes of 500 Euros per ton) to 75 and 76 (92 and 93) percent. At the same time the difference in the present value of net lump-sum transfers between rural and urban households decreases (increases) from 8,000 Euros to 3,000 (11,000) Euros with carbon taxes of 100 (500) Euros per ton.

Next, the carbon tax within the ETS2, will likely not be constant over time, but rather increasing (Kalkuhl et al., 2023). Thus, I check the sensitivity of the constant carbon tax in the baseline with an increasing price path. I start with a relatively low tax of 100 Euros per ton in 2019, which then increases linearly to 250 Euros in 2030 and to 520 Euros in 2045, where it remains.[32] These numbers are based on the price scenario estimated by Kalkuhl et al. (2023) for the ETS2. Again, all qualitative results persist. The transition is initially slower but its speed increases with the level of the carbon tax, so that the share of clean technologies and the reduction in carbon emissions by 2050 are very similar to the baseline of a constant carbon tax of 300 Euros per ton. The difference in the present value of net transfers with lump-sum transfers between rural and urban households decreases from 8,000 Euros in the baseline with the constant carbon tax of 300 Euros per ton to 6,000 Euros. This reduction is caused by redistribution happening at a later point of the transition which reduces the present value due to household discounting. Also, the political support based on the welfare analysis is slightly higher, because the distortionary effects caused by the carbon tax realize later. Overall, these changes are only marginal and the main results from the baseline persist.

Finally, I check the sensitivity of the baseline results relative to two very extreme ways of transferring the carbon revenues back to households. I transfer the revenues either only to rural households or only to urban households. In these very extreme scenarios, the average paths hardly change. But the level of redistribution increases substantially. If transferring all carbon tax revenues to rural households, the difference in the present value of net transfers increases to 27,000 Euros. If transferring all revenues to urban households, this difference even rises to 43,000 Euros, more than the average annual net household income. The spatial redistribution is larger in the second case because rural households have higher carbon tax payments. As a result, the price premium for clean houses increases in the region in which households receive transfers from 15 percent in the baseline to 20 percent, while it falls in the other region to 7 to 8 percent. Also the price drop for dirty houses in the region in which households do not receive transfers increases substantially, from around 5 percent in the baseline to 8 to 12 percent. The political support for this policy is naturally much higher in the region in which households receive transfers, where the spatial difference in the political support is larger for the analysis based on monetary outcomes than for the welfare analysis. The overall support, however, is very similar to the one in the baseline analysis. This sensitivity analysis confirms that the baseline analysis is robust to these extreme scenarios and again shows that the way in which carbon tax emissions are rebated has sizeable effects on the spatial redistribution, the political support and through the general equilibrium effects on housing prices.

5 Conclusion

This paper presents new empirical evidence on the heterogeneity of carbon footprints across income groups in rural and urban regions in the German household sector. Furthermore, it develops a novel and rich theoretical framework to study the distributional consequences of carbon taxes along the transition to clean technologies across regions. I use this framework to evaluate different recycling schemes for carbon tax revenues in terms of their spatial redistribution and the implications for their political support. Empirically, I show that rural households consume more heating and car energy

[32] Figure A24 plots this price path over the transition period.

and use heating technologies that pollute more. As a result, their carbon footprint is about 2.2 tons higher than that of comparable urban households, about 12 percent of the average household's carbon footprint in Germany in 2018. Thus, spending carbon taxes on lump-sum transfers redistributes from rural to urban regions. Based on the quantitative model, the difference in the present value of net transfers is about 8,000 Euros, implying a political majority for carbon taxes only in the urban region. Place-based transfers which are set to avoid any spatial redistribution do not reduce the speed of transitioning to clean technologies and find political majorities in both regions. Subsidies for housing renovations lead to a faster transition, but only find little support among the electorate, even when the positive externalities of reducing carbon emissions are taken into account. In addition, I find that carbon taxes have sizeable general equilibrium effects, mitigating the heterogeneous impact of the carbon tax, as they increase urban relative to rural rents, by a quarter to 6,000 Euros. Finally, carbon taxes increase the price for clean, non-emitting houses by 5 percent and decreasing the price of dirty, carbon-emitting houses by the same amount. Since this paper models households as tenants, these effects are accounted for in their rents. One avenue for future research is to adopt this framework to model homeowners and landlords, who might be effects by these valuation effects heterogeneously depending on their financial ability to renovate their houses.

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A Additional details of empirical analysis

This section provides details and sensitivity checks on the empirical part of this paper. I start with the analysis on household energy consumption before studying carbon footprints.

A.1 Regression equations and detailed results on energy consumption

For car energy expenditures, I regress household i's car energy expenditures, denoted *gasoline* on its city size category, denoted *citysize*, its annual net income, denoted y, the household size, denoted *hhsize*, and the age of the main earner, denoted *age*. For the residential heating expenditures, I additionally control for the heating technology of household i, denoted *technology*. Finally, I use logit specifications to estimate the effect of the city size on the probability that household i uses oil or district heating, respectively. The three regression equations read

$$gasoline_i = \alpha_1 + \alpha_2 citysize_i + \alpha_3 y_i + \alpha_4 hhsize_i + \alpha_5 age_i + \epsilon_{c,i}$$

$$heating_i = \beta_1 + \beta_2 citysize_i + \beta_3 y_i + \beta_4 hhsize_i + \beta_5 age_i + \beta_6 technology_i + \epsilon_{h,i}$$

$$logit(\mathbb{1}(technology_i = 1)) = \gamma_1 + \gamma_2 citysize_i + \gamma_3 y_i + \gamma_4 hhsize_i + \gamma_5 age_i + \epsilon_{\lambda,i}.$$

Table A1 documents the estimation results for car and heating energy expenditures. The first two columns show the baseline estimation results. Increasing the city size by one category reduces annual expenditures for gasoline and residential heating significantly by 291 and 51 Euros, respectively. Columns (3) and (5) document the results without control variables and show that the coefficients increase to 361 and 91, respectively. Finally, I examine the sensitivity of the results with respect to (i) excluding households without a car and (ii) additionally controlling for the living space and the year of construction of the house. Columns (4) and (6) show the results decrease but remain highly significant.

Subfigures (a) and (c) in Figure A2 show the average marginal effects of the city size on the probability to use oil and district heating as the main heating technology, respectively. For oil, increasing the city size category by one decreases by probability by around 10 percentage points, while it increases for district heating by the same amount. These effects are highly significant. Subfigures (b) and (d) show that these results hardly change when excluding all control variables.

Figure A1: Regression outputs gasoline and heating expenditures

	(1) gasoline	(2) heating	(3) gasoline	(4) gasoline	(5) heating	(6) heating
city_size	-291.2***	-50.61***	-360.5***	-223.8***	-91.07***	-22.94***
	(5.774)	(6.647)	(6.446)	(6.439)	(7.130)	(6.894)
age	-9.060***	7.702***		-12.11***		4.828***
	(0.289)	(0.348)		(0.327)		(0.353)
income_net	0.0337***	0.00993***		0.0269***		0.00417***
	(0.00203)	(0.00108)		(0.00180)		(0.00101)
hh_size	263.1***	125.2***		218.5***		68.58***
	(9.287)	(6.674)		(8.465)		(7.090)
1.EF23		-678.5***				-726.0***
		(16.04)				(16.60)
2.EF23		45.12***				-30.17**
		(9.356)				(9.803)
3.EF23		156.2***				37.18
		(23.38)				(22.49)
4.EF23		-239.5***				-383.2***
		(35.97)				(36.16)
5.EF23		-812.4***				-826.4***
		(25.98)				(28.23)
living_space						4.510***
						(0.236)
house_year						-96.06***
						(5.001)
_cons	1366.2***	272.1***	1975.2***	1748.3***	1138.9***	398.2***
	(27.02)	(30.31)	(14.35)	(30.07)	(17.34)	(32.86)
N	42226	42226	42226	35308	42226	42226

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: Notes: This figure shows the regression outputs for the different regressions on gasoline and heating expenditures. The first two columns show the baseline results. Columns (3) and (5) show the results without control variables. Column (4) runs the baseline specification for gasoline but excludes all households without cars. Lastly, column (6) shows the results on heating expenditures when additionally to the baseline specification also controlling for the living space and the building year of the house.

Figure A2: Average marginal effects for logit regression

(a) Oil - baseline

	dy/dx	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
city_size	**-.0987182**	**.0024094**	**-40.97**	**0.000**	**-.1034407**	**-.0939958**

(b) Oil - no controls

	dy/dx	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
city_size	**-.0996811**	**.0023913**	**-41.69**	**0.000**	**-.1043679**	**-.0949944**

(c) District Heating - baseline

	dy/dx	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
city_size	**.0975485**	**.0021346**	**45.70**	**0.000**	**.0933648**	**.1017322**

(d) District Heating - no controls

	dy/dx	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
city_size	**.1035812**	**.0019945**	**51.93**	**0.000**	**.099672**	**.1074903**

Notes: Subfigures (a) and (c) show the average marginal effects of the city size category on the probability to use oil or district heating systems as main heating system, respectively, for the baseline specification. Subfigures (b) and (d) show the results without control variables.

Finally, Figure A3 documents the predicted values shown in Figures 1 and 2 in the empirical part of this paper. It shows the predicted values of the different regressions for the three city size categories and the averages of the other variables.

Figure A3: Predicted values for different city sizes (baseline)

(a) Car energy

_at	Margin	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
1	1551.1	7.540453	205.70	0.000	1536.321	1565.879
2	1259.861	4.699994	268.06	0.000	1250.649	1269.072
3	968.621	7.34858	131.81	0.000	954.2181	983.024

(b) Heating expenditures

_at	Margin	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
1	1010.695	8.963522	112.76	0.000	993.1263	1028.263
2	960.0876	5.687125	168.82	0.000	948.941	971.2342
3	909.4807	8.526257	106.67	0.000	892.7695	926.1918

(c) Share oil heating

_at	Margin	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
1	.2960245	.0033161	89.27	0.000	.2895251	.3025239
2	.1821981	.0020383	89.39	0.000	.178203	.1861931
3	.1055759	.0024227	43.58	0.000	.1008274	.1103244

(d) Share district heating

_at	Margin	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
1	.0824002	.0018514	44.51	0.000	.0787715	.0860288
2	.1575429	.0018977	83.02	0.000	.1538235	.1612623
3	.2802794	.0037987	73.78	0.000	.2728341	.2877247

Notes: This figure shows the predicted values of the different regressions for three city size categories and the average values of net household income, age of the main earner, and the housing size.

A.2 Regression equations and detailed results for carbon footprints

Next, I specify the regression equations for the analysis on indirect and direct carbon footprints. As in the case of car energy consumption, I regress household i's direct and indirect carbon footprints on its city size category, its annual net income, and the age of the main earner.

$$ICF_i = \alpha_1 + \alpha_2 citysize_i + \alpha_3 y_i + \alpha_4 hhsize_i + \alpha_5 age_i + \epsilon_{\alpha,i}$$

$$DCF_i = \beta_1 + \beta_2 citysize_i + \beta_3 y_i + \beta_4 hhsize_i + \beta_5 age_i + \epsilon_{\beta,i}$$

Figure A4 shows the results. The first three columns show the main results for indirect carbon footprints as well as for direct carbon footprints from heating and car energy. Column (1) shows that indirect carbon footprints increase statistically significantly with the city size, but that the magnitude of this effect is economically negligible. Columns (2) and (3) document that increasing the city size category by one decreases direct carbon footprints for heating and car energy significantly by 0.56 and 0.68 tons, respectively. Since I model households as tenants in the quantitative model, columns (4) to (6) show the regression results when only tenants are included. The results do not change substantially. The Figures A5 and A6 show the respective figures for direct and indirect carbon footprints, when only tenants are included. Figures A5 and A6 resemble Figures 3a and 3b from the empirical part of this paper, but only include tenants. Again, the results are very similar to those on the overall population.

Figure A4: Regression outputs for indirect and direct carbon emissions

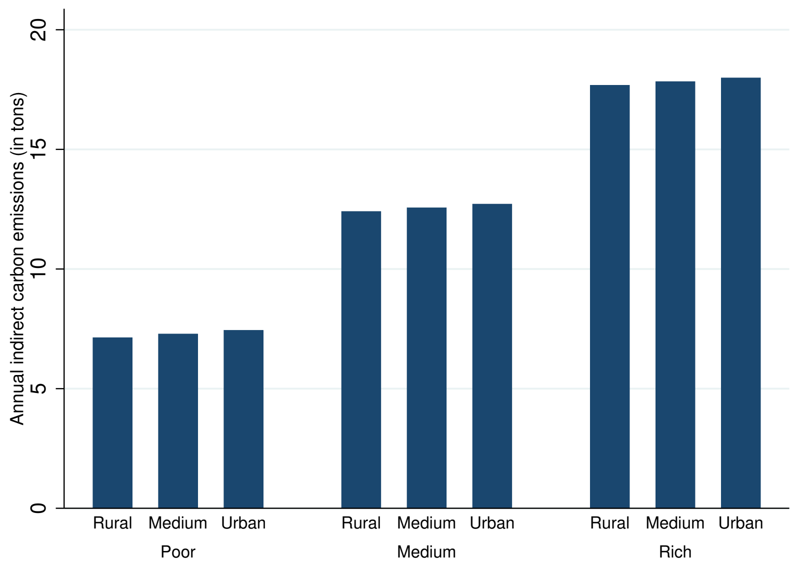
	(1) CF_indirect	(2) CF_direct_heat	(3) CF_direct_car	(4) CF_indirect	(5) CF_direct_heat	(6) CF_direct_car
city_size	0.154***	-0.560***	-0.681***	0.230***	-0.476***	-0.724***
	(0.00701)	(0.00468)	(0.0339)	(0.0195)	(0.0334)	(0.00988)
inc_cat	5.274***	0.785***	1.232***	4.328***	0.518***	1.247***
	(0.0392)	(0.0657)	(0.00654)	(0.0472)	(0.0352)	(0.0313)
age	0.0640***	0.0384***	-0.0223***	0.0276***	0.00917***	-0.0183***
	(0.000931)	(0.000324)	(0.000292)	(0.000276)	(0.000209)	(0.000256)
hh_size	1.412***	0.322***	0.452***	1.263***	0.476***	0.410***
	(0.0130)	(0.0342)	(0.0145)	(0.0427)	(0.000466)	(0.0161)
_cons	-4.707***	0.264***	2.273***	-2.025***	1.337***	2.163***
	(0.104)	(0.0517)	(0.0944)	(0.0392)	(0.0307)	(0.0988)
N	42226	42226	42226	19565	19565	19565

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

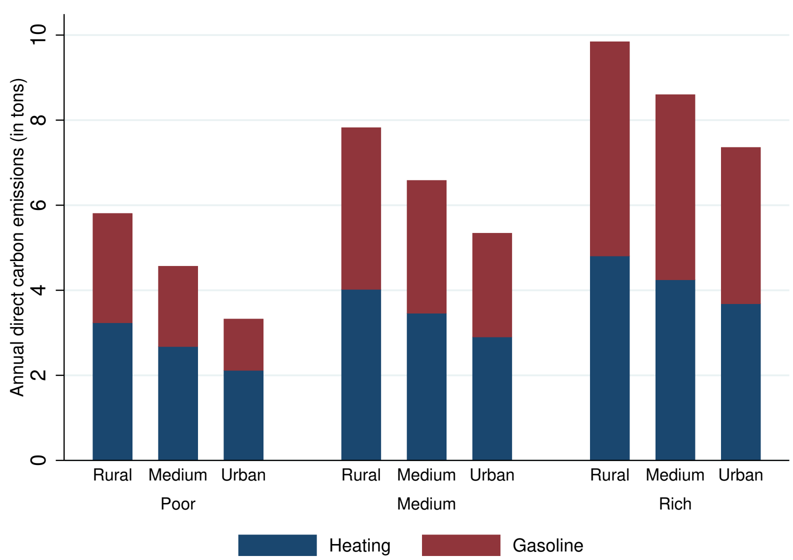
Notes: Notes: This figure shows the regression outputs for the different regressions on household carbon footprints. The first three columns show the results for indirect carbon footprint as well for direct carbon footprints for heating and car energy for the overall population. Columns 4 to 6 show the results for tenants.

