Essays in Macroeconomics

Inaugural-Dissertation

zur Erlangung des Grades eines Doktors
der Wirtschafts- und Gesellschaftswissenschaften

durch

die Rechts- und Staatswissenschaftliche Fakultät der
Rheinischen Friedrich-Wilhelms-Universität Bonn

vorgelegt von

Lennard Schlattmann

aus Borken

Bonn

2025

Dekan:	Prof. Dr. Martin Böse
Erstreferent:	Prof. Dr. Moritz Kuhn
Zweitreferent:	Prof. Dr. Pavel Brendler
Tag der mündlichen Prüfung:	19. September 2025

Acknowledgements

First and foremost, I would like to thank my advisors Moritz Kuhn, Pavel Brendler, and Christian Bayer. I am especially grateful to my first advisor, Moritz Kuhn, for his intellectual guidance and support throughout my doctoral studies. I have learned tremendously from our joint work and our discussions on my own research, which have deepened my understanding of economic research and sharpened my analytical thinking. I am also deeply grateful to my second advisor, Pavel Brendler, who has been a great mentor and has always been there to provide me with profound feedback and insights. His support extended well beyond our office discussions, and I particularly valued our runs in the Siebengebirge and Eifel. I am grateful for the time and dedication he invested in my development. I would also like to thank my third advisor, Christian Bayer. In particular, his invaluable feedback during the final stages of my dissertation played a crucial role in shaping my job market paper and preparing me for the academic job market.

I would also like to thank the entire faculty of the Institute for Macroeconomics and Econometrics for their valuable feedback during our weekly seminars and individual discussions, and Heide, Beate, and Kim for their administrative support. I am also grateful to the Bonn Graduate School of Economics and the University of Bonn for providing me with an excellent research environment and financial support.

The people I met along the way were an integral part of my doctoral studies. Not only do I share similar memories with them, but they have also become close friends. In particular, I would like to thank Gero, Johannes, Leanne, Max, Björn and my office mates Sebastian, Fabio, and Tim.

Lastly, I would like to thank my family. They have always been there for me, for which I am immensely grateful. I want to express my special gratitude to my parents, Theresia and Ralf, and my sister, Luise, who supported me in every way possible. Finally, I want to thank my partner, Leonie, who has always been by my side and supported me through the ups and downs of my studies. I am grateful for her love and her approach to life.

Contents

List of Figures

List of Tables

Introduction

Understanding the role of public policy in shaping individual behavior, and thus broader economic outcomes, is fundamental to the design of effective policy interventions. Individuals do not make decisions in a vacuum: their choices are shaped by incentives, constraints, and the economic and institutional context in which they operate. This dissertation contributes to the ongoing discussion by examining how individual decisions interact with the design of public policies in two areas that are both economically and politically salient: social mobility and climate policy. Across three chapters, I investigate how structural features of the economic environment, such as regional disparities in labor demand and heterogeneity in household carbon emissions, mediate the effects of policy interventions. These features shape not only how individuals respond to policies, but also who benefits and who bears the costs, with significant implications for both the effectiveness of policies and their distributional consequences.

Chapter 1 studies the intergenerational persistence of occupational choices, a critical mechanism underlying income persistence and, hence, limited social mobility. While previous research has emphasized labor supply factors, such as the transmission of skills or parental information networks, this chapter highlights the role of regional labor demand. Combining data from the German Socio-Economic Panel with detailed measures of regional and occupation-specific vacancies for each combination of 400 regions and 436 occupations, I show that controlling for regional and occupation-specific demand reduces occupational persistence by up to 10 percent, as much as controlling for educational attainment. This finding suggests that large differences in regional labor demand across occupations, together with low labor market mobility of workers, can explain a significant share of the observed intergenerational persistence of occupational choices. Thus, this chapter highlights the importance of considering structural constraints in the analysis of intergenerational mobility and suggests that policies aimed at improving labor market opportunities should take into account regional demand conditions.

Chapters 2 and 3 examine the distributional consequences of climate policies, focusing on carbon taxation and subsidies for carbon-neutral technologies. As climate change mitigation policies gain traction globally, understanding their distributional implications becomes increasingly urgent for policymakers in order to design policies that find political majorities.

Chapter 2, which is joint work with Moritz Kuhn, studies the distributional effects of climate policies along the income distribution, by combining empirical evidence with a quantitative life-cycle model. Empirically, we identify infrequently adjusted consumption goods, i.e. consumption commitment goods such as cars or heating systems, together with their complementary consumption (gas, oil), as prime candidates for climate policies. They generate 35 percent of household carbon emissions while accounting for only 11 percent of household expenditures. Motivated by this observation, we develop a life-cycle model of heterogeneous households that explicitly models these consumption commitments. We identify a trade-off between emission reduction and redistribution, as the policy mix that reduces emissions the fastest, i.e. financing a percentage subsidy for carbon-neutral technologies through a carbon tax, redistributes substantially from low- to high-income households and thus does not find majority support. We then show that financing percentage subsidies with progressive income taxes can achieve both substantial emission reductions and broad political support, while only marginally slowing carbon emission reductions. These results underscore that the design of climate policy instruments is key to balancing effectiveness and political support in the energy transition.

Chapter 3 turns to the spatial dimension of climate policy, exploring how rural and urban households are differentially affected by carbon taxation. Combining expenditure data from German households with data on the carbon intensities of different consumption goods, I show that rural households emit 2.2 tons more carbon per year than comparable urban households, representing about 12 percent of the average carbon footprint. This difference is driven by three factors: rural households rely more on private transportation, larger houses, and oil-based heating systems. I then develop a spatial general equilibrium model to assess the redistributive effects of different mechanisms for recycling carbon tax revenues to households. Within this framework, I also take into account the general equilibrium effects of carbon taxes on housing markets, as households are allowed to migrate across regions. I find that spending carbon tax revenues on lump-sum transfers redistributes from rural to urban areas due to their heterogeneous emission profiles. For a carbon tax of 300 euros per ton, the difference in the present value of net transfers between rural and urban households reaches 8,000 euros. The general equilibrium effects of this policy mix are sizeable, increasing urban relative to rural rents and thus mitigating the heterogeneous impact of the carbon tax by a quarter to 6,000 Euros. In contrast, place-based transfers, which allocate revenues based on local average emissions, avoid this redistribution without slowing the transition to clean technologies. As a result, they find majority support in both regions, while lump-sum transfers find majority support only in the urban region.

Together, these chapters emphasize the importance of designing economic policy with close attention to how individuals respond to incentives, and how these responses are shaped by the environments in which people live and work. By examining the interplay between individual behavior, policy instruments, and structural features such as regional labor markets and spatial variation in emissions, this dissertation contributes to a deeper understanding of how to design effective policies that find broad political support. In doing so, it highlights that the political feasibility of policies aimed at improving social mobility or addressing climate change depends not only on their aggregate effects, but also on how these effects are distributed across income groups and regions.

Chapter 1

Regional Labor Demand and Occupational Persistence in Germany

1.1 Introduction

When entering the labor market, many children decide to work in their parents' occupations.[1] Despite a long tradition of documenting this intergenerational persistence in occupational choices, the underlying mechanisms of this behavior are still not fully understood. Identifying the determinants of this persistence has crucial implications along several dimensions. First, persistence in occupations is a major driver of persistence in income and thus of social mobility. Hence, if society wants to enhance social mobility, we need to understand the causes of persistence in occupations. Second, high levels of persistence in occupations potentially mirror inefficient allocations of talent as individuals might not be allocated to occupations based on their skills but rather based on information networks or even nepotism. So what drives persistence in occupations?

For answering this question the literature has exclusively focused on supply side effects, e.g. the transmission of abilities and parental information networks as mechanisms (Kramarz and Skans, 2014; Lo Bello and Morchio, 2022), by assuming that children can freely choose in which occupation to work. In reality, however, children only find a job in a given occupation if there is also an employer looking for an employee in this occupation. Thus, the main contribution of this paper is to quantify the importance of demand side effects. For doing so, I employ annual vacancy data for each combination of 400 regions and 436 occupations based on all vacancies which are reported to the German Federal Employment Agency, around

1. This following behavior has been well documented in the literature. Examples include studies on specific occupations, such as medical doctors (Lentz and Laband, 1989) or pharmacists (Mocetti, 2016), on aggregated occupational groups, such as liberal professions (Aina and Nicoletti, 2018), as well as on whole countries, such as the United States (Blau and Duncan, 1967) or the United Kingdom (Lo Bello and Morchio, 2022).