Figure A5: Indirect carbon footprints across regions and income - only tenants



Notes: This figure shows the predicted indirect carbon emissions for tenants of different income and city size groups with average age and household size. The three income categories *Poor*, *Medium*, and *Rich* are based on three equally sized net household income categories. The three city size categories *Rural*, *Medium*, and *Urban* refer to city sizes of less than 20,000, 20,000 to 100,000 and more than 100,000 inhabitants.

Figure A6: Direct carbon footprints across regions and income - only tenants



Notes: This figure shows the predicted direct carbon emissions for tenants of different income and city size groups with average age and household size. The three income categories *Poor*, *Medium*, and *Rich* are based on three equally sized net household income categories. The three city size categories *Rural*, *Medium*, and *Urban* refer to city sizes of less than 20,000, 20,000 to 100,000 and more than 100,000 inhabitants.

B Additional derivations for the model

This section provides additional derivations for the quantitative model. I start with the household problem before presenting the derivations for the firm sector. Finally, I define the stationary equilibrium.

B.1 Full dynamic household problem

This subsection presents the full dynamic household problem. In each period, households have 12 alternatives to choose from, resulting in 12 value functions depending on the four discrete decisions: moving (M) vs. not moving (NM) to the other region, adjusting the housing type (HA) vs. not adjusting it (NHA), buying a new car (CA) vs. not buying a new car (NCA), and buying a dirty car (DCA) vs. buying a clean car (CCA). The value function of not moving, not adjusting housing, and not buying a new car is given by

$$V_t^{\text{NM,NHA,NCA}}(l_t, y_t, \kappa, \lambda_t^c, \lambda_t^h) = \max_{\{h_t, e_t^c, e_t^h\}} \quad u(x_t, h_t, e_t^h, e_t^c, l_{t+1}) + \beta\, \mathbb{E}\left[V_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda_{t+1}^c, \lambda_{t+1}^h) \mid y_t\right]$$

$$s.t. \qquad x_t = y_t + T_t^\pi + T_t^\tau - \rho(l_{t+1}, \lambda_{t+1}^h) h_t - [p_t^{eh} + (1 - \lambda_{t+1}^h)\xi_l^h \tau] e_t^h - [p^{ec} + (1 - \lambda_{t+1}^c)\xi^c \tau] e_t^c.$$

As the household neither moves to the other region, nor adjusts the car or housing type, the law of motion for these states is

$$l_{t+1} = l_t, \quad \lambda_{t+1}^c = \lambda_t^c, \quad \lambda_{t+1}^h = \lambda_t^h.$$

The other value function are analogous, where the laws of motion are given by

$$l_{t+1} = \begin{cases} l_t & \text{if not moving,} \\ 1 & \text{if moving and } l_t = 0, \\ 0 & \text{if moving and } l_t = 1, \end{cases}$$

$$\lambda_{t+1}^h = \begin{cases} \lambda_t^h & \text{if no housing type adjustment,} \\ 1 & \text{if housing type adjustment and } \lambda_t^h = 0, \\ 0 & \text{if housing type adjustment and } \lambda_t^h = 1, \end{cases}$$

and

$$\lambda_{t+1}^c = \begin{cases} \lambda_t^c & \text{if no car type adjustment,} \\ 1 & \text{if housing type car and } \lambda_t^c = 0, \\ 0 & \text{if housing type car and } \lambda_t^c = 1. \end{cases}$$

The expected values are given by

$$
\begin{aligned}
&\mathbb{E}\left[V_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] = \\
&\max\{\mathbb{E}\left[V^{\mathrm{NM}}_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right], \mathbb{E}\left[V^{\mathrm{M}}_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] + \epsilon_l\}
\end{aligned}
$$

where

$$
\begin{aligned}
&\mathbb{E}\left[V^{\mathrm{NM}}_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] = \\
&\max\{\mathbb{E}\left[V^{\text{NM, NHA}}_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right], \mathbb{E}\left[V^{\text{NM, HA}}_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] + \epsilon_h\} \\
&\mathbb{E}\left[V^{\mathrm{M}}_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] = \\
&\max\{\mathbb{E}\left[V^{\text{M, NHA}}_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right], \mathbb{E}\left[V^{\text{M, HA}}_{t+1}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] + \epsilon_h\}
\end{aligned}
$$

and further

$$
\begin{aligned}
&\mathbb{E}\left[V^{\text{NM, NHA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] = \\
&\max\{\mathbb{E}\left[V^{\text{NM, NHA, NCA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right], \mathbb{E}\left[V^{\text{NM, NHA, CA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] + \epsilon_c\} \\
&\mathbb{E}\left[V^{\text{NM, HA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] = \\
&\max\{\mathbb{E}\left[V^{\text{NM, HA, NCA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right], \mathbb{E}\left[V^{\text{NM, HA, CA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] + \epsilon_c\} \\
&\mathbb{E}\left[V^{\text{M, NHA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] = \\
&\max\{\mathbb{E}\left[V^{\text{M, NHA, NCA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right], \mathbb{E}\left[V^{\text{M, NHA, CA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] + \epsilon_c\} \\
&\mathbb{E}\left[V^{\text{M, HA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] = \\
&\max\{\mathbb{E}\left[V^{\text{M, HA, NCA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right], \mathbb{E}\left[V^{\text{M, HA, CA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] + \epsilon_c\}
\end{aligned}
$$

and finally

$$
\begin{aligned}
&\mathbb{E}\left[V^{\text{NM, NHA, CA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] = \\
&\max\{\mathbb{E}\left[V^{\text{NM, NHA, CA, DC}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right], \mathbb{E}\left[V^{\text{NM, NHA, CA, CC}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] + \epsilon_{ct}\} \\
&\mathbb{E}\left[V^{\text{NM, HA, CA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] = \\
&\max\{\mathbb{E}\left[V^{\text{NM, HA, CA, DC}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right], \mathbb{E}\left[V^{\text{NM, HA, CA, CC}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] + \epsilon_{ct}\} \\
&\mathbb{E}\left[V^{\text{M, NHA, CA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] = \\
&\max\{\mathbb{E}\left[V^{\text{M, NHA, CA, DC}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right], \mathbb{E}\left[V^{\text{M, NHA, CA, CC}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] + \epsilon_{ct}\} \\
&\mathbb{E}\left[V^{\text{M, HA, CA}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] = \\
&\max\{\mathbb{E}\left[V^{\text{M, HA, CA, DC}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right], \mathbb{E}\left[V^{\text{M, HA, CA, CC}}(l_{t+1}, y_{t+1}, \kappa, \lambda^c_{t+1}, \lambda^h_{t+1}) \mid y_t\right] + \epsilon_{ct}\},
\end{aligned}
$$

where ϵ_l, ϵ_h, ϵ_c, and ϵ_{ct} represent the type-1 extreme value shocks.

B.2 Housing Construction Firm

This subsection derives the optimal decisions for the housing construction firm. I start with the construction of housing before moving on to renovations.

B.2.1 Housing Construction

The representative construction firm has to decide how much dirty and clean housing to build in the rural and urban region, taking housing prices, $q^j_{l,t}$, wages,$w^j_{l,t}$, and the number of land permits, $\overline{L_l}$, as given. Hence, the problem reads

$$\max_{I^{h,j}_{l,t}} q^j_{l,t} I^{h,j}_{l,t} - w^j_{l,t} N^j_{l,t} \quad \text{s.t} \quad I^{h,j}_{l,t} = \psi^{h,j}_{l,t} \left(N^j_{l,t}\right)^{\alpha^h_l} \overline{L_l}^{1-\alpha^h_l}$$

rewriting the budget constraint and plugging it into the objective function yields

$$\max_{I^{h,j}_{l,t}} q^j_{l,t} I^{h,j}_{l,t} - w^j_{l,t} \left(\psi^{h,j}_{l,t}\right)^{-\frac{1}{\alpha^h_l}} I_{l,t}^{\frac{1}{\alpha^h_l}} \overline{L_l}^{\frac{\alpha^h_l - 1}{\alpha^h_l}}$$

which gives the first-order condition

$$q^j_{l,t} - \left(\psi^{h,j}_{l,t}\right)^{-\frac{1}{\alpha^h_l}} \frac{w^j_{l,t}}{\alpha^h_l} I_{l,t}^{\frac{1-\alpha^h_l}{\alpha^h_l}} \overline{L_l}^{\frac{\alpha^h_l - 1}{\alpha^h_l}} = 0.$$

Hence, the optimal level of newly build housing is given by

$$I^{h,j}_{l,t} = \left(\alpha^h_l \frac{q^j_{l,t}}{w^j_{l,t}}\right)^{\frac{\alpha^h_l}{1-\alpha^h_l}} \left(\psi^{h,j}_{l,t}\right)^{\frac{1}{1-\alpha^h_l}} \overline{L_l}.$$

Finally, the firm needs to decide whether to build clean or dirty housing on the permitted land. To do this, it compares the profits in each case. Note, that the firm always build either clean or dirty houses. Therefore, the condition for building clean housing is given by

$$
\begin{array}{rcl}
\tau^{cl} & > & \tau^{di} \\
\Leftrightarrow q_{l,t}^{cl} I_{l,t}^{h,cl} - w_{l,t}^{cl} N_{l,t}^{cl} & > & q_{l,t}^{di} I_{l,t}^{h,di} - w_{l,t}^{di} N_{l,t}^{di} \\
\Leftrightarrow q_{l,t}^{cl} I_{l,t}^{h,cl} - w_{l,t}^{cl} \left(\psi_{l,t}^{h,di}\right)^{-\frac{1}{\alpha_l^h}} \left(I_{l,t}^{h,j}\right)^{\frac{1}{\alpha_l^h}} \overline{L_l}^{\frac{\alpha_l^h - 1}{\alpha_l^h}} & > & q_{l,t}^{di} I_{l,t}^{h,di} - w_{l,t}^{di} \left(\psi_{l,t}^{h,di}\right)^{-\frac{1}{\alpha_l^h}} \left(I_{l,t}^{h,j}\right)^{\frac{1}{\alpha_l^h}} \overline{L_l}^{\frac{\alpha_l^h - 1}{\alpha_l^h}} \\
\Leftrightarrow q_{l,t}^{cl} \left[\left(\alpha_l^h \frac{q_{l,t}^{cl}}{w_{l,t}^{cl}}\right)^{\frac{\alpha_l^h}{1-\alpha_l^h}} \left(\psi_{l,t}^{h,cl}\right)^{\frac{1}{1-\alpha_l^h}} \overline{L_l} \right] & - & w_{l,t}^{cl} \left(\psi_{l,t}^{h,di}\right)^{-\frac{1}{\alpha_l^h}} \left[\left(\alpha_l^h \frac{q_{l,t}^{cl}}{w_{l,t}^{cl}}\right)^{\frac{\alpha_l^h}{1-\alpha_l^h}} \left(\psi_{l,t}^{h,cl}\right)^{\frac{1}{1-\alpha_l^h}} \overline{L_l} \right]^{\frac{1}{\alpha_l^h}} \overline{L_l}^{\frac{\alpha_l^h - 1}{\alpha_l^h}} \\
> q_{l,t}^{di} \left[\left(\alpha_l^h \frac{q_{l,t}^{di}}{w_{l,t}^{di}}\right)^{\frac{\alpha_l^h}{1-\alpha_l^h}} \left(\psi_{l,t}^{h,di}\right)^{\frac{1}{1-\alpha_l^h}} \overline{L_l} \right] & - & w_{l,t}^{di} \left(\psi_{l,t}^{h,di}\right)^{-\frac{1}{\alpha_l^h}} \left[\left(\alpha_l^h \frac{q_{l,t}^{di}}{w_{l,t}^{di}}\right)^{\frac{\alpha_l^h}{1-\alpha_l^h}} \left(\psi_{l,t}^{h,di}\right)^{\frac{1}{1-\alpha_l^h}} \overline{L_l} \right]^{\frac{1}{\alpha_l^h}} \overline{L_l}^{\frac{\alpha_l^h - 1}{\alpha_l^h}} \\
\Leftrightarrow \left(q_{l,t}^{cl} \psi_{l,t}^{h,cl}\right)^{\frac{1}{1-\alpha_l^h}} \left(\frac{\alpha_l^h}{w_{l,t}^{di}}\right)^{\frac{\alpha_l^h}{1-\alpha_l^h}} \overline{L_l} - \left(\alpha_l^h \psi_{l,t}^{h,cl} \frac{q_{l,t}^{cl}}{w_{l,t}^{cl}}\right)^{\frac{1}{1-\alpha_l^h}} \overline{L_l} & > & \left(q_{l,t}^{di} \psi_{l,t}^{h,di}\right)^{\frac{1}{1-\alpha_l^h}} \left(\frac{\alpha_l^h}{w_{l,t}^{di}}\right)^{\frac{\alpha_l^h}{1-\alpha_l^h}} \overline{L_l} - \left(\alpha_l^h \psi_{l,t}^{h,di} \frac{q_{l,t}^{di}}{w_{l,t}^{di}}\right)^{\frac{1}{1-\alpha_l^h}} \overline{L_l} \\
\Leftrightarrow \left(q_{l,t}^{cl} \psi_{l,t}^{h,cl}\right)^{\frac{1}{1-\alpha_l^h}} \overline{L_l} \left[\left(\frac{\alpha_l^h}{w_{l,t}^{cl}}\right)^{\frac{\alpha_l^h}{1-\alpha_l^h}} - \left(\frac{\alpha_l^h}{w_{l,t}^{cl}}\right)^{\frac{1}{1-\alpha_l^h}} \right] & > & \left(q_{l,t}^{di} \psi_{l,t}^{h,di}\right)^{\frac{1}{1-\alpha_l^h}} \overline{L_l} \left[\left(\frac{\alpha_l^h}{w_{l,t}^{di}}\right)^{\frac{\alpha_l^h}{1-\alpha_l^h}} - \left(\frac{\alpha_l^h}{w_{l,t}^{di}}\right)^{\frac{1}{1-\alpha_l^h}} \right] \\
\Leftrightarrow q_{l,t}^{cl} \psi_{l,t}^{h,cl} & > & q_{l,t}^{cl} \psi_{l,t}^{h,cl} \\
\Leftrightarrow q_{l,t}^{cl} & > & q_{l,t}^{di} \left(\frac{\psi_{l,t}^{di}}{\psi_{l,t}^{cl}}\right) \\
\Leftrightarrow q_{l,t}^{cl} \Omega_{l,t}^{h} & > & q_{l,t}^{di},
\end{array}
$$

where the step from the fourth-to-last equation to the third-to-last equation comes from the fact that in equilibrium all wages in the economy are equal to one.

B.2.2 Housing Renovations

For renovating dirty into clean housing, the construction firm solves the following problem:

$$
\max_{I_{l,t}^{ren}} q_{l,t}^{cl} I_{l,t}^{ren} - w_{l,t}^{ren} N_{l,t}^{ren} - q_{l,t}^{di} h_{l,t}^{di} \quad \text{s.t} \quad I_{l,t}^{ren} = \Omega_{l,t}^{ren} \min\left\{ \left(N_{l,t}^{ren}\right)^{\alpha^{ren}}, h_{l,t}^{di} \right\}
$$

The construction firm converts one unit of dirty housing into $\Omega_{l,t}^{ren}$ units of clean housing. The TFP-parameter $\Omega_{l,t}^{ren}$ is time-varying and region-specific. Hence, optimality requires that

$$
\begin{array}{rcl}
h_{l,t}^{di} & = & \dfrac{I_{l,t}^{ren}}{\Omega_{l,t}^{ren}} \\
N_{l,t}^{ren} & = & \left(\dfrac{I_{l,t}^{ren}}{\Omega_{l,t}^{ren}}\right)^{\frac{1}{\alpha^{ren}}}
\end{array}
$$

Hence, the construction firm solves

$$\max_{I^{ren}_{l,t}} q^{cl}_{l,t} I^{ren}_{l,t} - w^{ren}_{l,t} \left(\frac{I^{ren}_{l,t}}{\Omega^{ren}_{l,t}} \right)^{\frac{1}{\alpha^{ren}}} - q^{di}_{l,t} \frac{I^{ren}_{l,t}}{\Omega^{ren}_{l,t}}$$

which gives the first-order-condition

$$q^{cl}_{l,t} - \frac{w^{ren}_{l,t}}{\alpha^{ren}\Omega^{ren}_{l,t}} \left(\frac{I^{ren}_{l,t}}{\Omega^{ren}_{l,t}} \right)^{\frac{1-\alpha^{ren}}{\alpha^{ren}}} - \frac{q^{di}_{l,t}}{\Omega^{ren}_{l,t}} = 0.$$

Thus, plugging in the equilibrium wage of $w^{ren}_{l,t} = 1$, the optimal level of housing renovations is given by

$$I^{ren}_{l,t} = \Omega^{ren}_{l,t} \left[\alpha^{ren} \left(\Omega^{ren}_{l,t} q^{cl}_{l,t} - q^{di}_{l,t} \right) \right]^{\frac{\alpha^{ren}}{1-\alpha^{ren}}} .$$

Finally, the profits from renovations are given by

$$\pi^r = q^{cl}_{l,t} I^{ren}_{l,t} - \left(\frac{I^{ren}_{l,t}}{\Omega^{ren}_{l,t}} \right)^{\frac{1}{\alpha^{ren}}} - q^{di}_{l,t} \frac{I^{ren}_{l,t}}{\Omega^{ren}_{l,t}} \quad \text{with} \quad I^{ren}_{l,t} = \Omega^{ren}_{l,t} \left[\alpha^{ren} \left(\Omega^{ren}_{l,t} q^{cl}_{l,t} - q^{di}_{l,t} \right) \right]^{\frac{\alpha^{ren}}{1-\alpha^{ren}}} .$$

Plugging $I^{ren}_{l,t}$ into the profits equations gives

$$\begin{aligned}
\pi^r &= I^{ren}_{l,t} \left(q^{cl}_{l,t} - \left(I^{ren}_{l,t} \right)^{\frac{1-\alpha^{ren}}{\alpha^{ren}}} \left(\Omega^{ren}_{l,t} \right)^{-\frac{1}{\alpha^{ren}}} - q^{di}_{l,t} \left(\Omega^{ren}_{l,t} \right)^{-1} \right) \\
&= \Omega^{ren}_{l,t} \left[\alpha^{ren} \left(\Omega^{ren}_{l,t} q^{cl}_{l,t} - q^{di}_{l,t} \right) \right]^{\frac{\alpha^{ren}}{1-\alpha^{ren}}} \left(q^{cl}_{l,t} - \left(\left[\Omega^{ren}_{l,t} \left[\alpha^{ren} \left(\Omega^{ren}_{l,t} q^{cl}_{l,t} - q^{di}_{l,t} \right) \right]^{\frac{\alpha^{ren}}{1-\alpha^{ren}}} \right] \right)^{\frac{1-\alpha^{ren}}{\alpha^{ren}}} \frac{1}{\left(\Omega^{ren}_{l,t} \right)^{\frac{1}{\alpha^{ren}}}} - \frac{q^{di}_{l,t}}{\Omega^{ren}_{l,t}} \right) \\
&= \Omega^{ren}_{l,t} \left[\alpha^{ren} \left(\Omega^{ren}_{l,t} q^{cl}_{l,t} - q^{di}_{l,t} \right) \right]^{\frac{\alpha^{ren}}{1-\alpha^{ren}}} \left(q^{cl}_{l,t} - \left(\Omega^{ren}_{l,t} \right)^{\frac{1-\alpha^{ren}-1}{\alpha^{ren}}} \left(\left[\alpha^{ren} \left(\Omega^{ren}_{l,t} q^{cl}_{l,t} - q^{di}_{l,t} \right)^{\frac{\alpha^{ren}}{1-\alpha^{ren}}} \right] \right)^{\frac{1-\alpha^{ren}}{\alpha^{ren}}} - \frac{q^{di}_{l,t}}{\Omega^{ren}_{l,t}} \right) \\
&= \left[\alpha^{ren} \left(\Omega^{ren}_{l,t} q^{cl}_{l,t} - q^{di}_{l,t} \right) \right]^{\frac{\alpha^{ren}}{1-\alpha^{ren}}} \left(\Omega^{ren}_{l,t} q^{cl}_{l,t} - \alpha^{ren} \left(\Omega^{ren}_{l,t} q^{cl}_{l,t} - q^{di}_{l,t} \right) - q^{di}_{l,t} \right)
\end{aligned}$$

B.3 Definition of Stationary Equilibrium

To ease notation, the vector of household states is denoted as $s := (l, y, \kappa, \lambda^c, \lambda^h)$. A stationary recursive equilibrium is a set of decision rules $\{x, h, e^c, e^h, l', \lambda^{c\prime}, \lambda^{h\prime}\}$, value functions $\{V^{NM,NHA,NCA}$, $V^{NM,NHA,CA,CC}$, $V^{NM,NHA,CA,DC}$, $V^{NM,HA,NCA}$, $V^{NM,HA,CA,CC}$, $V^{NM,HA,CA,DC}$, $V^{M,NHA,NCA}$ $V^{M,NHA,CA,CC}$, $V^{M,NHA,CA,DC}$, $V^{M,HA,NCA}$, $V^{M,HA,CA,CC}$, $V^{M,HA,CA,DC}$, $V^{NM,NHA}$, $V^{NM,HA}$, $V^{M,NHA}$, $V^{M,HA}$, V^{NM}, V^{M}, $V\}$, prices $\{q^{cl}_r, q^{cl}_u, q^{di}_r, q^{di}_u, p^{cl}_r, p^{cl}_u, p^{di}_r, p^{di}_u, p^{c,cl}, p^{c,di}, p^{ec}, p^{eh}, r\}$, aggregate variables $\{H^{cl}_r, H^{cl}_u, H^{di}_r, H^{di}_u, I^{h,cl}_r, I^{h,cl}_u, I^{h,di}_r, I^{h,di}_u, I^{ren}_r, I^{ren}_u, L_r, L_u, N, N^{cl}_r, N^{cl}_u, N^{di}_r, N^{di}_u, N^{ren}_r, N^{ren}_u, N^{c,cl}$, $N^{c,di}, N^{eh}, N^{ec}, E^c, E^h, Y, C^{cl}, C^{di}\}$, and a stationary distribution over the state space μ such that:

1. Given prices, households solve their optimization problem with the associated value functions and decision rules.
2. Given prices, the construction firm maximizes profits with associated units of labor demand, housing investments, and housing renovations.
3. Given prices, the rental firm maximizes profits with the associated housing stocks.
4. Given prices, the production firm maximizes profits with the associated number of cars, energy, and the non-housing, non-energy good.
5. The governmental budget constraint is balanced.
6. The labor market clears at wage $w = 1$ and the labor demand for producing the non-housing, non-energy are determined residually as $N^x = 1 - N_r^{cl} - N_u^{cl} - N_r^{di} - N_u^{di} - N_r^{ren} - N_u^{ren} - N^{c,cl} - N^{c,di} - N^{eh} - N^{ec}$.
7. In each location l and for each housing type j, the rental market clears at rent p_l^j.
8. In each location l and for each housing type j, the housing market clears at housing price q_l^j.
9. The markets for car and heating energy as well as for cars clear.
10. The market for the non-housing, non-energy good clears:

$$X = \int_0^1 x_{i,t} di$$

where the left-hand side describes the supply and the right-hand side the demand.

C Additional model results

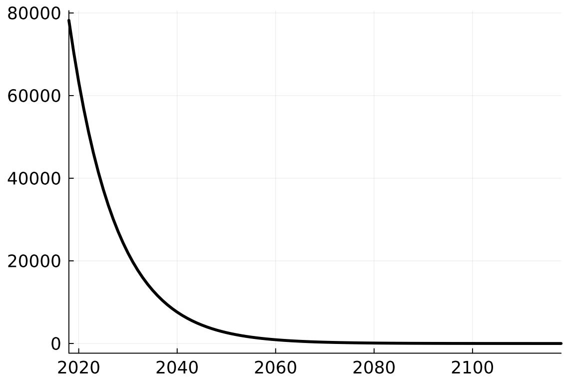
This section provides more details on the results of the quantitative analysis. First, I show details on the calibration and additional results for the baseline specification. Thereafter, I check the robustness of the baseline results by providing an extensive sensitivity analysis.

C.1 Further results for the baseline model

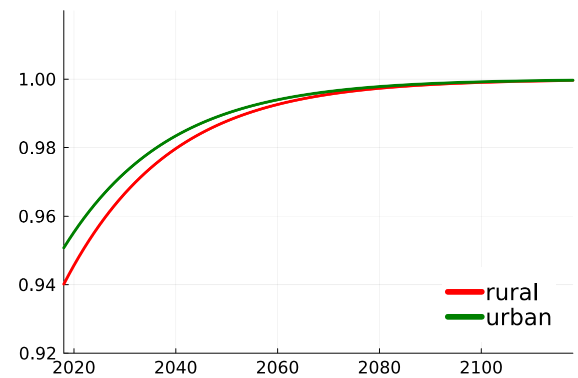
Figure A7 plots the convergence of the productivity levels and prices for clean technologies along the transition. Subfigure A7a shows the price premium for clean cars. I calibrate this price premium to match the observed adoption rates for electric vehicles from 2019 to 2023. Initially, prices for clean cars are around 76,000 Euros higher than those for dirty cars but converge to the latter quite fast. By 2023 and 2035 the price premia have fallen to around 40,000 and 12,000 Euros, respectively. The initial price premium is higher than estimates from the literature, ranging between 20,000 and 30,000 Euros (Holland et al., 2021; Lévay et al., 2017). This difference might be driven by additional factors that explain the relative slow adoption of electric cars in the data, such as limited recharging possibilities. As the model does not capture these additional factors, it contributes them to a higher initial price of clean cars.

Figure A7: Convergence of productivities and prices of clean technologies

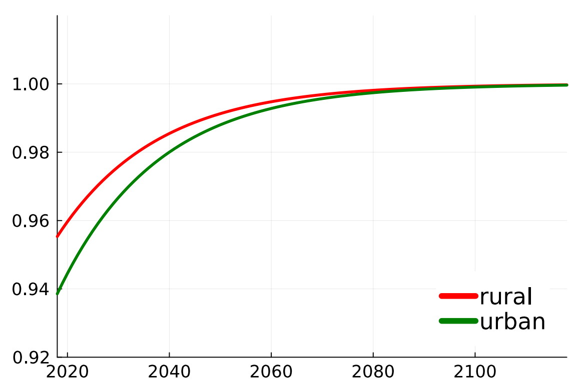
(a) Price premium for clean cars



(b) Relative productivity clean housing construction



(c) Productivity for housing renovations

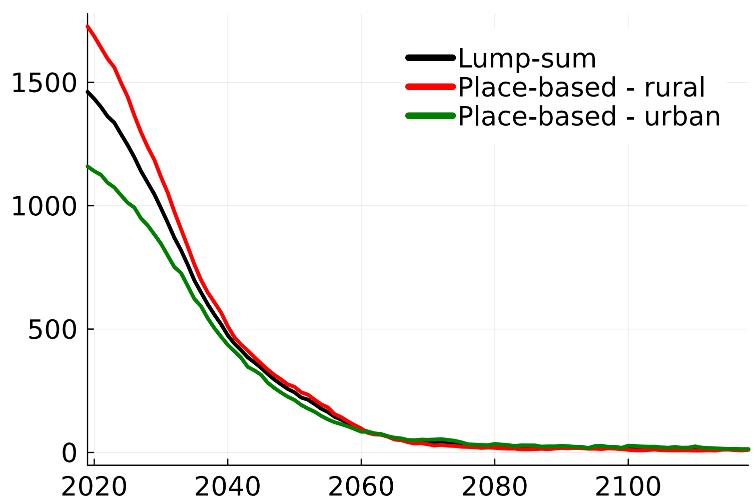


Notes: Panel (a) shows the price premium of clean cars relative to dirty cars in Euros over the transition period. Similarly, Panel (b) shows the productivity of clean housing construction relative to dirty housing construction over the transition period. Finally, Panel (c) shows the productivity of transforming dirty into clean houses along the transition for both regions.