600,000 each year. I show that conditioning on regional labor demand reduces the level of intergenerational persistence in occupational choices[2] by around 5 to 10 percent, the same order of magnitude as conditioning on children's years of education does. The importance of regional labor demand stems from two empirical observations. First, there is a high regional heterogeneity in labor demand for different occupations in Germany. Second, workers are very immobile and many work in the same regional labor market as their parents. Combining both observations implies that children and parents face a similar regional labor demand, which differs to parent-child pairs in other regions. The second contribution is to document that persistence levels increase in the fineness of classifying occupations and, more surprisingly, a high level of homogeneity in the degree of persistence for different parent-child combinations. At the finest classification, the probability for a son to work in a given occupation increases by factors of 21 or 24 if his mother or his father work in this occupation, respectively. The third contribution is to show that children who follow into their parents' occupation experience a wage premium of around 6 percent during the first two years of their first full-time job. Also their annual unemployment risk halves from around 7 to 3.5 percent during the first five years and both effects fade out with tenure.

Methodologically, this paper exploits regional and occupation-specific vacancy shares, used as proxies for regional labor demand, by merging them with the German Socioeconomic Panel (SOEP). In total, I use annual vacancy shares for each combination of 400 regions and 436 occupations, defined by the ISCO08 4-digit classification. Hence, 174,400 different shares are obtained, which are computed based on all vacancies which are reported to the German Federal Employment Agency, around 600,000 each year. Assuming a logistic model, I first compute persistence levels without and thereafter with conditioning on vacancy shares. Comparing both values gives a measure of how important regional labor demand is for persistence in occupational choices. Intuitively, a son of a miner growing up in Bottrop, a city in the industrial Ruhr area where in 2013 9.4 percent of full-time employees worked as miners and quarriers, might not become a miner because of his father's information networks or the transmission of abilities but simply because the labor demand for miners in Bottrop is especially high. This labor demand channel seems to be particularly relevant as this paper documents first a high degree of heterogeneity in regional labor demand for different occupations in Germany and second a low labor market mobility as in my sample around 85 percent of full-time working children still live in the same region as their parents. In order to put the importance of regional labor demand into context, I repeat the same exercise but compute the level of persistence conditional on

2. Throughout the paper, persistence is defined as the percentage increase in the probability to work in a given occupation if the parent works in this occupation relative to someone whose parent does not work in this occupation. A more formal definition is provided in Section 1.2.

children's education level. This way, I compare the regional labor demand channel with the education channel which has been shown to be important for social mobility (Caucutt and Lochner, 2020; Heckman and Mosso, 2014). The result that regional labor demand is a relevant channel for persistence is further supported by proxying regional labor demand with regional, occupation-specific employment shares, which constitute an alternative measure for labor demand.

Next to quantifying the importance of regional labor demand for persistence, this paper investigates the impact of following into the parent's occupation on wages and unemployment risk. Evaluating these impacts for different subgroups with respect to the child's gender, education level, and tenure allows to identify heterogeneous impacts along these dimensions. First, the wage premium and the reduced unemployment risk for occupational followers fade out 2 and 5 years after labor market entry, respectively. Second, both impacts are primarily driven by those individuals without a high school degree, indicating that this subgroup especially benefits from following, at least in the short-run. Third, while daughters seem to benefit slightly more in terms of the initial wage premium, sons profit more in terms of the reduced unemployment risk.

There are two branches of literature this work relates to. First, there are papers showing that heterogeneity in local labor markets has important implications along several economic dimensions. It results in workers in different areas earning different wages even after adjusting for costs of living (Moretti, 2010) or facing different unemployment risks and employment opportunities (Bilal, 2021; Kline and Moretti, 2013; Kuhn et al., 2021). Typically, these local differences are explained by agglomeration effects of productive firms in certain areas (Bilal, 2021) and by more efficient worker-firm matching (Dauth et al., 2022). This paper contributes to this literature by showing that local labor markets also play an important role for intergenerational persistence in occupational choices and hence for social mobility.

Second, there is a literature on how networks impact occupational decisions. Starting from the seminal work by Granovetter (1973) the literature has shown that networks (Brown et al., 2016; Dustmann et al., 2016; Glitz and Vejlin, 2021) and especially strong social ties, like parents (Kramarz and Skans, 2014), are important for occupational choices. Consequently, a substantial share of children follows into their parent's occupation (Aina and Nicoletti, 2018; Blau and Duncan, 1967; Lentz and Laband, 1989; Lo Bello and Morchio, 2022; Mocetti, 2016). While this following behavior has been well established, the key underlying channels are far less clear. My paper contributes here on the labor demand as well as on the labor supply side. For the former, it is the first to document and quantify the importance of regional labor demand for intergenerational persistence in occupational choices. For the latter, it extends the supporting evidence in favor of a popular theory developed by Dustmann et al. (2016), which suggests that information networks rather than the transmission of abilities are the main driver of occupational persistence on the labor supply side, in two dimensions. First, I show that their model predictions of an initial wage premium for occupational followers which fades out with tenure are supported when defining following based on finely classified occupations instead of firms. This definition is arguably more suitable for studying the intergenerational transmission of abilities and skills as they are most likely not firm but rather occupation-specific. Second, I further show that their predictions still hold for the type of network which has been shown to be most important for labor market outcomes: immediate family members.

The remainder of this paper is structured as follows: Section 1.2 introduces the data and provides descriptive results before Section 1.3 describes the empirical strategy applied. Thereafter, Section 1.4 provides the empirical results, which are discussed, related to the literature, and supported by robustness checks in Section 1.5. Finally, Section 1.6 concludes.

1.2 Data and descriptive results

This section first introduces the different datasets employed and the most important definitions used in this paper. Thereafter, the data cleaning process is described and descriptive results are shown.

1.2.1 Data and definitions

This paper makes use of two data sources. First, it applies data from the German Socioeconomic Panel (SOEP), Wave 37, which spans a time period from 1984 to 2020. The SOEP provides information on labor market outcomes such as wages, occupations, and unemployment spells as well as a large set of other socioeconomic variables. While being representative on the national level, one drawback of the SOEP is that it is not representative at the county level. Thus, in order to obtain representative regional, occupation-specific vacancy shares, which will serve as proxies for regional labor demand, this paper additionally uses data from the German Federal Employment Agency (Bundesagentur für Arbeit, BA). This BA dataset includes annual vacancy and employment shares according to the ISCO-08 classification up to the 4-digit level. Vacancy shares are based on all vacancies reported to the BA between 2011 and 2020, around 600,000 each year, and employment shares are computed based on all employees in Germany who are subject to mandatory social insurance contributions from 2013 to 2020, around 30 million employees each year. Merging this rich dataset with the SOEP allows to control for regional and occupation-specific labor demand when studying intergenerational persistence in occupational choices.

In order to quantify the degree of occupational persistence, the most natural measure would be to simply compute the percentage shares of children who work in the same occupation as at least one of their parents.[3] Only looking at percentage shares for quantifying persistence, however, has two important drawbacks. First, it neglects occupational concentration. If everyone worked in one occupation, the percentage share of followers would be equal to one, even though this high persistence might not be driven by actual following behavior. Second, it does not account for differences in the distributions of children's and parents' occupations. For a given following behavior percentage shares of followers mechanically decrease when the distributions of both subgroups differ substantially.

Both drawbacks are not present when using likelihood ratios instead of percentage shares. Hence, following the definition typically used for diagnostic inference in medicine (Doi et al., 2022), I define the likelihood ratio of occupation j as

$$LR_j = \frac{P\left(o = j \mid o^P = j\right)}{P\left(o = j \mid o^P \neq j\right)},$$

where o and o^P refer to the child's and parent's occupation, respectively.[4] Thus, the likelihood ratio of occupation j is given by dividing the probability of a child working in occupation j if the parent is working in this occupation by the probability of doing so if the parent is not working in this occupation. Making the connection to the medicine literature, one can think of children with a parent working in occupation j as being treated, while those without a parent working in occupation j are untreated. Hence, the goal is to compare the "risk" of working in occupation j between these two subgroups. Intuitively, a likelihood ratio of one would indicate that children's occupations are independent from their parents' occupations, while a ratio of 2 implies that the probability of working in a given occupation doubles if one has a parent working in this occupation compared to someone whose parents do not work in this occupation.

In order to obtain an aggregate measure of persistence, likelihood ratios are weighted by the number of children working in each occupation. Formally, the weighted likelihood ratio is defined as

$$WLR = \sum_{j=1}^{J} w_j LR_j \tag{1.2.1}$$

3. Table 1.A.3 in Appendix 1.A depicts these statistics.

4. Dal Bó et al. (2009) use a similar measure which they call *dynastic bias* and which is defined by dividing the conditional probability of a father working in a given occupation if the son works in this occupation by the unconditional probability of a father working in this occupation.

where J is the number of different occupations and the weights w_j are based on the number of children working in occupation j and defined as

$$w_j = \frac{n_j}{N}$$

where N and n_j refer to the total number of children and the number of children working in occupation j, respectively.

Next to the likelihood ratios, this paper will refer to the excess probability as measure of persistence which is simply defined by subtracting one from the likelihood ratios. Intuitively, the excess probability indicates the percentage increase in the probability to work in a given occupation if the parent works in this occupation relative to someone whose parents does not work in this occupation.

1.2.2 SOEP - descriptive results

Out of the total sample size of 742,822 person-year observations, I drop those who are not in the relevant age group, hence those below 16 and above 65 years, and those who are not in the labor force, like students or individuals caring for children or elderly, which leaves 490,535 person-year observations.[5] Since I am interested in intergenerational links, I only keep those individuals who have a parent in this subsample which leaves 107,524 observations. Finally, I exclude all individuals whose parent does not have any information on their occupation which generates the baseline dataset including 78,089 observations. Furthermore, for the analysis of regional labor demand, I can only employ SOEP data from 2011 onward because vacancy shares are only available from 2011 to 2021, which sums up to 28,620 person-year observations. For studying aspects which do not require regional information the baseline SOEP sample is used.

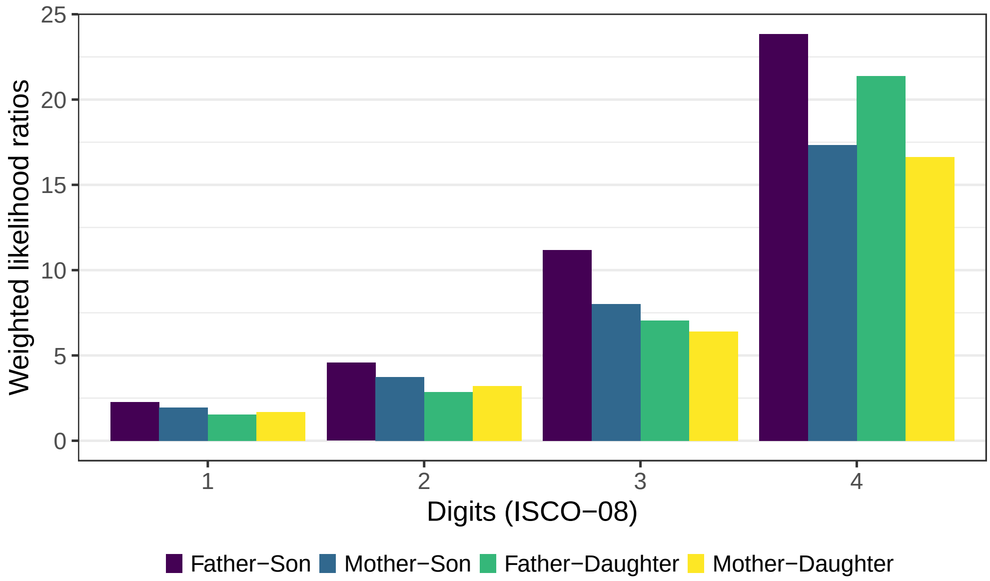
Splitting the baseline SOEP sample by gender reveals that sons make up around 56 percent and are thus slightly overrepresented. Note that children are followed up until their parents retire. Hence, some children might start their own family during this period, which might be a reason of daughters being underrepresented, as they leave the labor market after starting an own family to a larger share. Robustness checks are conducted only focusing on those children who still live in the same household as their parents because parent-child ties are arguably stronger for this subgroup.[6]

5. Tables 1.A.1 and 1.A.2 in Appendix 1.A list the different steps.

6. This subgroup amounts to 43,823 children-year observations and thus includes around 55 percent of the baseline sample.

Figure 1.2.1 depicts the weighted likelihood ratios following the ISCO-08 classification[7] for all four parent-child combinations and levels of occupational disaggregation, respectively. The ISCO-08 classification includes 10, 43, 130, and 436 different occupations for the digit levels 1 to 4.

Figure 1.2.1. Weighted likelihood ratios of occupational followers



Notes: Weighted likelihood ratios are computed according to Equation 1.2.1 including the period from 1984 to 2020.

This figure clearly indicates that persistence increases in the fineness of classifying occupations. The purple bar on the very left for example shows that sons were around 2.5 times as likely to work in a given occupation, defined at the 1-digit level, if their father also worked in this occupation relative to a son whose father worked in another occupation.[8] Examples of this broad level of disaggregation are the categories of *Legislators, senior officials, and managers* or *Craft and related trades workers*. For the finest level of classification, sons were more than 24 times as likely to work in a given occupation if their father worked in this occupation. Examples for this level of disaggregation are occupations like *Dentists*, *Roofers* or *Miners and Quarriers*. So moving from classifications of 1-digit to 4-digit increases persistence measured by weighted likelihood ratios by a factor of 10.

7. The SOEP data provides occupational information according to the ISCO-08 classification only from 2012 onward. Before 2012 it provides this information based on the ISCO-88 classification which I translated to the ISCO-08 classification based on schemes provided by the International Labour Organization.

8. Tables 1.A.6 and 1.A.7 in Appendix 1.A depict the likelihood ratios for each occupation defined at the 1-digit level separately.

While there is a high degree of heterogeneity across classification levels, the differences within classifications across the four parent-child combinations are relatively small. For the finest classification the probability for a son to work in a given occupation increases by factors of 24 or 21 if his father or his mother works in this occupation, respectively. For daughters the respective numbers are 18 and 17. Furthermore, while persistence is highest for father-son pairs for all levels of occupational disaggregation, there is no clear ordering for the remaining three pairs. Interestingly, these levels of persistence are not driven by self-employment as Table 1.A.5 in Appendix 1.A shows.

In order to compare these values with those documented by Lo Bello and Morchio (2022) for fathers and sons in the United Kingdom between 1991 and 2008, there are three adjustments to make. Next to changing the definition of likelihood ratios by dividing by the unconditional probability of a son/daughter working in a given occupation, I follow their assumptions and exclude soldiers and classify unemployed individuals according to the occupation of their next job. Doing so yields a weighted likelihood ratio of 2.39 for father-sons pairs at the 1-digit level which is still considerably larger than the 1.72 documented in Lo Bello and Morchio (2022), suggesting a relatively high persistence in occupational choices in Germany.[9]

1.2.3 BA data - descriptive results

In order to include information about regional labor market characteristics, I merge the SOEP data with regional and occupation-specific employment and vacancy shares provided by the German Federal Employment Agency (Bundesagentur für Arbeit, BA). This dataset provides annual employment and vacancy shares for 400 German regions and occupations based on the ISCO-08 classification up to 4-digit. This finest level of disaggregation includes 436 different occupations and thus provides me with 174,400 shares. Annual vacancy shares are computed based on all vacancies reported to the BA, around 600,000 each year, while employment shares are computed based on all employees who are subject to mandatory social insurance contributions, around 30 million individuals each year. As vacancy shares are potentially a very volatile proxy for regional labor demand, I conduct checks using employment shares which are a more robust measure.

In order for regional labor demand to play a role for intergenerational persistence in occupational choices and hence for social mobility, two conditions have to be fulfilled. First, there has to be some heterogeneity in regional labor demand

9. Table 1.A.4 in Appendix 1.A shows all weighted likelihood ratios after these adjustments. Unfortunately, the value for father-son pairs at the 1-digit classification is the only number that can be compared as Lo Bello and Morchio (2022) only look at father-son pairs, define the 2-digit level slightly finer, and do not have data for finer classifications.

for different occupations across Germany because otherwise regions would be irrelevant for occupational choices. Second, a large share of children needs to live in the same region as their parents, such that they face the same labor demand.

Figure 1.2.2. Occupation with highest vacancy rate in 2020 (ISCO-08, 2-digit)