Subfigures A7b and A7c show the discount in the productivity of producing clean relative to dirty houses and the productivity of renovations. The initial productivity levels are calibrated to match the observed difference in production costs for clean and dirty housing construction and the observed renovation rate, respectively. The initial productivity of clean housing construction is slightly higher in the urban region. This is because housing prices per square meter are more expensive in the urban region, implying that a given difference in production costs between clean and dirty housing construction, for example due to heat pumps instead of oil heating systems, results in a smaller relative production discount for the urban region. For housing renovations the productivity level is higher in the rural region. As the overall housing stock is larger in the rural region, the number of housing renovations is also higher, implying a higher productivity level. For the quantitative results, these minor differences are not important. The rate of convergence is calibrated based on estimates from LCP Delta (2021) suggesting that the price of heat pumps falls by 40 percent over 10 years. I extrapolate this rate of convergence over the transition period.

Figure A8 shows the annual transfers to households that balance the governmental budget for lump-sum and place-based transfers with a carbon tax of 300 Euros per ton of carbon. For lump-sum transfers the annual transfers is initially around 1,500 Euros and decreases along the transition with overall carbon emissions. With place-based transfers, rural and urban households receive initially transfers of about 1730 and 1160 Euros, respectively.

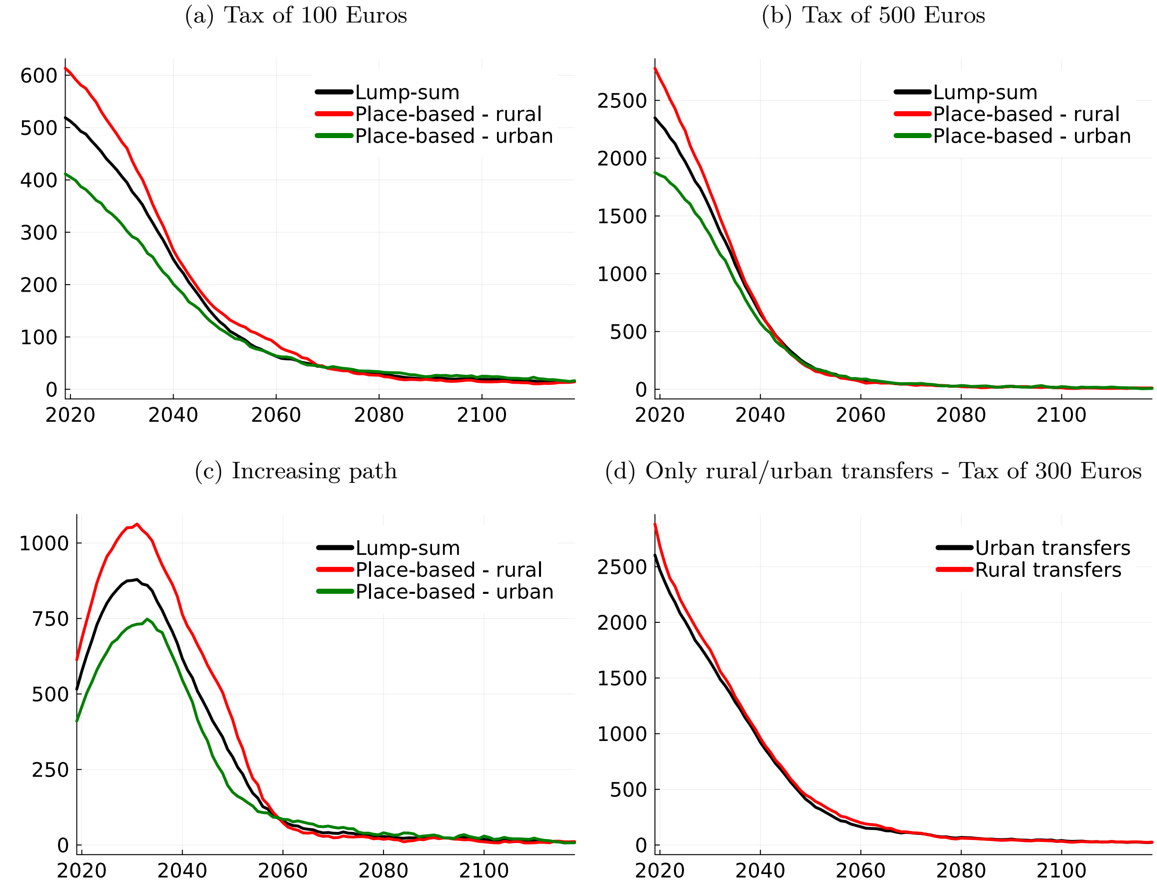
Figure A8: Transfer levels for different carbon taxes and policies



Notes: This figure shows the annual transfers which balance the governmental budget for a carbon tax of 300 Euros and are rebated back to households.

Figure A9 shows how the level of transfers change with different levels of carbon taxes and rebating policies. With lower (higher) carbon taxes the level of transfers naturally decreases (increases). Note that with carbon taxes of 500 Euros per ton, the level of transfers decreases faster than with carbon taxes of 100 Euros, as carbon emissions decrease faster with higher carbon taxes. With an increasing carbon tax path, as specified in Figure A24, the level of transfers initially increases as the carbon tax level increases. Thereafter, the reduction in emissions prevail and the level of transfers decreases. Finally, the transfers when reimbursing only rural or only urban households are similar to the ones with carbon taxes of 500 Euros per ton.

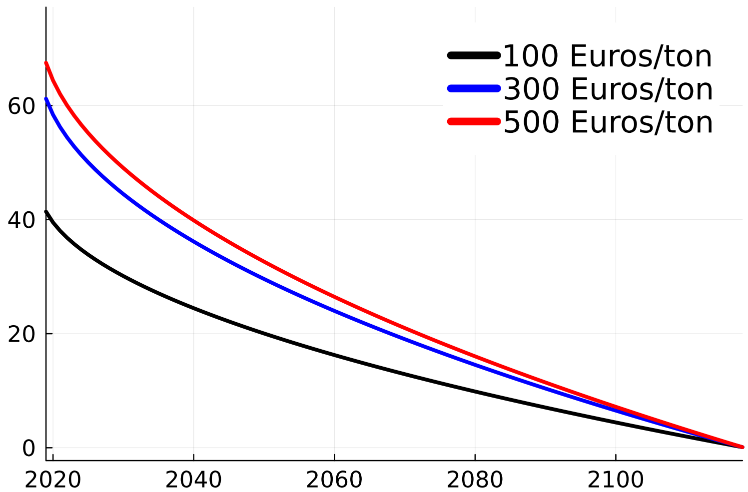
Figure A9: Transfer levels for sensitivity analysis



Notes: This figure shows the annual transfers which balance the governmental budget and are rebated back to households for different carbon tax levels and rebating policies.

Figure A10 shows the subsidy levels that balance the governmental budget along the transition for carbon taxes of 100, 300, and 500 Euros, respectively. As carbon tax revenues increase with the carbon tax level, the percentage subsidy does so, too. Over time the carbon tax revenues fall and so do the subsidies.

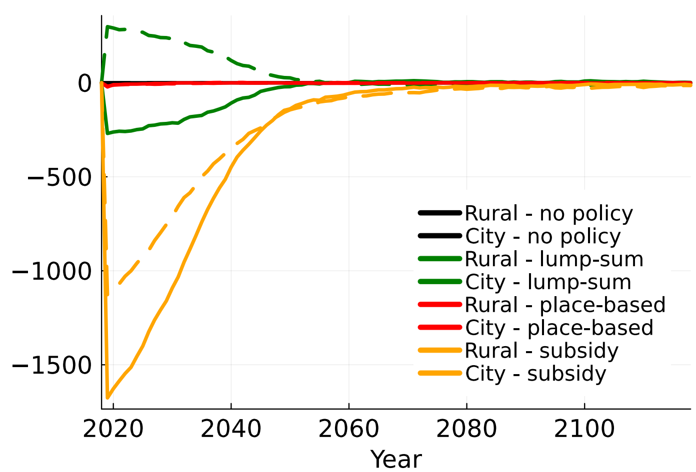
Figure A10: Subsidy level on housing renovations (%)



Notes: This figure shows the percentage subsidy on housing renovations for carbon taxes of 100, 300, and 500 Euros per ton of carbon.

Figure A11 shows the spatial redistribution for the baseline specification with carbon taxes of 300 Euros per ton of carbon. Without policy and with place-based transfers, there is no redistribution by construction. The figure for lump-sum transfers has been shown in the main text in Figure 7a. In case of subsidies on housing renovations, the spatial difference in net transfers is the same as in the case of lump-sum transfers but due to the missing direct transfer households have negative net transfers.

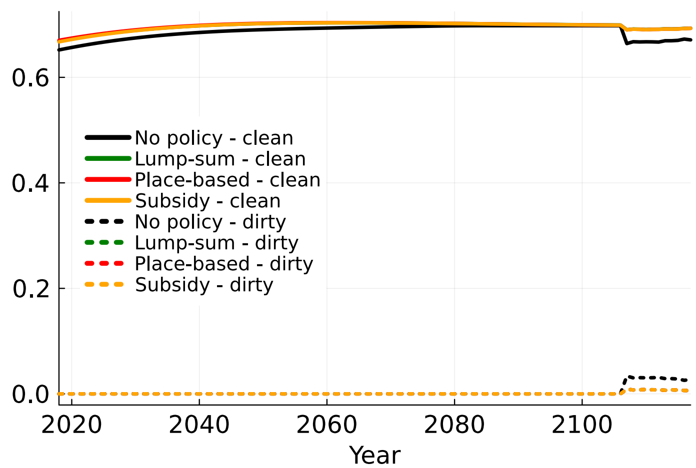
Figure A11: Spatial redistribution along the transition period



Notes: This figure shows the net transfers of rural and urban households for the different policy scenarios along the transition.

Figure A12 shows that housing construction rate for both housing types and the different policy scenarios. Except for the last 9 years of the transition, when housing prices have converged sufficiently, the housing construction firm only builds clean houses, as their prices are higher.

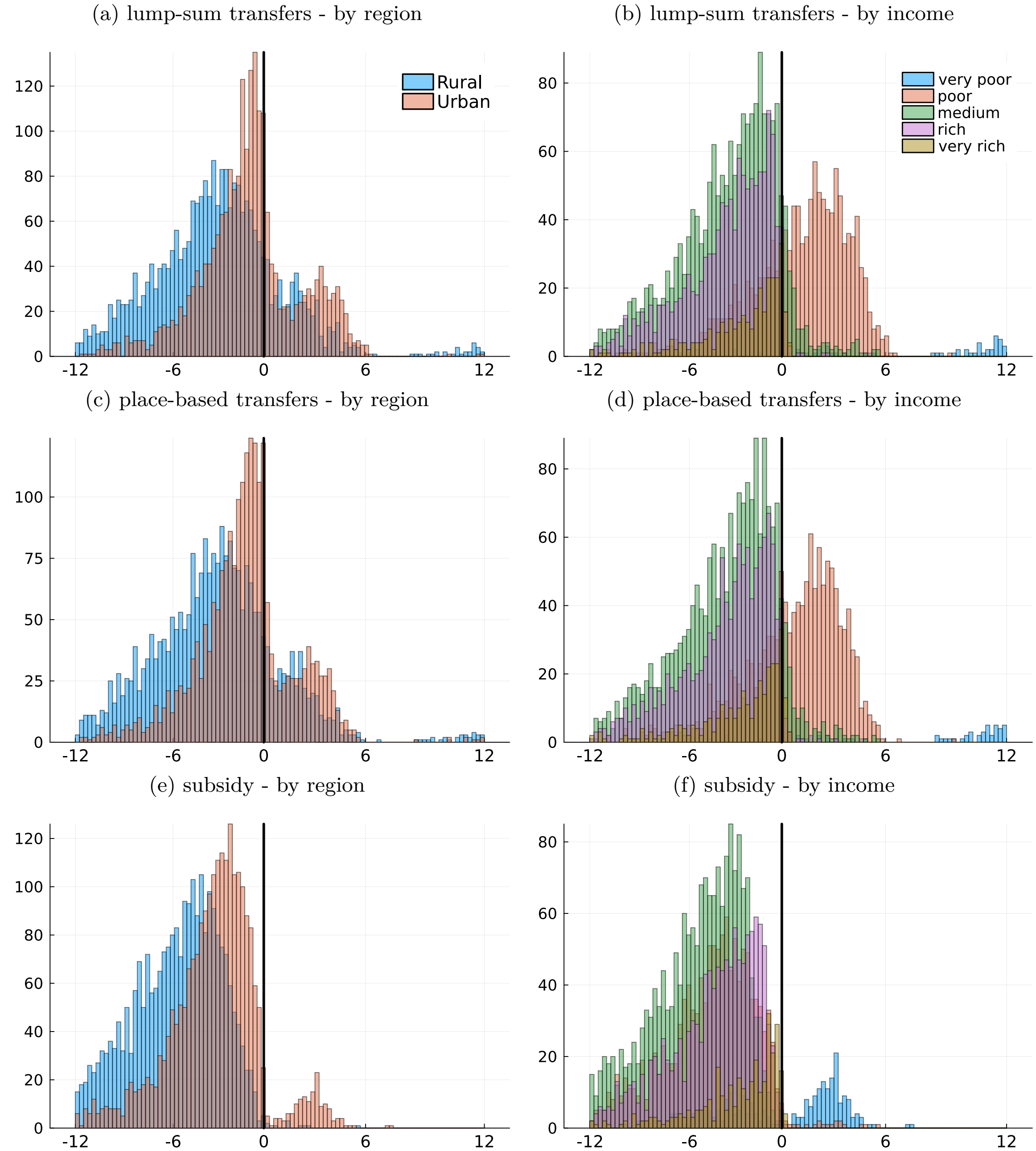
Figure A12: Housing construction by housing type



Notes: This figure shows the construction rates, being defined as the share of newly build housing units relative to the total housing stock in the initial steady state, for both housing types and the different policy scenarios.