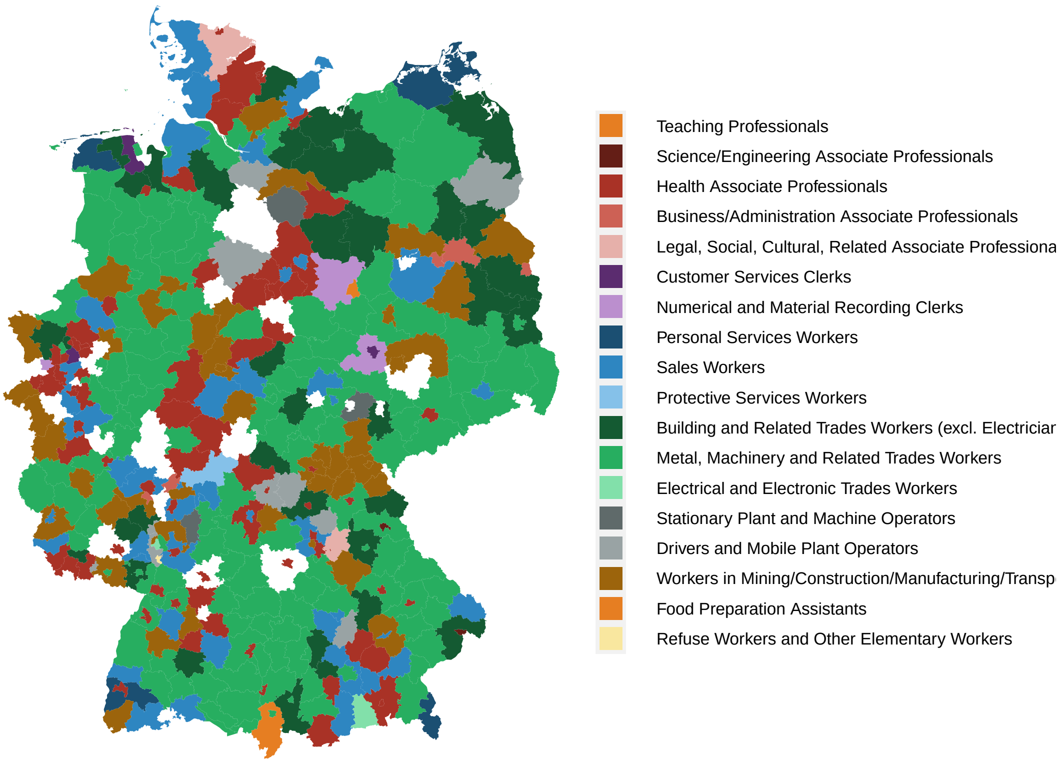


Figure 1.2.2 reveals a substantial heterogeneity in regional labor demand across Germany and hence provides evidence that the first condition is satisfied. It depicts the occupation with the highest number of vacancies, defined at the ISCO-08 2-digit level, for every region in Germany in 2020. Out of all 43 occupations of this classification, 18 have the highest number of vacancies in at least one region. One aspect becoming visible in this figure are the different mining locations in Germany, being colored in brown. For example, in the very West the Rhenish coal district is easily detectable. Hence, depending on the region one is living in, the regional labor demand for a given occupation can differ substantially.

Regarding the second condition, I find that depending on the parent-child combination between 82 and 86 percent of children in my sample live in the same region as their parents. This finding of workers being immobile, especially when having family ties in a given region, is consistent with what the literature has shown (Huttunen et al., 2018). Combining the high level of regional heterogeneity in labor demand across Germany with the immobility of workers suggests that regional labor demand potentially plays an important role for occupational choices and hence for social mobility. Intuitively, a son of a miner in a coal district might not necessarily become a miner himself because of his father's occupation but simply because it is the predominant occupation in this region. The next section describes the methodology to quantify this channel.

1.3 Empirical strategy

This section outlines the empirical strategies used for quantifying the relevance of regional labor demand for occupational persistence as well as for studying the impact of following into parents occupations on wages and unemployment risk.

1.3.1 Importance of regional labor demand for persistence

In order to quantify the importance of regional labor demand for intergenerational persistence in occupational choices, I compute weighted likelihood ratios conditioning on regional and occupation-specific vacancy shares using a logistic model. More formally, the regression reads

$$logit(\mathbb{1}(o_{i,t} = j)) = \alpha + \beta_1 \mathbb{1}(o^P_{i,t} = j) + \beta_2 \theta_{i,t} + \epsilon_{i,t},$$

where $\mathbb{1}(o_{i,t} = j)$ and $\mathbb{1}(o^P_{i,t} = j)$ are functions indicating whether child i and its parent are working in occupation j in year t, respectively. The vacancy share of occupation j in the region children i lives in year t is given by $\theta_{i,t}$.[10] Based on these regressions, I compute the predicted values of working in a specific occupation, conditional on the parent's occupation and the regional occupation-specific vacancy share.

Thus, the likelihood ratio of occupation j conditioning on the regional labor demand, formally

$$LR^{vac}_j = \frac{P\big(o = j \mid o^P = j, \theta\big)}{P\big(o = j \mid o^P \neq j, \theta\big)},$$

isolates the part of persistence which is independent of regional labor demand. A prominent example would be parental information networks or the transmission of abilities. Comparing the conditional and unconditional weighted likelihood ratios gives a measure of how important regional labor demand is for persistence.

10. As I am computing likelihood ratios separately for each of the four parent-child combinations, I am also account for potential gender differences.

Formally, the percentage reduction in persistence after conditioning on regional labor demand is given by

$$\theta^{share} = \frac{WLR - WLR^{vac}}{WLR - 1}.$$

Thus, θ^{share} describes the percentage reduction in persistence after conditioning on regional labor demand.

In order to put this number into context, I repeat the same exercise but now quantify the importance of children's education level on persistence. As education has been shown in the literature to be a key determinant for intergenerational persistence, it constitutes a relevant comparison. Analogously to before, I defined the share of persistence generated by education as

$$educ^{share} = \frac{WLR - WLR^{educ}}{WLR - 1}, \tag{1.3.1}$$

where WLR^{educ} is computed by weighting

$$LR_j^{educ} = \frac{P\left(o = j \mid o^P = j, e\right)}{P\left(o = j \mid o^P \neq j, e\right)}, \tag{1.3.2}$$

where e describes children's education level measured in years of education.

1.3.2 Impact of following on wages

Besides quantifying the impact of regional labor demand on persistence, I further document how following into the parent's occupation impacts labor market outcomes. In particular, I provide evidence on the impact on actual hourly gross wages and the annual risk of becoming unemployed for all parent-child combinations and years since the first full-time job. In order to identify the impact of working in the same occupation on wages, I run the following regression

$$log(wage_{i,t}) = \alpha + \beta follower_{i,t} + \gamma X_{i,t} + \epsilon_{i,t}, \tag{1.3.3}$$

where $wage_{i,t}$ is the actual hourly gross wage and $follower_{i,t}$ is an indicator function being equal to one if child i works in the same occupation as at least one of its parents in period t. Since the SOEP data provides occupational information according to the ISCO-08 classification only for 2013 onward, while it provides information according to the ISCO-88 classification for 1984 to 2017, occupations are defined according to the latter using the 4-digit classification. X is a set of control variables consisting of a third-degree age polynomial, gender, marital status, years of education, region, migration background as well as a second-order tenure polynomial, the firm size, and survey year. Importantly, X further includes the occupation.[11] Thus, the estimated coefficients hold within occupations. As I do not employ the BA data for this regression, I can apply the whole baseline SOEP sample.

In order to focus on children's first major job and abstract from potential smaller vacation or college jobs, I follow a similar strategy as proposed by Topel and Ward (1992). While they define labor market entry as the first quarter in which earnings exceed 70 percent of the minimum wage for full-time work given that the following four quarters do also satisfy this condition, I have to slightly deviate as Germany only introduced its first statuary minimum wage in 2015. Thus, I define labor market entry as the first year in which individuals work full-time given that they continue to do so in the following year.

1.3.3 Impact of following on unemployment risk

Next to differences in wages, I also study whether following into the parent's occupation impacts the probability of becoming unemployed. For doing so, I run the following regression

$$\mathbb{1}(u_{i,t+1} = 1) = \alpha + \beta follower_{i,t} + \gamma X_{i,t} + \epsilon_{i,t} \quad \text{if} \quad \mathbb{1}(e_{i,t} = 1),$$

where $\mathbb{1}(u_{i,t+1} = 1)$ and $\mathbb{1}(e_{i,t} = 1)$ indicate individuals who are full-time employed in period t but become unemployed in the period thereafter, $t+1$. As before $follower_{i,t}$ is equal to one if children i works in the same occupation as at least one of its parents and $X_{i,t}$ is the same set of control variables as in the wage regression. Hence, β describes the impact of working full-time in the same occupation as at least one of your parents on the likelihood of becoming unemployed next period relative to someone who works full-time in another occupation.

1.4 Results

This section presents the empirical results. First, it quantifies the relevance of regional labor demand for intergenerational persistence in occupational choices before studying how children with and without parents working in the same occupation differ with respect to hourly wages and unemployment risk.

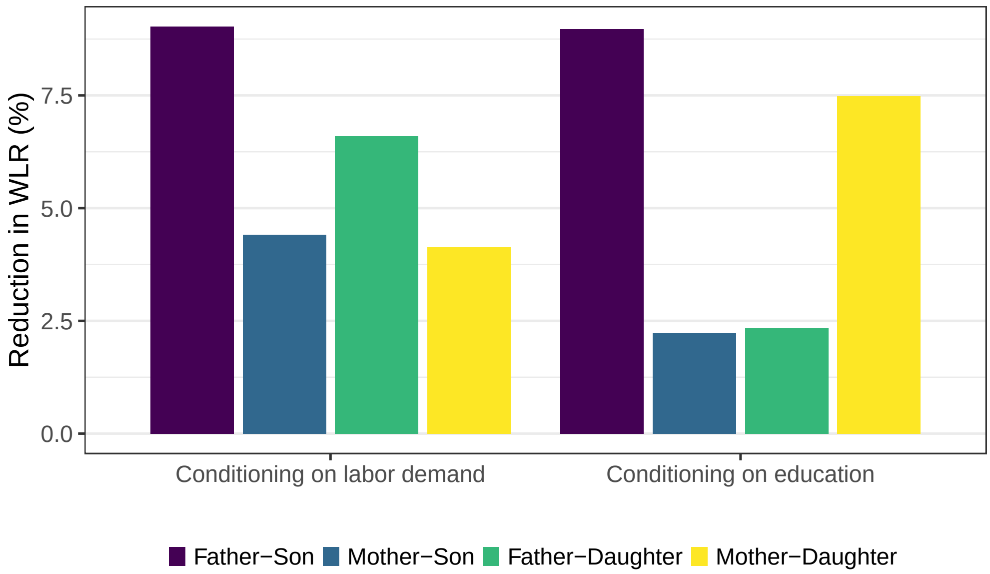
1.4.1 Importance of regional labor demand for persistence

Figure 1.4.1 depicts the percentage reductions in persistence after conditioning on regional labor demand and education, as defined in Equations 1.3.1

11. This set of control variables is the same as the one used in Lo Bello and Morchio (2022), except that I exclude smoking behavior due to data limitations.

and 1.3.2. Conditioning on regional labor demand, proxied by regional and occupation-specific vacancy shares, reduces persistence by around 5 to 10 percent. Conditioning on education, measured in years of schooling, generates persistence levels of a similar magnitude. While for father-son pairs it seem to be particularly important and explains around 13 percent, it is less important for cross-gender following. This result suggests that regional labor demand is a relevant factor for persistence in occupations and thus for social mobility. But it also shows that the largest share of persistence remains unexplained.

Figure 1.4.1. Reduction in WLRs after controlling for regional labor demand and education



Notes: For this figure, occupations are defined at the 4-digit level. As vacancy data is only available from 2011 onward, I also restrict the analysis for education on this subsample to guarantee comparability.

1.4.2 Impact of following on wages

Table 1.4.1 shows the impact of working in the same 4-digit occupation as at least one parent on the actual gross hourly wage depending on the time horizon since the first full-time job. Occupational followers have a significant wage premium of around 5.6 percent during the first two years, which fades out thereafter. As the mean actual gross hourly wage for this period and subgroup was around 10 Euros, this premium translates into an increased hourly wage of around 50 Cent. Thus, monthly and yearly gross income for occupational followers is around 80 and 1,000 Euros higher, respectively. When splitting the sample by education into those with and without high school degree, the coefficients indicate that the wage premium is almost entirely driven by the lower educated subsample, which has a highly significant initial wage premium of around 8 percent. Finally, looking at sons and daughters separately indicates that the impact for daughters seems to be slightly stronger.

Table 1.4.1. Impact of following on gross hourly wages

Specification	N	Coefficient				
		All	No HS	HS	Sons	Daughters
First 2 y. after first FT job	11,551	0.056**	0.082***	0.032	0.052	0.068*
		(0.025)	(0.031)	(0.038)	(0.032)	(0.039)
2 - 5 y. after first FT job	9,468	-0.018	0.011	-0.016	-0.035	0.046
		(0.026)	(0.060)	(0.027)	(0.035)	(0.041)
6 - 10 y. after first FT job	9,644	-0.020	0.121	-0.041	-0.048	0.047
		(0.025)	(0.076)	(0.027)	(0.034)	(0.034)
> 10 y. after first FT job	11,056	0.011	0.069	0.004	0.021	0.027
		(0.017)	(0.065)	(0.017)	(0.020)	(0.026)

Notes: This figure shows the effect of working in the same occupation as at least one of the parents on actual hourly gross wages. Occupations are defined according to the ISCO-88 4-digit and the ISCO-08 4-digit classifications for the time spans 1984 to 2012 and 2013 to 2020, respectively. Standard errors are clustered on the individual level and written in parentheses.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

1.4.3 Impact of following on unemployment risk

Table 1.4.2 depicts the results with respect to unemployment risk. Occupational followers have a significantly lower risk of becoming unemployed during the first five years after their first full-time job. Considering that the average probability of becoming unemployed for this group is 5 percent, the reduction by 2.2 percentage points almost halves children's unemployment risk.

Table 1.4.2. Impact of following on unemployment risk

Specification	N	Coefficient				
		All	No HS	HS	Sons	Daughters
First 2 y. after first FT job	9,708	-0.021***	-0.032***	-0.017**	-0.027***	-0.013
		(0.007)	(0.012)	(0.009)	(0.009)	(0.012)
2 - 5 y. after first FT job	7,814	-0.022***	-0.039*	-0.021***	-0.033***	-0.007
		(0.006)	(0.020)	(0.006)	(0.008)	(0.012)
6 - 10 y. after first FT job	8,461	-0.006	0.000	-0.005	-0.019*	0.002
		(0.008)	(0.019)	(0.009)	(0.011)	(0.014)
> 10 y. after first FT job	9,552	-0.006	-0.043	0.001	-0.006	-0.008
		(0.009)	(0.034)	(0.009)	(0.012)	(0.014)

Notes: This figure shows the effect of working in the same occupation as at least one of the parents on the probability of becoming unemployed the following year. Occupations are defined according to the ISCO-88 4-digit and the ISCO-08 4-digit classifications for the time spans 1984 to 2012 and 2013 to 2020, respectively. Standard errors are clustered on the individual level and written in parentheses.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Splitting the sample by education, shows that those without a high school degree do also benefit most from following, as their unemployment risk decreases by 3.2

to 3.9 percentage points. The average unemployment risk for this group is around 7 percent. While in terms of wages daughters seem to benefit more from following, sons benefit more with respect to unemployment risk. While for daughters the risk only decreases insignificantly, for sons the annual unemployment risk is reduced by around 3 percentage points.

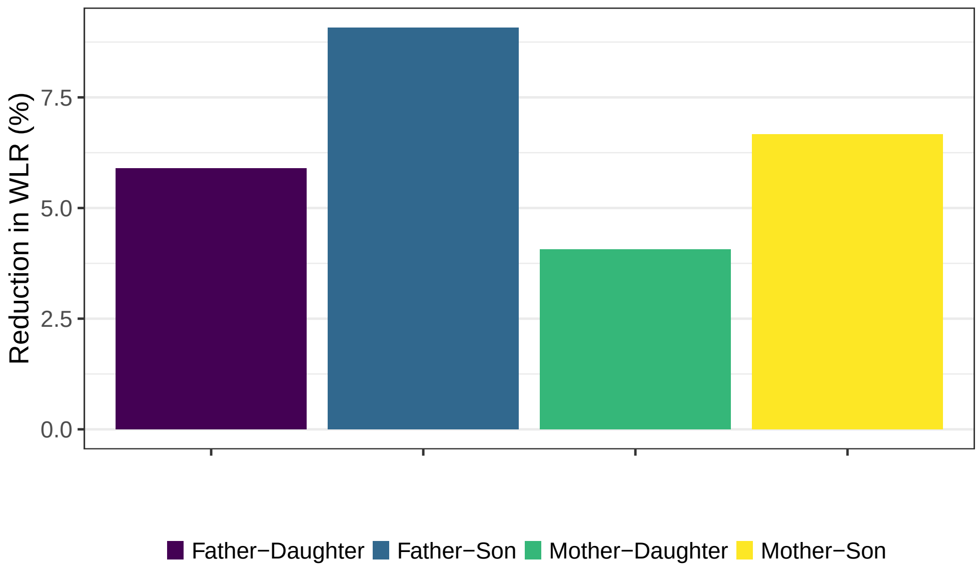
1.5 Robustness checks and discussion

In order to examine the robustness of my results, this section conducts several checks. Thereafter follows a discussion on the implications of these results.

1.5.1 Robustness checks

In order to ensure the plausibility and robustness of my main results, I conduct several checks. First, with respect to quantifying the importance of regional labor demand for persistence, I repeat the same exercise described in Section 1.3.1 but now I condition on employment instead of vacancy shares. The idea is that vacancy shares might be an imperfect measure for contemporaneous labor demand, as they are volatile and might thus not mirror actual labor market opportunities in a given occupation. Employment shares, however, are a much more stable measure and hence complement vacancy shares as proxy for labor demand.

Figure 1.5.1. Reduction in WLRs after controlling for employment shares



Notes: For this figure, occupations are defined at the 4-digit level. As employment data is only available from 2013 onward, this analysis is restricted to this subsample.

Figure 1.5.1 shows that resulting percentage reductions on persistence. For all four parent-child pairs, the reductions are very similar to the ones found using vacancy shares supporting the robustness of my main result.

In order to further investigate the impact of following into the parent's occupation, I conduct two checks. First, in order to check the robustness of the results, I exclude all children of self-employed parents as the wage premium and the reduced unemployment risk might be driven by self-employed who employ their own children.