Finally, Figure A13 shows the distribution of welfare effects by region and income for the different policy scenarios. Overall, the share of households with positive welfare effects is lower than the share with positive present values of net transfers, as the distortionary effect of the tax is accounted for.

Figure A13: Welfare effects (CEV)



Notes: Panels (a), (c), and (e) show the distributions of CEVs depending on the location in which households lived in the first period of the transition for the different policy scenarios. Panels (b), (d), and (f) show the same distributions for different income groups.

C.2 Sensitivity analysis

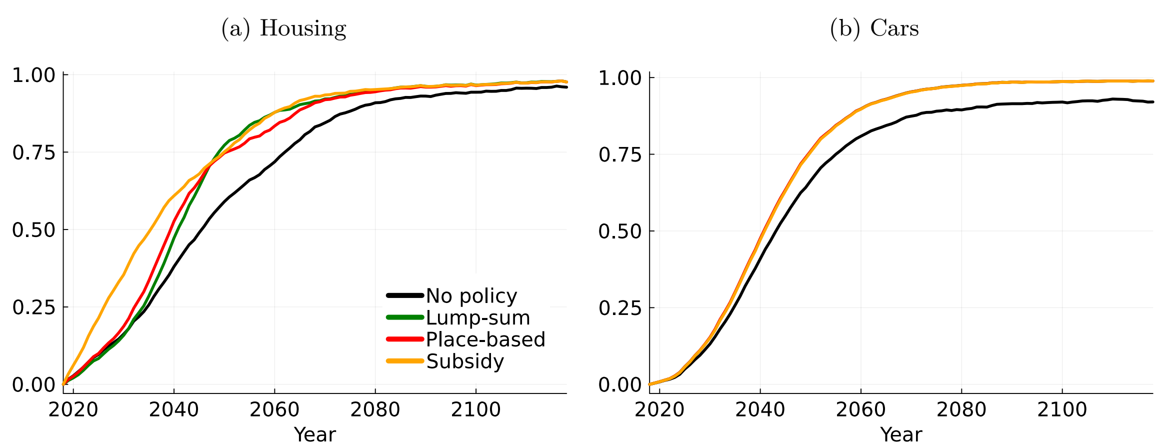
For the policy analysis in the main part, I focus on a constant carbon tax of 300 Euros per ton of carbon emissions. Within the European ETS2, there is, however, no fixed price per ton of emissions but rather a given number of issued certificates which allow firms to emit carbon emissions. These certificates are traded on the market such that the resulting price per ton of carbon emissions is endogenous and depends on the demand and supply of these certificates. The carbon tax of 300 Euros per ton is well in line with empirical estimates but there is also a high uncertainty about its exact level and path (Kalkuhl et al., 2023). Hence, this subsection tests the robustness of my main results with respect to this type of uncertainty. I document the transitional paths for a low- and high-carbon tax scenario with tax levels of 100 and 500 Euros per ton of carbon and an increasing carbon tax path which is based on estimates for the ETS2 from Kalkuhl et al. (2023) starting at 100 Euros and gradually increasing to 520 Euros in 2045, where it stays for the remaining transition.

Finally, I consider two extreme ways of recycling carbon tax revenues. All carbon tax revenues are either paid only to rural or only to urban households. These checks help to understand how sensitive my main results are with respect to these extreme forms of spatial redistribution.

C.2.1 Carbon taxes of 100 Euros per ton of carbon emissions

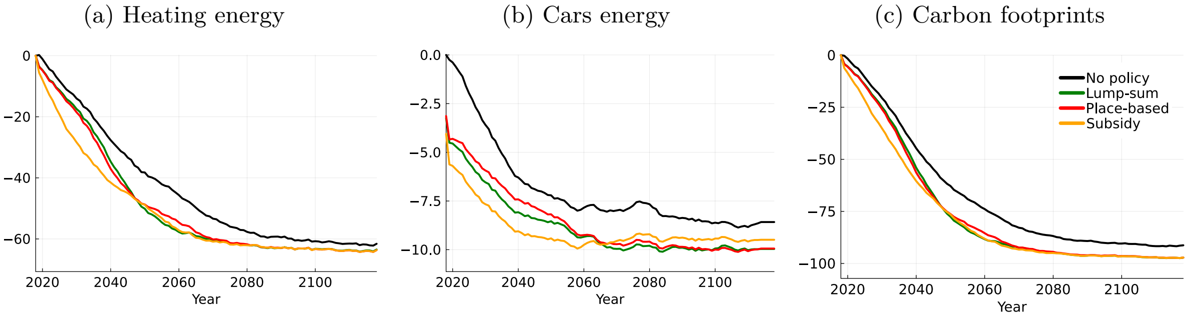
Figure A14 shows the share of households with clean technologies along the transition. As expected, a carbon tax of 100 Euros per ton of carbon speeds up the transition less than the baseline tax of 300 Euros. While in the baseline the share of households with clean houses and cars were around 88 and 85 percent by 2050, carbon taxes of 100 Euros lead to shares of around 75 percent for both goods. As a result, also the decline in energy consumption and carbon footprints happen slower. While in the baseline carbon taxes reduced emissions by 87 to 90 percent by 2050, carbon taxes of 100 Euros lead to a fall by around 80 percent. Figure A16 shows that the level of spatial redistribution, and the net migration flows are considerably smaller. The difference in the present value of net transfers between rural and urban households is 3,000 Euros, compared to the 8,000 Euros in the baseline.

Figure A14: Share of clean technologies along the transition - carbon tax of 100 Euros



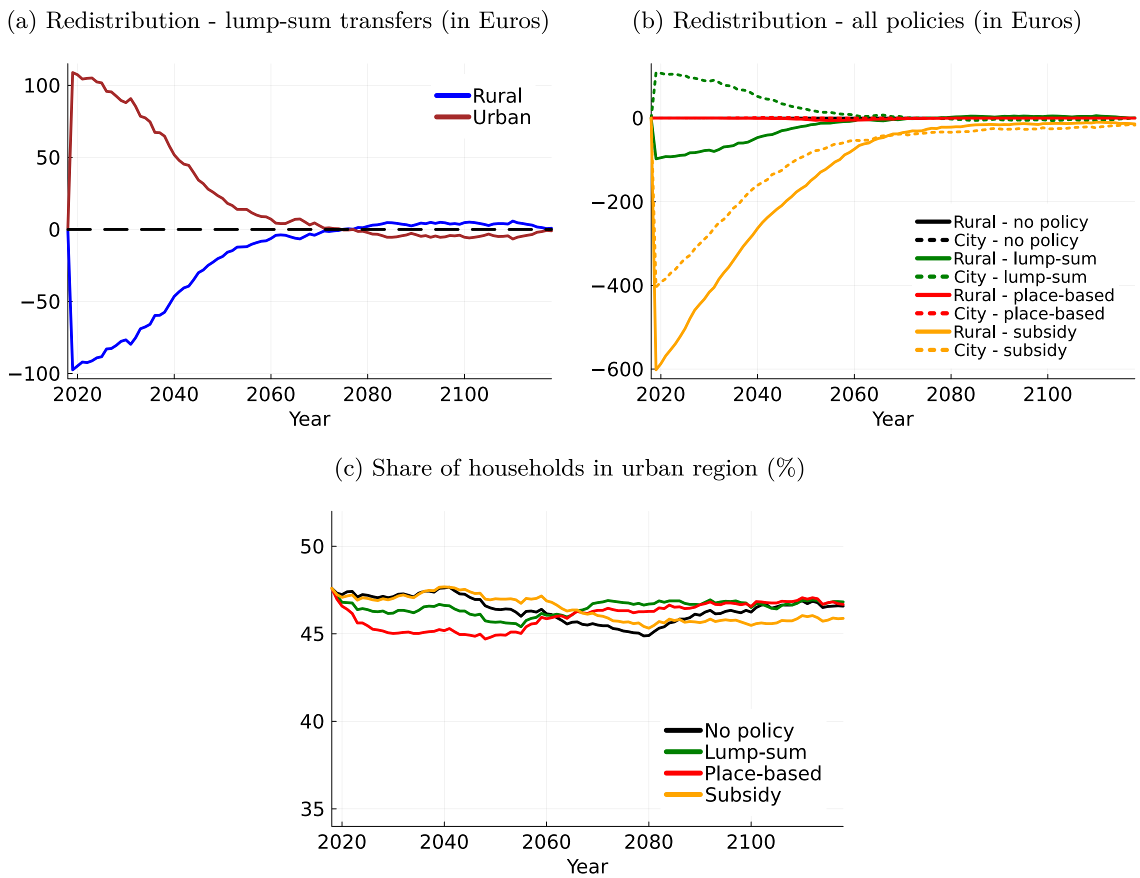
Notes: Panel (a) shows the share of households with clean houses along the transition period for the different policy scenarios considered. Panel (b) shows the corresponding share of households with clean cars along the transition.

Figure A15: Percentage changes over the transition - carbon tax of 100 Euros



Notes: Panel (a) and Panel (b) show the percentage change in heating and car energy along the transition for the considered policy scenarios. Panel (c) depicts the resulting path of carbon footprints. Finally, Panel (d) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers.

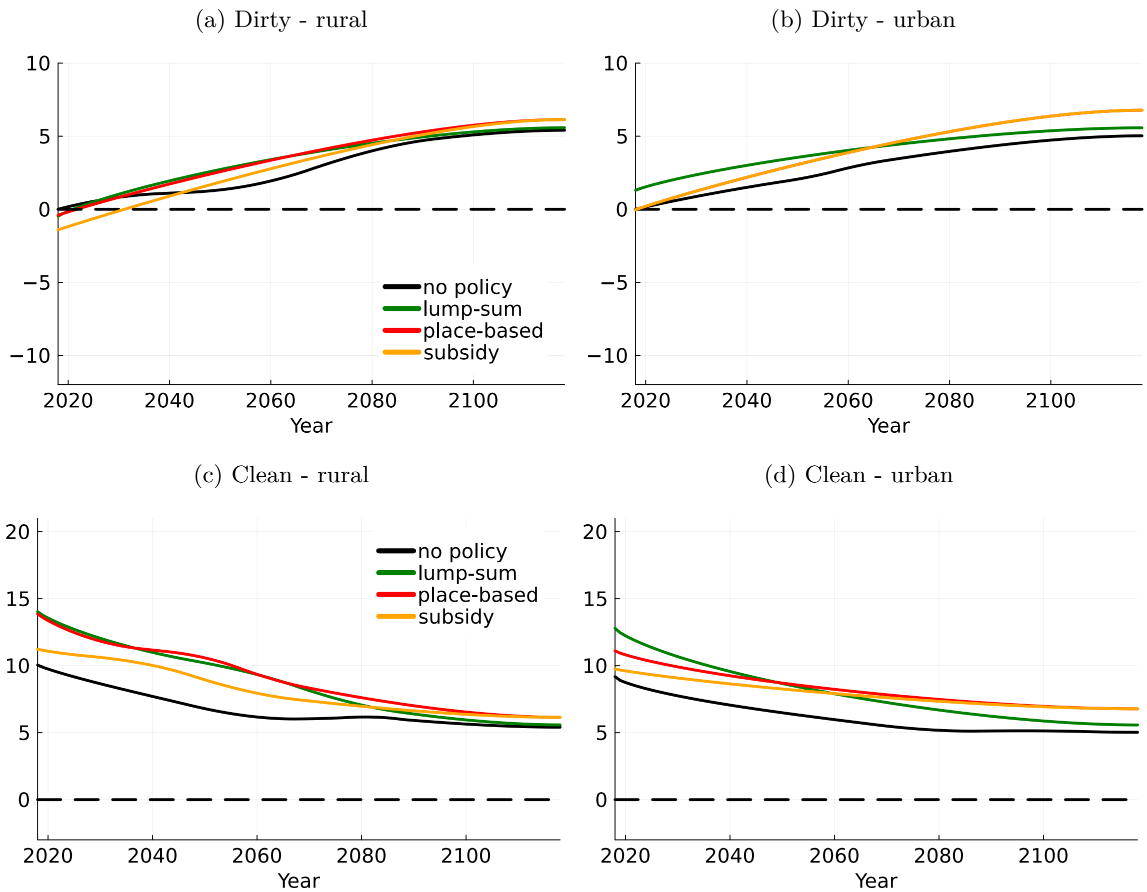
Figure A16: Location choices and redistribution over the transition - carbon tax of 100 Euros



Notes: Panel (a) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers. Panel (b) shows the share of the population living in the urban region along the transition for the different policy scenarios.

The changes in housing prices are also smaller with carbon taxes of 100 Euros per ton of carbon. Figure A17 documents that the initial price premium of clean housing increases by 1 to 4 percentage points with carbon taxes relative to the scenario without carbon taxes, while this premium was around 5 percentage points in the baseline scenario with carbon taxes of 300 Euros per ton of carbon. Also the initial price drop for dirty houses is only around 1 percentage point with carbon taxes, while it was around 5 percentage points in the baseline.

Figure A17: Housing price changes over the transition - carbon tax of 100 Euros

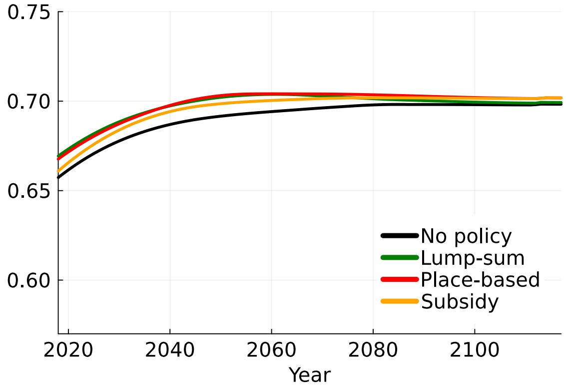


Notes: Panel (a) shows the percentage change of the housing price of dirty houses in the rural region relative to the price in the initial stationary equilibrium for dirty housing along the transition for the different policy scenarios. Panels (b) - (d) show the corresponding paths for dirty houses in the urban region and for clean houses in the dirty and clean region, respectively.

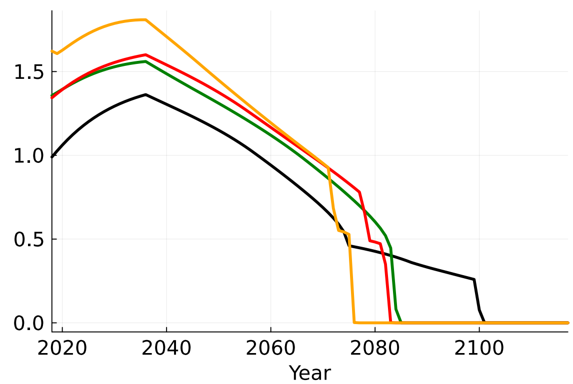
Finally, housing construction still reacts very little in response to the carbon tax and housing renovations react less strong, as Figure A18 documents.