Table 1.5.1. Impact of following on wages without children of self-employed

Specification	N	Coefficient				
		All	No HS	HS	Sons	Daughters
First 2 y. after first FT job	10,261	0.071***	0.065**	0.071*	0.065*	0.089**
		(0.025)	(0.032)	(0.038)	(0.034)	(0.038)
2 - 5 y. after first FT job	8,145	-0.002	-0.032	0.021	-0.012	0.046
		(0.024)	(0.050)	(0.026)	(0.034)	(0.036)
6 - 10 y. after first FT job	7,975	0.018	0.064	0.006	0.013	0.049
		(0.021)	(0.064)	(0.022)	(0.028)	(0.032)
> 10 y. after first FT job	9,127	0.020	0.075	0.015	0.044**	0.020
		(0.016)	(0.050)	(0.016)	(0.019)	(0.025)

Notes: This figure shows the effect of working in the same occupation as at least one of the parents on actual hourly gross wages excluding children of self-employed. Occupations are defined according to the ISCO-88 4-digit and the ISCO-08 4-digit classifications for the time spans 1984 to 2017 and 2018 to 2020, respectively. Standard errors are clustered on the individual level and written in parentheses.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Table 1.5.2. Impact of following on unemployment risk without children of self-employed

Specification	N	Coefficient				
		All	No HS	HS	Sons	Daughters
First 2 y. after first FT job	8,460	-0.017**	-0.028**	-0.013	-0.028**	-0.008
		(0.008)	(0.014)	(0.010)	(0.011)	(0.014)
2 - 5 y. after first FT job	6,618	-0.020***	-0.022	-0.023***	-0.029***	-0.007
		(0.007)	(0.024)	(0.006)	(0.010)	(0.013)
6 - 10 y. after first FT job	6,884	-0.002	0.008	-0.001	-0.007	0.003
		(0.010)	(0.023)	(0.013)	(0.014)	(0.017)
> 10 y. after first FT job	7,718	0.004	-0.030	0.009	0.008	-0.001
		(0.011)	(0.040)	(0.011)	(0.014)	(0.017)

Notes: This figure shows the effect of working in the same occupation as at least one of the parents on the probability of becoming unemployed next year excluding children of self-employed. Occupations are defined according to the ISCO-88 4-digit and the ISCO-08 4-digit classifications for the time spans 1984 to 2012 and 2013 to 2020, respectively. Standard errors are clustered on the individual level and written in parentheses.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Tables 1.5.1 and 1.5.2 show that this is not the case. When excluding children of self-employed, the initial wage premium for followers even increases to 7.1 percent and becomes significant to the one-percent significance level. Interestingly, the impact for children without a high school degree is slightly reduced, while the one for those individuals with a high school degree is stronger. This observation might indicate that lower educated children earn higher wages when working for self-employed parents, while the opposite is true for higher educated children. With respect to the reduction in unemployment risk, there are no substantial changes observable.

Table 1.5.3. Impact of following on wages - only children living in parents' household

Specification	N	Coefficient				
		All	No HS	HS	Sons	Daughters
First 2 y. after first FT job	10,294	0.068***	0.079***	0.061	0.056*	0.097**
		(0.023)	(0.028)	(0.038)	(0.031)	(0.038)
2 - 5 y. after first FT job	6,413	-0.001	0.033	-0.002	-0.028	0.059
		(0.030)	(0.056)	(0.035)	(0.041)	(0.046)
6 - 10 y. after first FT job	3,506	-0.054	0.038	-0.081*	-0.056	0.046
		(0.038)	(0.077)	(0.046)	(0.046)	(0.047)
> 10 y. after first FT job	2,680	-0.009	0.032	-0.023	-0.006	-0.041
		(0.043)	(0.081)	(0.053)	(0.054)	(0.080)

Notes: This figure shows the effect of working in the same occupation as at least one of the parents on actual hourly gross wages for the subgroup of children who live in their parents' household. Occupations are defined according to the ISCO-88 4-digit and the ISCO-08 4-digit classifications for the time spans 1984 to 2017 and 2018 to 2020, respectively. Standard errors are clustered on the individual level and written in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Table 1.5.4. Impact of following on unemployment risk - only children living in parents' household

Specification	N	Coefficient				
		All	No HS	HS	Sons	Daughters
First 2 y. after first FT job	8,567	-0.020***	-0.033***	-0.014	-0.027***	-0.010
		(0.008)	(0.012)	(0.011)	(0.010)	(0.014)
2 - 5 y. after first FT job	5,179	-0.032***	-0.067***	-0.023***	-0.051***	-0.014
		(0.007)	(0.021)	(0.008)	(0.009)	(0.017)
6 - 10 y. after first FT job	2,955	-0.005	-0.041	-0.000	-0.013	0.033
		(0.016)	(0.028)	(0.022)	(0.017)	(0.043)
> 10 y. after first FT job	2,124	0.005	-0.046	0.027	-0.033	0.115
		(0.038)	(0.069)	(0.048)	(0.043)	(0.085)

Notes: This figure shows the effect of working in the same occupation as at least one of the parents on the probability of becoming unemployed next year for the subgroup of children who live in their parents' household. Occupations are defined according to the ISCO-88 4-digit and the ISCO-08 4-digit classifications for the time spans 1984 to 2012 and 2013 to 2020, respectively. Standard errors are clustered on the individual level and written in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Second, in order to check the plausibility of the result, I restrict the sample to only those children who still live in their parents' household. This subgroup amounts to more than 52,000 children-year observations and thus includes around 55 percent of the baseline sample. The idea is that the relationship of these children to their parents is arguably closer and, if rather parental information networks than the transmission of innate abilities are the main driver of persistence, one would thus expect stronger results.

Tables 1.5.3 and 1.5.4 show that this is indeed the case. The initial wage premium rises to 6.8 percent and becomes significant at the one-percent level, supporting the plausibility of the presented results. While the impact on unemployment risk during the first two years hardly changes, it becomes stronger during years two to five and rises from 2.2 to 3.2 percentage points. Interestingly, the difference in impacts for sons and daughters also increases suggesting that the unemployment risk for the former decreases by 5.1 and for the latter by 1.4 percentage points during this period. This result that the impacts of following into the parent's occupation become stronger when parent-child ties are closer also supports rather a theory of parental information networks than of transmitting innate abilities.

1.5.2 Discussion

My main result, indicating that regional labor demand is an important driver of intergenerational persistence in occupational choices and thus of social mobility, has potentially important implications on the discussion about the substantial decline in interstate mobility in the United States over the last decades (Kaplan and Schulhofer-Wohl, 2017; Molloy et al., 2011; Molloy et al., 2017). While in 1990 around 3 percent of Americans moved between states each year this number has fallen by half in the following 30 years (Kaplan and Schulhofer-Wohl, 2017). Two causes for this decline have been discussed in the literature, which have opposing implications for my main result on this discussion. On the one hand, Kaplan and Schulhofer-Wohl (2017) argue that interstate mobility fell because geographic specificity of returns to occupations declined and workers' ability to learn about other locations before moving both increased. Based on this theory lower regional mobility does not imply lower social mobility because with more similar labor markets, social advancement is possible even without regional mobility. On the other hand, Cooke (2013) find that the fall in migration is correlated with more people living in dual-earner households which potentially made households less mobile. If this channel dominates and my results also hold for the United States, the reduction in regional mobility does translate into lower social mobility. Hence, a fruitful path for future research could be to study whether my results are generalizable to other countries, in particular for the United States.

The results on the impact of following into the parent's occupation are qualitatively as well as quantitatively very similar to what has been found in the context of referrals more general (Brown et al., 2016; Burks et al., 2015; Dustmann et al., 2016; Glitz and Vejlin, 2021). Glitz and Vejlin (2021) apply comprehensive Danish administrative data and show that workers who found their jobs through former coworkers' referrals earn initially 4.6 percent higher wages and are 2.3 percentage points less likely to leave their firm during the first year. They rationalize this finding with a learning model built in Jovanovic (1979) and further developed in Simon and Warner (1992) and Dustmann et al. (2016). In this model, firms can either hire new employees via the external or the referral market. The core idea is that for those hired via the latter uncertainty about match-specific quality is lower as referrals provide information which the firm and the employee otherwise would not have. As workers are partially insured against low realizations of their productivity by simply leaving the firm, potential wage growth is higher for employees hired via the external market. Consequently, referral hires have higher reservation wages and turn down wage offers that identical external hires would accept, resulting in an initial wage premium for those hired via referrals. Furthermore, this subgroup is on average better matched. As uncertainty about match-specific quality resolves over time, workers with low productivity realizations separate from the firm resulting in higher unemployment risk for individuals hired via the external market, and both the wage premium and differences in unemployment risk fade out with tenure.

Not only do my results replicate these model predictions, the finding that the impact of following is particularly strong for children without a high school degree does also fit in this theory very well. As lower educated individuals have fewer school degrees and certificates as signals of their abilities, the uncertainty about the match quality is arguably higher and the impact of parental information thus stronger. Hence, my results are in line with the model predictions and therefore expand the supporting evidence in two dimensions. First, differently to the supporting literature so far, which defines following based on working in the very same firm (Brown et al., 2016; Burks et al., 2015; Dustmann et al., 2016; Glitz and Vejlin, 2021), this paper defines it based on working in the same finely classified occupation. This broader definition of followers has two advantages. First, it allows accounting for parental networks beyond a particular firm, which might be especially relevant for Germany with its large number of small craft businesses. Second, it is more suitable for studying the intergenerational transmission of abilities and skills as they are arguably not firm but rather occupation-specific. The second and probably more important dimension in which this paper extends the empirical evidence in favor of the theory developed in Dustmann et al. (2016) is that it looks at intergenerational occupational following behavior, and thus studies the type of social networks which has been shown to be most important for individual labor market outcomes: immediate family members (Eliason et al., 2022). The fact that my results are not only qualitatively but also quantitatively very similar to what has been found by Glitz and Vejlin (2021) for former coworkers further suggests that genes and thus the transmission of innate abilities are not of first-order importance for the following behavior. But even when agreeing on parental information networks being the main driver behind the persistence, the welfare consequences are not clear. On the one hand, the literature on referrals generally models this channel as welfare improving by reducing initial uncertainty about match-specific quality. For example, Dustmann et al. (2016) estimate that referrals, through the provision of additional information, increase total welfare in the economy by 0.62 percent. On the other hand, Lo Bello and Morchio (2022) model parental information networks rather as a form of nepotism, which results in children not working in the occupation in which they have a competitive advantage in. Hence, they find that shutting down parental networks increases welfare by 0.3 percent in consumption equivalent variation. Therefore, an interesting path for future research could be to combine both channels in a structural model and study the resulting impact of persistence on welfare.