Figure A18: Housing construction and renovations over the transition - carbon tax of 100 Euros

(a) Housing construction rate (%)



(b) Housing renovation rate (%)



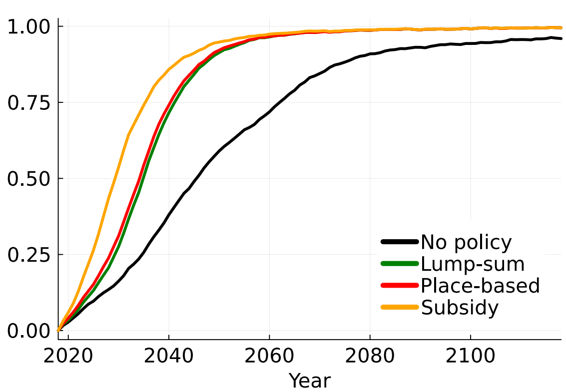
Notes: Panel (a) shows the share of newly constructed housing relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition. Panel (b) shows the share of housing renovations relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition.

C.2.2 Carbon taxes of 500 Euros per ton of carbon emissions

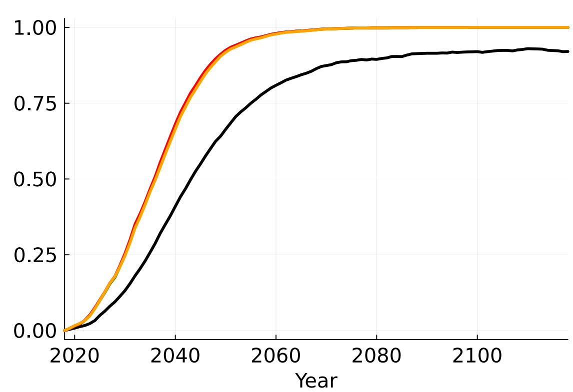
The results for the high-carbon tax scenario of 500 Euros per ton of carbon, lead to a faster transition to clean goods. While in the baseline around 88 to 90 percent of households use clean technologies, the share increases to 92 to 94 percent by 2050. Carbon emissions fall by 93 percent until 2050 compared to 88 percent in the baseline. Because of the higher carbon footprint, the spatial redistribution and the net migration flows become more important. The difference in the present value of net transfers between rural and urban households is increases to 11,000 Euros compared to 8,000 Euros in the baseline.

Figure A19: Share of clean technologies along the transition - carbon tax of 500 Euros

(a) Housing

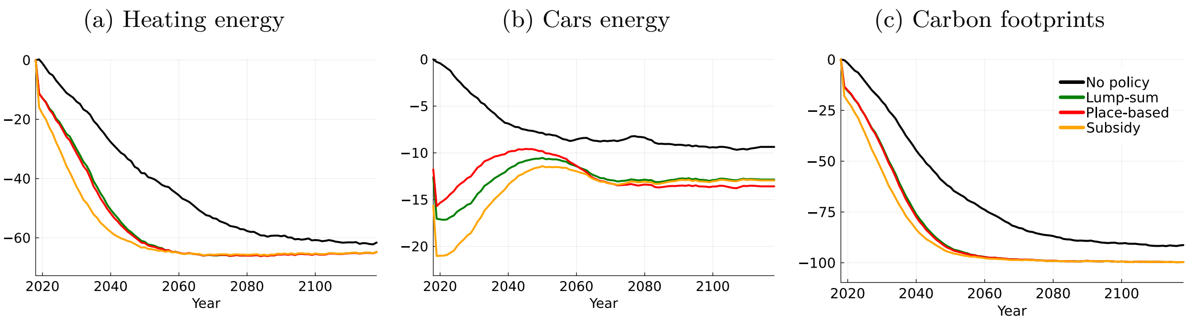


(b) Cars



Notes: Panel (a) shows the share of households with clean houses along the transition period for the different policy scenarios considered. Panel (b) shows the corresponding share of households with clean cars along the transition.

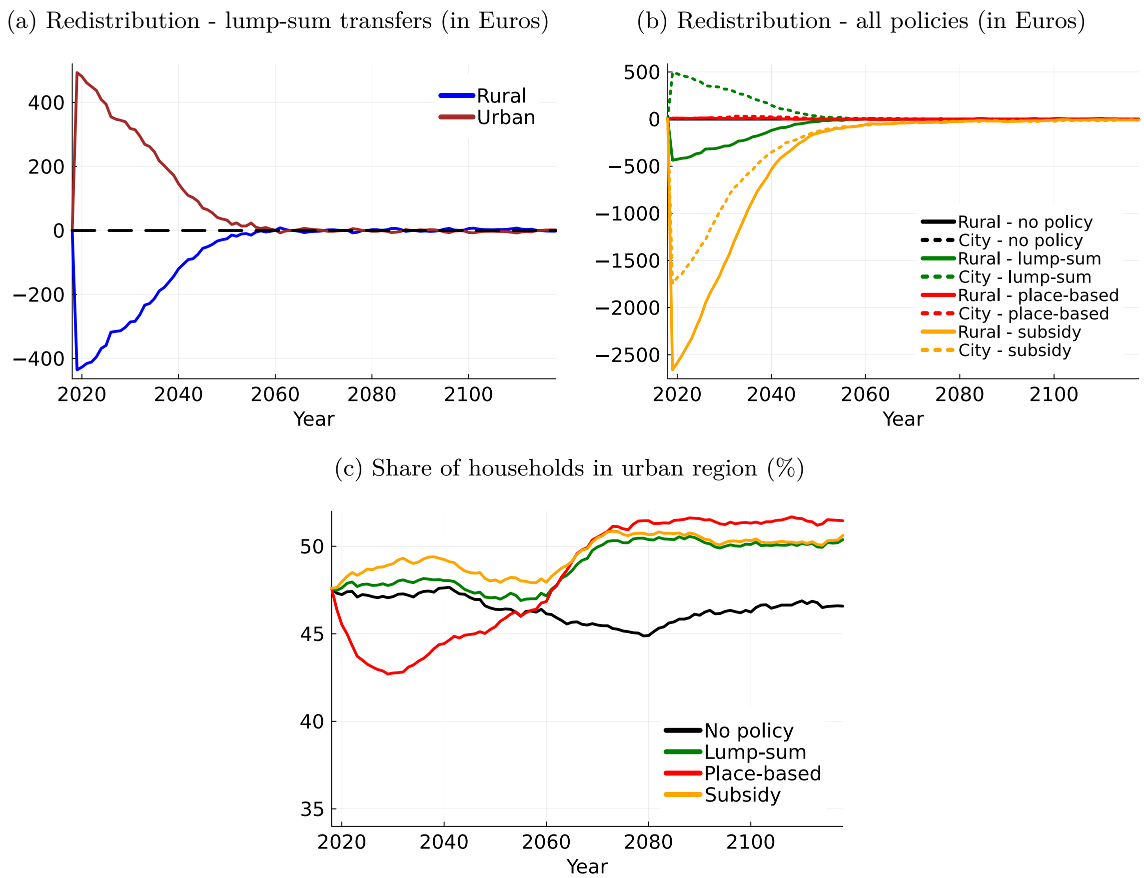
Figure A20: Percentage changes over the transition - carbon tax of 500 Euros



(a) Heating energy (b) Cars energy (c) Carbon footprints

Notes: Panel (a) and Panel (b) show the percentage change in heating and car energy along the transition for the considered policy scenarios. Panel (c) depicts the resulting path of carbon footprints. Finally, Panel (d) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers.

Figure A21: Location choices and redistribution over the transition - carbon tax of 500 Euros

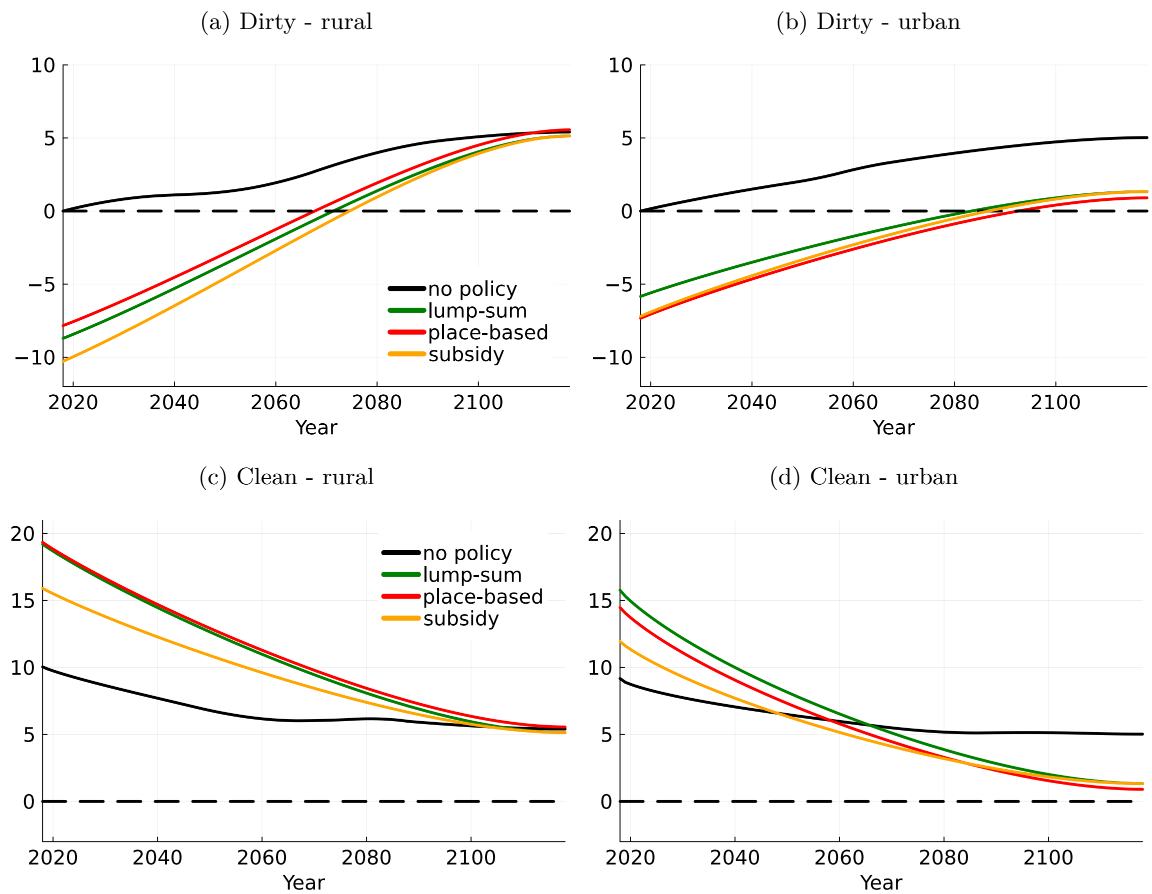


(a) Redistribution - lump-sum transfers (in Euros) (b) Redistribution - all policies (in Euros) (c) Share of households in urban region (%)

Notes: Panel (a) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers. Panel (b) shows the share of the population living in the urban region along the transition for the different policy scenarios.

The reaction of the housing prices is also much stronger. While the premium for clean houses with lump-sum and place-based transfers was around 14 to 15 percent, it increases to 15 to 19 percent with carbon taxes of 500 Euros. Also the initial price drop for dirty houses is with 6 to 10 percent larger than in the baseline, where it was around 4 to 5 percent.

Figure A22: Housing price changes over the transition - carbon tax of 500 Euros



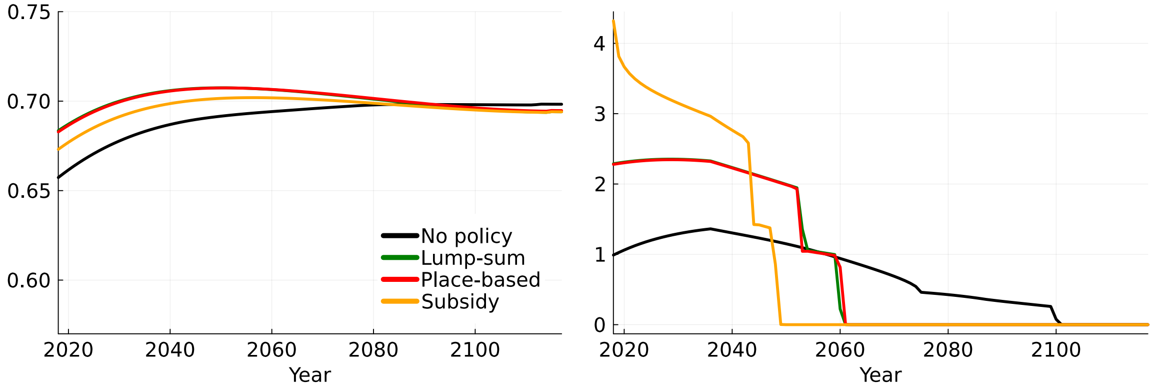
Notes: Panel (a) shows the percentage change of the housing price of dirty houses in the rural region relative to the price in the initial stationary equilibrium for dirty housing along the transition for the different policy scenarios. Panels (b) - (d) show the corresponding paths for dirty houses in the urban region and for clean houses in the dirty and clean region, respectively.

Finally, the housing renovation rate also reacts much stronger, in particular when rebating carbon tax revenues as subsidies on housing renovations. As higher carbon taxes lead to a larger price difference between clean and dirty houses and as the lead to higher percentage subsidies, the around 4 percent of the initial dirty housing stock is renovated in the first years of the transition.

Figure A23: Housing construction and renovations over the transition - carbon tax of 500 Euros

(a) Housing construction rate (%)

(b) Housing renovation rate (%)

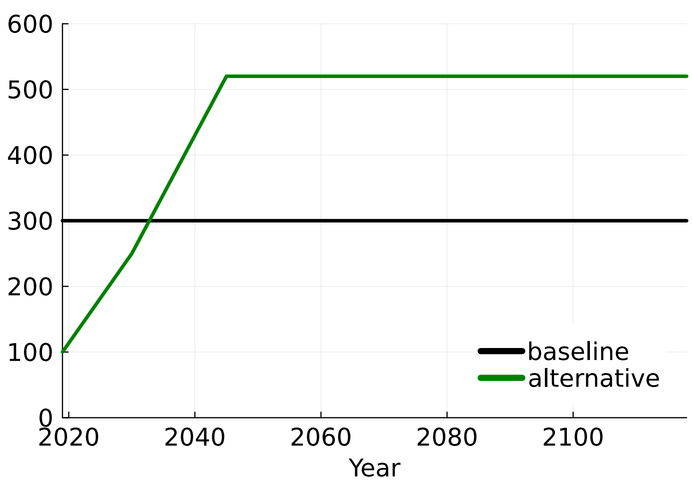


Notes: Panel (a) shows the share of newly constructed housing relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition. Panel (b) shows the share of housing renovations relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition.