1.6 Conclusion

In this paper, I study the underlying mechanisms behind the empirical observation that many children follow into their parent's occupation. In particular, I quantify how much of the persistence can be accounted for by a channel which the literature has abstracted from so far: regional labor demand. For that purpose regional and occupation-specific annual vacancy shares, computed based on all vacancies reported to the German Federal Employment Agency, are merged with the German Socioeconomic Panel (SOEP).

I find that controlling for regional labor demand, proxied by these vacancy shares, decreases the persistence by up to 10 percent when classifying occupations based on the finest level. This impact is of the same magnitude as controlling for children's education does and suggests that regional labor demand is of substantial importance for occupational persistence and thus for social mobility. Furthermore, I document that the degree of occupational following is relatively homogeneous across parent-child pairs. A child is around 20 times as likely to work in a given occupation if the parent works in this occupation compared to a child whose parent works in another occupation. Lastly, I show that children who follow into their parent's occupation experience a wage premium of around 6 percent during the first two years of their first full-time job. Also their annual unemployment risk halves during the first five years. Both results are primarily driven by those individuals without a high school degree. These results are qualitatively as well as quantitatively very similar to what has been found for referrals based on minority groups (Dustmann et al., 2016) and former coworker (Glitz and Vejlin, 2021), supporting the learning model developed in Dustmann et al. (2016). Consequently, the transmission of innate abilities does not seem to be of first-order importance but, next to regional labor demand, rather parental information networks are the major driver behind the following behavior of children.

For future research, there are at least two promising paths to take. First, it would be interesting to see whether the empirical results found in this paper also hold in other countries. In particular the case of the United States would be interesting as it could provide new implications for the fall in interstate migration observed over the last 40 years. Second, since, next to regional labor demand, parental networks seem to be the main driver behind the persistence in occupational choices, modeling this channel in greater detail and particularly focusing on its impact on the allocation of talent may yield new insights. So far, it has either been exclusively modeled as efficiency improving by reducing match-specific uncertainty, as in Dustmann et al. (2016), or as exclusively deteriorating efficiency as a form of nepotism, as in Lo Bello and Morchio (2022). Incorporating both channels in a structural model can thus yield new insights into the relative importance of both effects.

References

Aina, Carmen, and Cheti Nicoletti. 2018. "The intergenerational transmission of liberal professions." *Labour Economics* 51: 108–20.

Bilal, Adrien. 2021. "The geography of unemployment." Report. National Bureau of Economic Research.

Blau, Peter M, and Otis Dudley Duncan. 1967. "The American occupational structure." *ERIC*,

Brown, Meta, Elizabeth Setren, and Giorgio Topa. 2016. "Do informal referrals lead to better matches? Evidence from a firm's employee referral system." *Journal of Labor Economics* 34 (1): 161–209.

Burks, Stephen V, Bo Cowgill, Mitchell Hoffman, and Michael Housman. 2015. "The value of hiring through employee referrals." *Quarterly Journal of Economics* 130 (2): 805–39.

Caucutt, Elizabeth M, and Lance Lochner. 2020. "Early and late human capital investments, borrowing constraints, and the family." *Journal of Political Economy* 128 (3): 1065–147.

Cooke, Thomas J. 2013. "Internal migration in decline." *Professional Geographer* 65 (4): 664–75.

Dal Bó, Ernesto, Pedro Dal Bó, and Jason Snyder. 2009. "Political dynasties." *Review of Economic Studies* 76 (1): 115–42.

Dauth, Wolfgang, Sebastian Findeisen, Enrico Moretti, and Jens Suedekum. 2022. "Matching in cities." *Journal of the European Economic Association* 20 (4): 1478–521.

Doi, Suhail AR, Polychronis Kostoulas, and Paul Glasziou. 2022. "Likelihood ratio interpretation of the relative risk." *BMJ Evidence-Based Medicine*,

Dustmann, Christian, Albrecht Glitz, Uta Schönberg, and Herbert Brücker. 2016. "Referral-based job search networks." *Review of Economic Studies* 83 (2): 514–46.

Eliason, Marcus, Lena Hensvik, Francis Kramarz, and Oskar Nordström Skans. 2022. "Social connections and the sorting of workers to firms." *Journal of Econometrics*,

Glitz, Albrecht, and Rune Vejlin. 2021. "Learning through coworker referrals." *Review of Economic Dynamics* 42: 37–71.

Granovetter, Mark S. 1973. "The strength of weak ties." *American Journal of Sociology* 78 (6): 1360–80.

Heckman, James J, and Stefano Mosso. 2014. "The economics of human development and social mobility." *Annu. Rev. Econ.* 6 (1): 689–733.

Huttunen, Kristiina, Jarle Møen, and Kjell G Salvanes. 2018. "Job loss and regional mobility." *Journal of Labor Economics* 36 (2): 479–509.

Jovanovic, Boyan. 1979. "Job matching and the theory of turnover." *Journal of Political Economy* 87 (5, Part 1): 972–90.

Kaplan, Greg, and Sam Schulhofer-Wohl. 2017. "Understanding the long-run decline in interstate migration." *International Economic Review* 58 (1): 57–94.

Kline, Patrick, and Enrico Moretti. 2013. "Place based policies with unemployment." *American Economic Review* 103 (3): 238–43.

Kramarz, Francis, and Oskar Nordström Skans. 2014. "When strong ties are strong: Networks and youth labour market entry." *Review of Economic Studies* 81 (3): 1164–200.

Kuhn, Moritz, Iourii Manovskii, and Xincheng Qiu. 2021. "The geography of job creation and job destruction." Report. National Bureau of Economic Research.

Lentz, Bernard F, and David N Laband. 1989. "Why so many children of doctors become doctors: Nepotism vs. human capital transfers." *Journal of Human Resources*, 396–413.

Lo Bello, Salvatore, and Iacopo Morchio. 2022. "Like father, like son: Occupational choice, intergenerational persistence and misallocation." *Quantitative Economics* 13 (2): 629–79.

Mocetti, Sauro. 2016. "Dynasties in professions and the role of rents and regulation: Evidence from Italian pharmacies." *Journal of Public Economics* 133: 1–10.

Molloy, Raven, Christopher L Smith, and Abigail Wozniak. 2011. "Internal migration in the United States." *Journal of Economic perspectives* 25 (3): 173–96.

——, 2017. "Job changing and the decline in long-distance migration in the United States." *Demography* 54 (2): 631–53.

Moretti, Enrico. 2010. "Local labor markets." Report. National Bureau of Economic Research.

Simon, Curtis J, and John T Warner. 1992. "Matchmaker, matchmaker: The effect of old boy networks on job match quality, earnings, and tenure." *Journal of Labor Economics* 10 (3): 306–30.

Topel, Robert H, and Michael P Ward. 1992. "Job mobility and the careers of young men." *Quarterly Journal of Economics* 107 (2): 439–79.

Appendix 1.A Additional figures and tables

Table 1.A.1. Sample sizes

	N
Total sample	742,822
With parent in SOEP	151,854
Relevant age group (16-65)	149,589
With occ. info	108,827
Parents with occ. info	62,303
Final sample (baseline)	62,303
Final sample (for BA data)	18,784

Notes: This table presents the numbers of person-year observations during the data cleaning process including all years from 1984 to 2020.

Table 1.A.2. Family positions

	N	Share (percent)
< 20 years	8,522	13.7
20-24 years	18,817	30.2
25-29 years	13,179	21.1
30-34 years	8,949	14.4
> 34 years	12,836	20.6
Son	34,935	56.3
Daughter	27,098	43.7

Notes: This table depicts the number and the relative share of family positions in the final sample including all years from 1984 to 2020.