C.2.3 Increasing path of carbon emissions

Figure A24 shows the increasing carbon tax path relative to the baseline policy scenario with a constant carbon tax of 300 Euros per ton of carbon. This increasing path is based on forecasts by Kalkuhl et al. (2023) on the carbon tax within the ETS2 which will be introduced in the European Union in 2027 onward and which is explicitly targeted at emissions from gasoline and residential heating. Starting from a carbon tax of 100 Euros per ton of carbon, the tax steadily increases to a level of 520 Euros per ton in 2045, where it stays for the rest of the transition.

Figure A24: Alternative path of carbon taxes



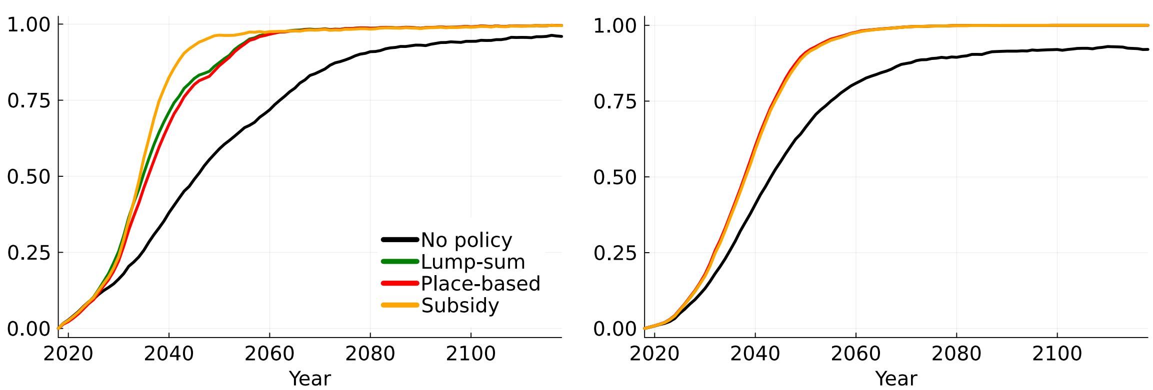
Notes: This figure shows the alternative, increasing carbon price path and the baseline constant carbon tax path.

Figure A25 shows that the adoption of clean technologies happens slower than in the baseline due to the lower initial carbon tax. As carbon taxes increase, the share of clean technologies is very similar to the one in the baseline by 2050. As a result, also the reduction in emissions by 2050 is very similar. The overall level of spatial redistribution is very similar to the one in the baseline, but its level remains almost constant from 2019 to 2050, while in the baseline it fell substantially along the transition. The difference in the present value of net transfers is 6,000 Euros, while it was 8,000 Euros in the baseline. This difference comes from the fact that, due to the increasing carbon tax path, redistribution happens later in the transition, decreasing its present value due to household discounting.

The housing prices, construction and renovation rates are also very similar to the baseline. Tables A1 and A2 show the political support for the increasing carbon tax scenario compared to the three constant carbon tax paths. For the both, the monetary and welfare analysis, the support is slightly higher than in case of the constant 300 Euro carbon tax, which is caused the higher carbon taxes and thus larger distortions being postponed and thus discounted.

Figure A25: Share of clean technologies along the transition - increasing carbon tax path

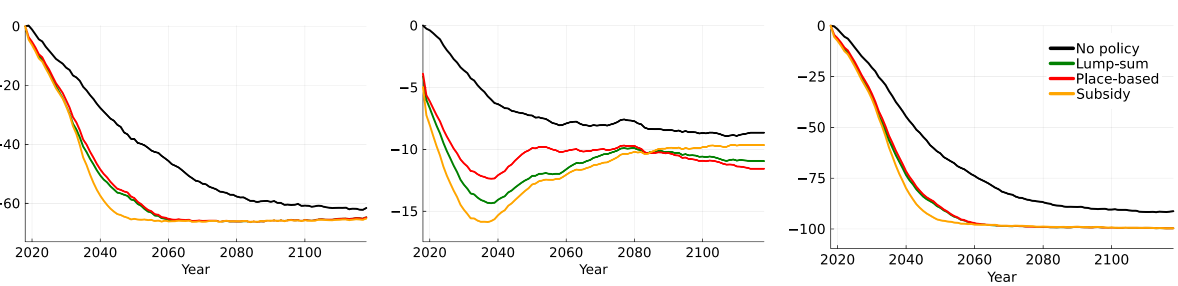
(a) Housing (b) Cars



Notes: Panel (a) shows the share of households with clean houses along the transition period for the different policy scenarios considered. Panel (b) shows the corresponding share of households with clean cars along the transition.

Figure A26: Percentage changes over the transition - increasing carbon tax path

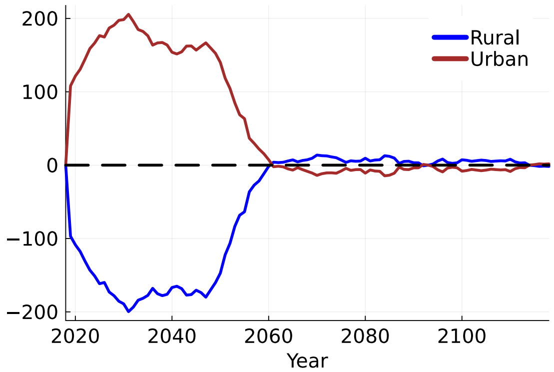
(a) Heating energy (b) Cars energy (c) Carbon footprints



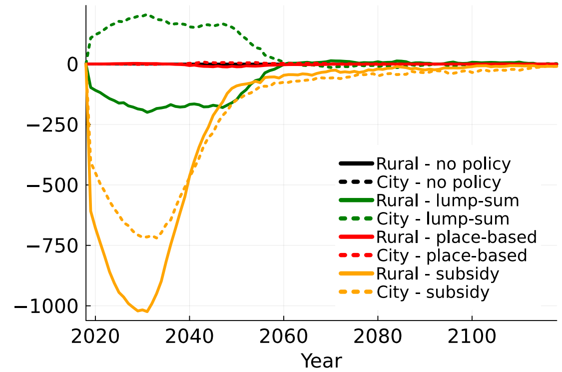
Notes: Panel (a) and Panel (b) show the percentage change in heating and car energy along the transition for the considered policy scenarios. Panel (c) depicts the resulting path of carbon footprints. Finally, Panel (d) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers.

Figure A27: Location choices and redistribution over the transition - increasing carbon tax path

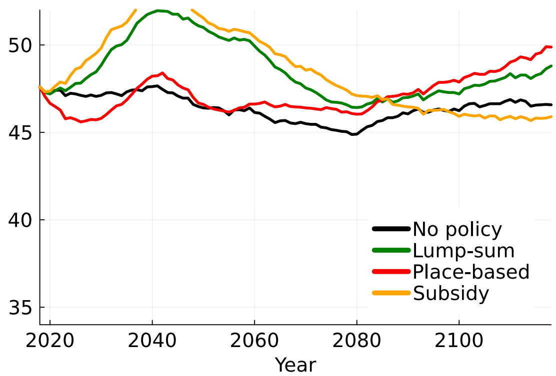
(a) Redistribution - lump-sum transfers (in Euros)



(b) Redistribution - all policies (in Euros)

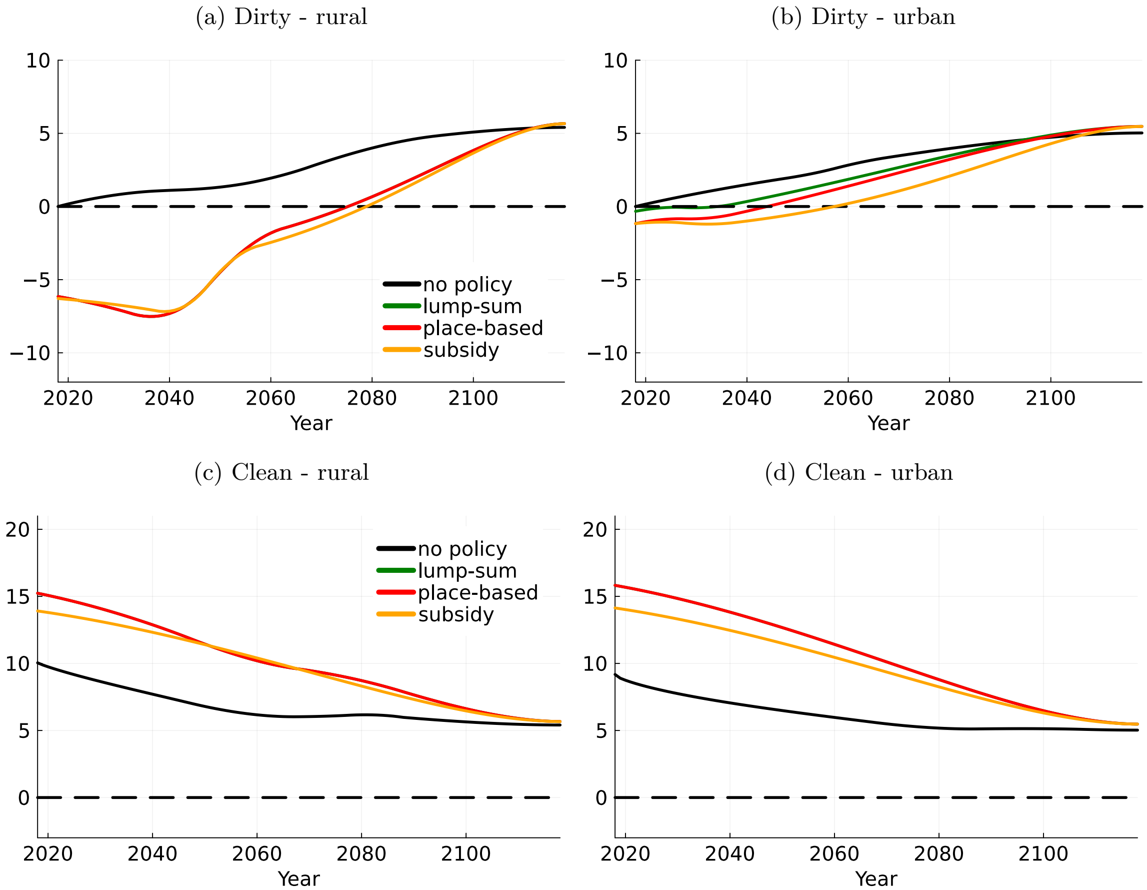


(c) Share of households in urban region (%)



Notes: Panel (a) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers. Panel (b) shows the share of the population living in the urban region along the transition for the different policy scenarios.

Figure A28: Housing price changes over the transition - increasing carbon tax path

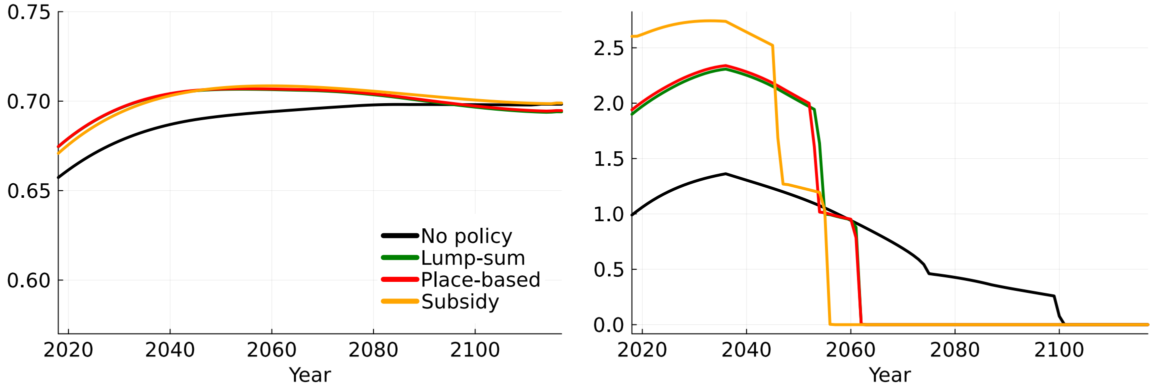


Notes: Panel (a) shows the percentage change of the housing price of dirty houses in the rural region relative to the price in the initial stationary equilibrium for dirty housing along the transition for the different policy scenarios. Panels (b) - (d) show the corresponding paths for dirty houses in the urban region and for clean houses in the dirty and clean region, respectively.

Figure A29: Housing construction and renovations over the transition - increasing carbon tax path

(a) Housing construction rate (%)

(b) Housing renovation rate (%)



Notes: Panel (a) shows the share of newly constructed housing relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition. Panel (b) shows the share of housing renovations relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition.

Table A1: Political support for climate policies - monetary decision - increasing carbon tax path

	Lump-sum			Place-based			Subsidy		
$\tau =$	100	300	500	100	300	500	100	300	500
All	60.1	59.9	60.1	62.2	62.4	62.1	0.0	0.0	0.0
Rural	48.2	48.1	48.1	63.3	63.2	63.0	0.0	0.0	0.0
Urban	73.3	73.1	73.2	61.0	61.3	61.1	0.0	0.0	0.0

Notes: This table shows the share of households who benefit from a given policy in monetary terms. I consider different rebating schemes and different carbon taxes levels.

Table A2: Political support for climate policies - welfare decision - increasing carbon tax path

	Lump-sum				Place-based			
$\tau =$	100	300	500	Rising	100	300	500	Rising
Baseline								
All	36.3	29.1	17.3	30.2	40.2	32.4	18.0	33.4
Rural	31.1	22.3	11.0	23.5	38.8	30.2	15.0	31.2
Urban	41.1	36.1	23.8	37.2	42.9	34.1	21.2	35.2
Positive ext.								
All	46.2	39.9	20.3	40.8	50.1	41.9	22.1	42.3
Rural	41.2	32.6	9.1	33.8	48.9	40.0	17.1	40.8
Urban	51.1	46.8	31.0	47.3	52.4	43.6	26.8	44.2

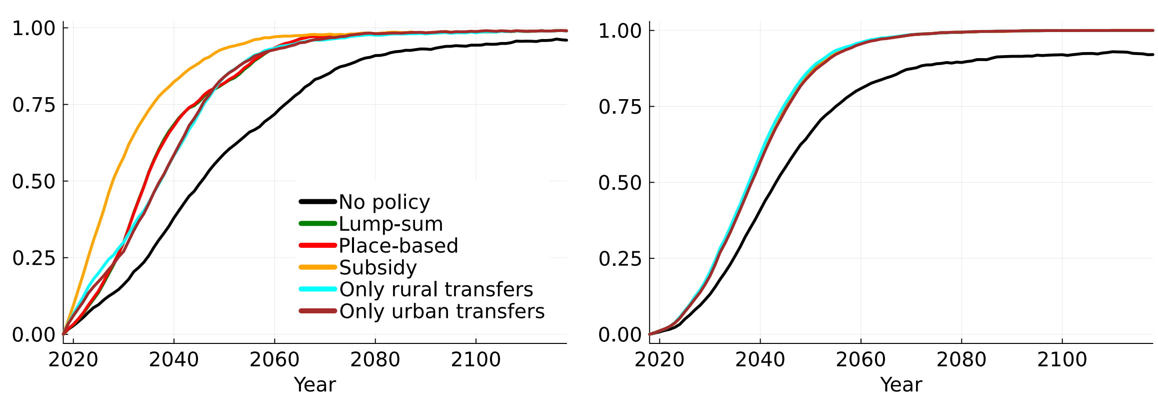
Notes: This table shows the share of households who benefit from a given policy in welfare terms. I consider different rebating schemes, different levels of carbon taxes, and specification with and without positive externalities of reduced emissions.

C.2.4 Transfers only to rural/urban households

Finally, I check how the results change when the revenues from carbon taxes of 300 Euros per ton are either paid only to rural or only to urban households. Figure A30 shows that the transitions to clean technologies do not change and as a consequences also the decline in carbon emission is very similar as in the baseline, as shown in Figure A31c.

Figure A30: Share of clean technologies along the transition - only rural/urban transfers

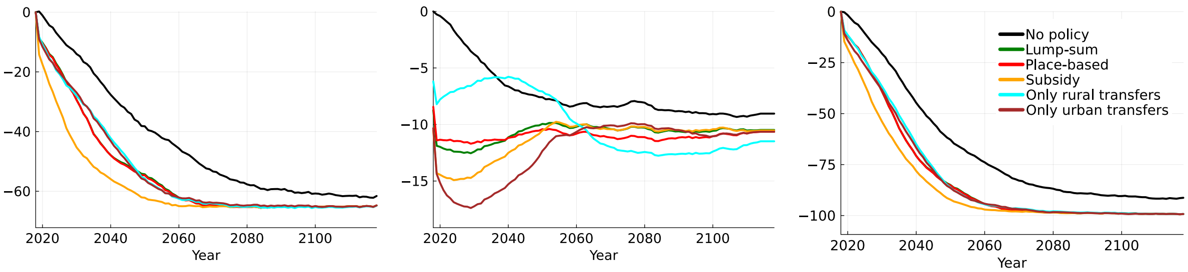
(a) Housing (b) Cars



Notes: Panel (a) shows the share of households with clean houses along the transition period for the different policy scenarios considered. Panel (b) shows the corresponding share of households with clean cars along the transition.

Figure A31: Percentage changes over the transition - only rural/urban transfers

(a) Heating energy (b) Cars energy (c) Carbon footprints

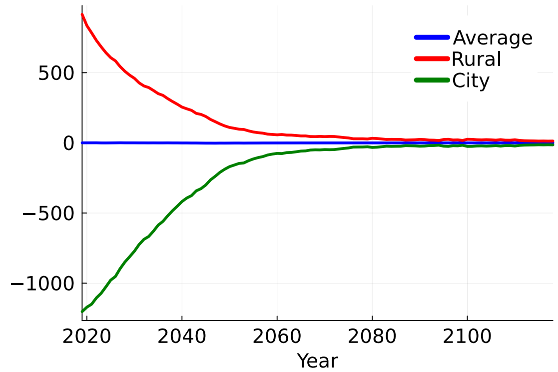


Notes: Panel (a) and Panel (b) show the percentage change in heating and car energy along the transition for the considered policy scenarios. Panel (c) depicts the resulting path of carbon footprints. Finally, Panel (d) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers.

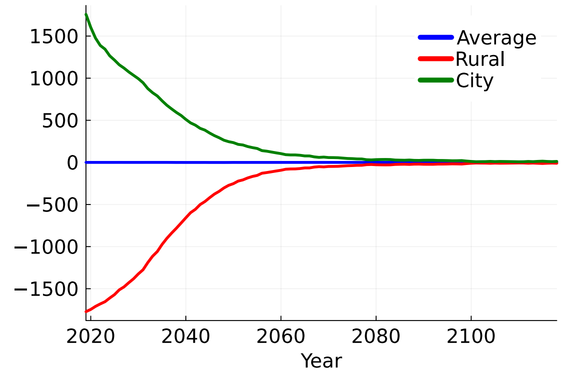
But the level of spatial redistribution increases substantially. When redistributing all tax revenues to rural households, they receive initially annual net transfers of 900 Euros, while urban households have net payments of around 1,200 Euros, as Subfigure A32 shows. The difference in the present value of net transfers between rural and urban households is around 27,000 Euros. When rebating carbon tax payments to urban households, this difference even increases, as the tax burden is larger for rural households. Urban households receive annual net transfers of around 1,600 Euros, while rural households have net payments of 1,700 Euros. This implies a difference in the present value of net payments of around 43,000 Euros. As a consequence the net migration flows change substantially across policy scenarios, as Subfigure A32c documents.

Figure A32: Location choices and redistribution over the transition - only rural/urban transfers

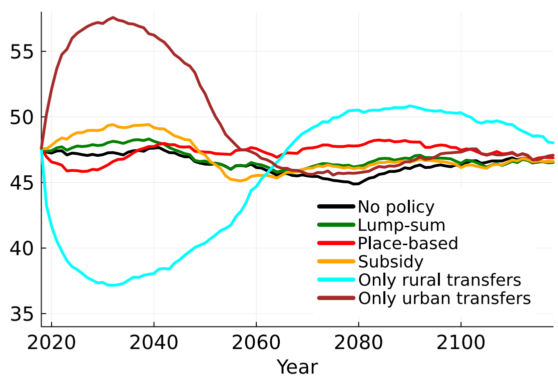
(a) Redistribution with rural transfers (in Euros)



(b) Redistribution with urban transfers (in Euros)



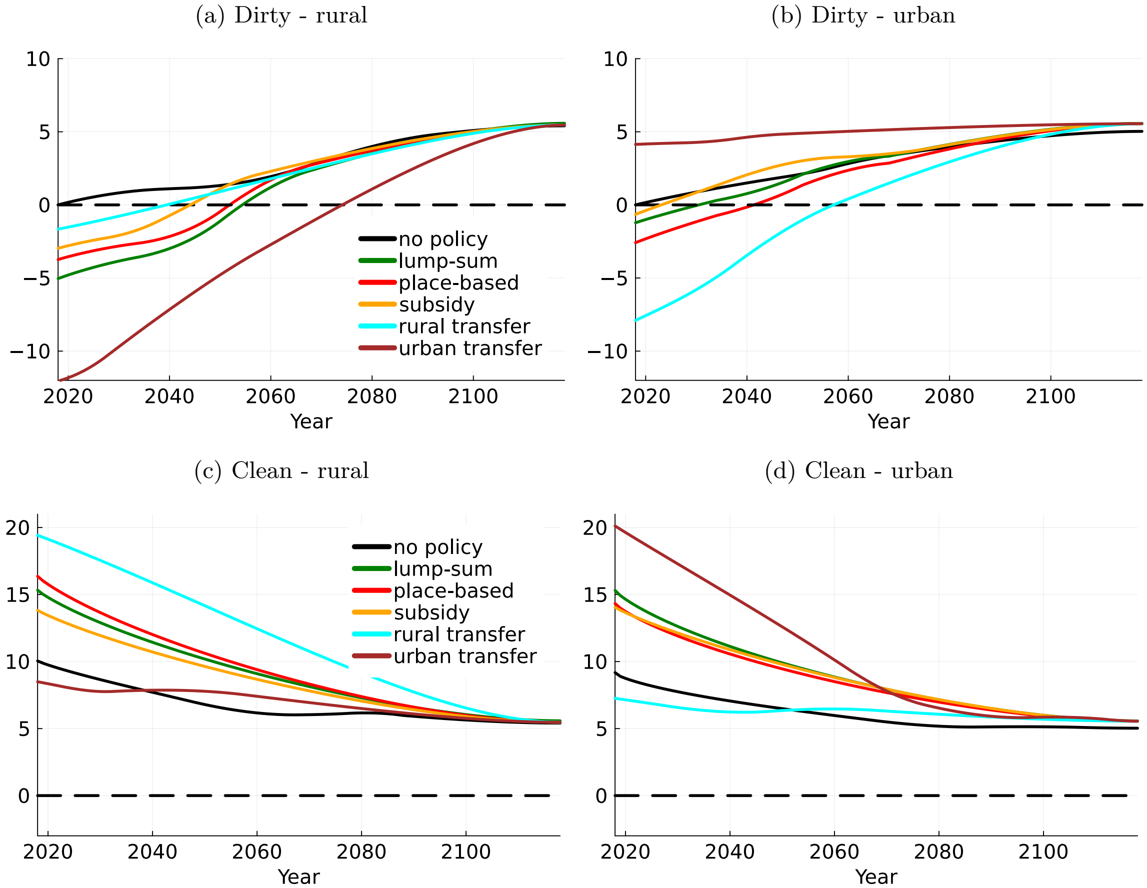
(c) Share of households in urban region (%)



Notes: Panel (a) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers. Panel (b) shows the share of the population living in the urban region along the transition for the different policy scenarios.

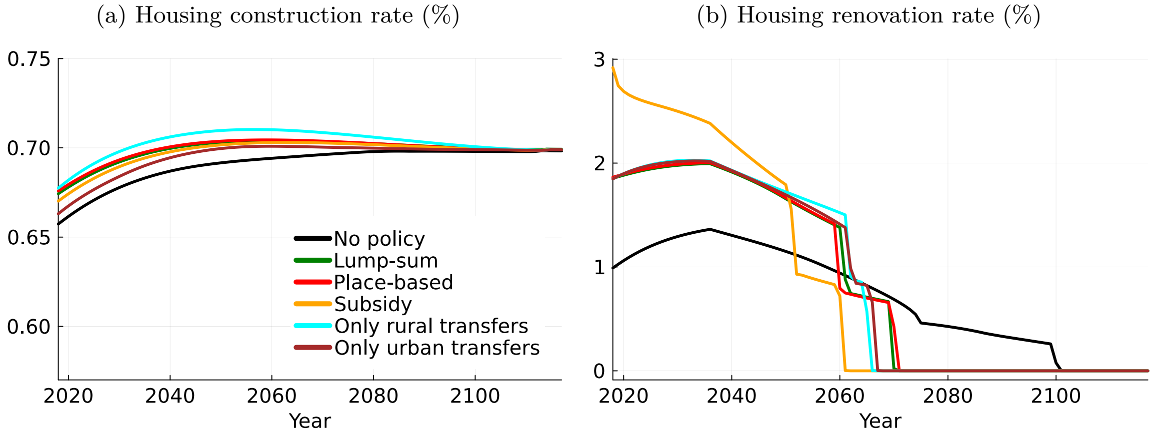
The housing prices do also change substantially with these extreme ways of redistribution. If only paying transfers to rural households, the initial price drop for dirty, urban houses amounts to 8 percent, while dirty housing prices in rural regions only fall slightly by one percent. In case transfers are only paid to urban households, the effects are even stronger. Dirty houses in the rural region loose around 12 percent in value, while those dirty houses in the urban region even gain around 4 percent in value. The initial price premium of clean houses increases in the region which receives the transfers by around 20 percent, while it increases in the other region, by around 7 to 8 percent, less than in the policy scenario without policy intervention. The construction and renovation rates do not change substantially.

Figure A33: Housing price changes over the transition - only rural/urban transfers



Notes: Panel (a) shows the percentage change of the housing price of dirty houses in the rural region relative to the price in the initial stationary equilibrium for dirty housing along the transition for the different policy scenarios. Panels (b) - (d) show the corresponding paths for dirty houses in the urban region and for clean houses in the dirty and clean region, respectively.

Figure A34: Housing construction and renovations over the transition - only rural/urban transfers



Notes: Panel (a) shows the share of newly constructed housing relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition. Panel (b) shows the share of housing renovations relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition.

Figures A3 and A4 show the political support for both policies. When evaluating support based on monetary outcomes, the overall support in the population remains independent of the was carbon tax revenues are rebated, even with these extreme ways of transfers. The support within regions, however, changes substantially. If paying transfers only to rural households, their support is around 84 percent, while only 12 percent of urban households benefit. The support in the urban region is not 0, because the urban vs. rural classification is based on where households live in the first year of the transition. Thus, some households who live in the urban region in the first period, might move to the rural region thereafter and receive transfers. If only paying transfers to the urban population, the differences in the political support become even larger. More than 90 percent of the urban population benefit, while only around 6 percent of the rural population do so. For the welfare analysis, the overall support is similar to the baseline results, but the differences in the support between rural and urban households become larger, even though they are smaller than in the evaluation based on monetary outcomes. Importantly, all qualitative results from the baseline analysis are still valid. The support based on the welfare analysis is lower because of the distortionary effects of the carbon tax, this effect is stronger in the rural region and becomes increases with the level of the carbon tax.

Table A3: Political support for climate policies - monetary decision - transfers for one region

	Rural transfer			Urban transfer		
$\tau =$	100	300	500	100	300	500
All	48.5	48.1	49.2	49.2	48.7	49.3
Rural	84.4	83.2	84.0	6.1	6.2	6.6
Urban	12.6	12.3	13.4	90.9	90.1	90.4

Notes: This table shows the share of households who benefit from a given policy in monetary terms. I consider different rebating schemes and different carbon taxes levels.

Table A4: Political support for climate policies - welfare decision - transfers for one region

	Rural transfer			Urban transfer		
$\tau =$	100	300	500	100	300	500
Baseline						
All	39.8	34.5	25.2	36.2	30.0	21.8
Rural	59.0	52.1	36.8	15.7	11.1	5.6
Urban	19.0	16.1	12.2	56.1	48.8	38.0
Positive ext.						
All	47.7	41.3	30.2	36.2	35.0	23.9
Rural	67.0	58.1	40.7	15.7	16.0	7.9
Urban	26.5	22.5	17.9	56.1	59.6	40.1

Notes: This table shows the share of households who benefit from a given policy in welfare terms. I consider different rebating schemes, different levels of carbon taxes, and specification with and without positive externalities of reduced emissions.