Table 1.A.3. Percentage share of occupational follower

Specification	N	Follower (Share in Percent)			
		Digit 1	Digit 2	Digit 3	Digit 4
Father - Sons	25,822	27.81	16.63	10.62	8.36
Mother - Sons	25,912	16.71	7.87	3.52	2.89
Father - Daughters	21,284	15.78	7.00	3.68	2.59
Mother - Daughters	20,870	26.65	15.68	9.93	8.80

Notes: This figure shows the percentage shares of occupational followers for different parent-child combinations and degrees of occupational classification. It includes data from the baseline SOEP sample ranging from 1984 to 2020 and is defined according to the ISCO-88 and ISCO-08 classifications for the years 1984 to 2017 and 2018 to 2020, respectively.

Table 1.A.4. WLRs of occupational followers - definition as in Lo Bello and Morchio (2022)

Specification	All	Weighted Likelihood Ratios			
		Digit 1	Digit 2	Digit 3	Digit 4
Father - Sons	19,647	2.39	3.87	11.08	28.67
Mother - Sons	19,187	1.91	2.77	6.21	17.27
Father - Daughters	15,932	1.58	2.25	7.35	14.68
Mother - Daughters	15,149	2.15	3.30	8.99	18.02

Notes: This figure shows the likelihood ratios as defined in Lo Bello and Morchio (2022) by dividing the conditional probability of working in a given occupation if the parent works in this occupation by the unconditional probability of working in this occupation for different parent-child combinations and levels of disaggregation according to the ISCO-88 classification. As in Lo Bello and Morchio (2022) soldiers are excluded and unemployed are classified according to their next occupation.

Table 1.A.5. WLRs of occupational followers - ISCO-88 - without self-employed

Specification	All	Weighted Likelihood Ratios			
		Digit 1	Digit 2	Digit 3	Digit 4
Father - Sons	16,760	2.36	3.75	10.04	27.45
Mother - Sons	16,150	1.76	2.79	6.11	16.97
Father - Daughters	13,010	1.52	2.22	6.92	11.80
Mother - Daughters	12,537	2.07	3.16	8.38	16.15

Notes: This figure shows the likelihood ratios as defined in Section 2 for different parent-child combinations and levels of disaggregation according to the ISCO-88 classification without self-employed children and children of self-employed parents.

Table 1.A.6. Likelihood ratios according to ISCO-88 1-digit

	FS	MS	FD	MD
Armed Forces	7.33	.	.	.
Legislators, senior officials and managers	1.87	1.30	2.51	5.39
Professionals	4.15	3.46	3.74	3.23
Technicians and associate professionals	1.64	1.19	1.16	1.40
Clerks	2.31	1.64	1.28	1.44
Service, shop and market sales workers	2.22	1.33	1.08	1.58
Skilled agricultural and fishery workers	18.36	15.94	2.52	2.02
Craft and related trades workers	1.49	1.40	1.71	4.10
Plant and machine operators and assemblers	2.68	1.68	2.45	7.87
Elementary occupations	2.96	1.89	2.22	3.70
Weighted average	2.47	1.91	1.58	2.15
Observations	19,996	19,490	15,936	15,161

Notes: This table presents the likelihood ratios according to the ISCO-88 1-digit classification for observations from 1984 to 2017 for the four different parent-child combinations. The observations refer to the number of sons/daughters with a father/mother being also full-time employed.

Table 1.A.7. Likelihood ratios according to ISCO-08 1-digit

	FS	MS	FD	MD
Legislators, senior officials and managers	5.93	2.38	0.61	6.04
Professionals	3.19	2.62	2.77	3.18
Technicians and associate professionals	1.92	1.33	1.21	1.38
Clerks	2.21	1.34	1.52	1.66
Service, shop and market sales workers	2.64	1.20	1.07	1.55
Skilled agricultural and fishery workers	17.51	32.66	.	.
Craft and related trades workers	1.96	1.28	1.50	4.07
Plant and machine operators and assemblers	3.20	1.45	1.07	11.12
Elementary occupations	3.30	1.62	1.59	3.40
Weighted average	2.75	2.14	1.45	2.11
Observations	4,731	5,958	4,177	5,205

Notes: This table presents the likelihood ratios according to the ISCO-08 1-digit classification for observations from 2013 to 2020 for the four different parent-child combinations. The observations refer to the number of sons/daughters with a father/mother being also full-time employed.

Table 1.A.8. Impact of following on wages - until 2017 only using ISCO-88 data

Specification	N	Coefficient				
		All	No HS	HS	Sons	Daughters
First 2 y. after first FT job	11,330	0.050**	0.080***	0.014	0.050*	0.060*
		(0.023)	(0.028)	(0.036)	(0.030)	(0.035)
2 - 5 y. after first FT job	9,360	-0.019	0.027	-0.020	-0.048	0.041
		(0.024)	(0.050)	(0.026)	(0.033)	(0.037)
6 - 10 y. after first FT job	9,631	-0.033	0.095*	-0.054**	-0.053*	0.039
		(0.023)	(0.054)	(0.026)	(0.032)	(0.029)
> 10 y. after first FT job	11,040	0.001	0.056	-0.009	0.008	0.016
		(0.016)	(0.049)	(0.016)	(0.019)	(0.025)

Notes: This figure shows the effect of working in the same occupation as at least one of the parents on actual hourly gross wages. Occupations are defined according to the ISCO-88 4-digit classification for the time period 1984 to 2017. Standard errors are clustered on the individual level and written in parentheses.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Table 1.A.9. Impact of following on unemployment risk - until 2017 only using ISCO-88 data

Specification	N	Coefficient				
		All	No HS	HS	Sons	Daughters
First 2 y. after first FT job	9,671	-0.023***	-0.032***	-0.015*	-0.028***	-0.012
		(0.007)	(0.011)	(0.008)	(0.009)	(0.011)
2 - 5 y. after first FT job	7,813	-0.019***	-0.043**	-0.016**	-0.031***	-0.003
		(0.007)	(0.020)	(0.007)	(0.008)	(0.012)
6 - 10 y. after first FT job	8,470	-0.007	-0.004	-0.005	-0.019*	0.003
		(0.007)	(0.018)	(0.009)	(0.010)	(0.013)
> 10 y. after first FT job	9,592	-0.006	-0.023	0.002	-0.001	-0.015
		(0.009)	(0.033)	(0.009)	(0.012)	(0.013)

Notes: This figure shows the effect of working in the same occupation as at least one of your parents on actual hourly gross wages. Occupations are defined according to the ISCO-88 4-digit classification for the time period 1984 to 2017. Standard errors are clustered on the individual level and written in parentheses.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

References

Lo Bello, Salvatore, and Iacopo Morchio. 2022. "Like father, like son: Occupational choice, intergenerational persistence and misallocation." *Quantitative Economics* 13 (2): 629–79.

Chapter 2

Distributional Consequences of Climate Policies

Joint with Moritz Kuhn

2.1 Introduction

Policies to slow climate change are high on the policy agenda of governments around the world. With two-thirds of total carbon emissions coming from household consumption, household consumption is at the center of the discussion on how to reduce carbon emissions. A wide range of climate taxes and subsidies have been proposed to increase the uptake of green, carbon-neutral consumer goods. However, a key question in times of high inequality is whether such policies will have adverse distributional consequences and can find majorities among the electorate. So far, quantitative answers to this question are scarce. The aim of this paper is to fill this gap by providing a quantitative analysis of different tax and transfer policies in terms of their reduction-redistribution trade-off.

As a first step, we use rich consumption data from the German Income and Consumption Survey (*Einkommens- und Verbrauchsstichprobe*, EVS) together with the EXIOBASE dataset, which provides information on the amount of carbon emissions produced by different consumption goods. Combining these two sources, we show that long-term consumption commitments, such as cars and heating systems, and their complements, such as gasoline and oil, are key to reducing carbon emissions. They generate more than 35 percent of total household carbon emissions while accounting for only about 11 percent of household expenditures. We also confirm the finding that high-income households have significantly higher carbon footprints than low-income households. This fact creates a policy trade-off between speeding up the reduction of carbon emissions through subsidies and the distributional consequences of such subsidies. A policy aimed at rapid reduction must be attractive to high-income households, which in turn implies that its financing will lead to transfers from low-income to high-income households. The redistribution will be further exacerbated during the transition period as high-income households are faster in adopting new carbon-neutral technologies, so that they receive subsidies earlier and would pay less carbon taxes if used for financing. To assess and quantify this reduction-redistribution trade-off, we build in the second step a quantitative life-cycle model with consumption commitments that can be either brown, e.g. traditional gasoline- or diesel-powered cars or oil heaters, or green and carbon neutral, e.g. electric cars or heat pumps. Using the calibrated model, we evaluate different subsidy policies, percentage and lump-sum subsidies for green commitment goods, in combination with different financing schemes, taxes on labor income, consumption taxes, or carbon taxes. We compare these different policies in terms of how quickly the adjustment process to green commitment goods takes place and what their distributional consequences are in terms of net transfers between low and high income households. We take these distributional consequences to determine if a policy mix will find political support or if the climate policy would fail in the political process.

We calibrate our model to Germany in 2018 and study the adoption process of green consumption commitment goods over time. We demonstrate that the model matches average consumption pattern for commitment consumption, saving behavior by income groups over the life-cycle, and importantly the available evidence on heterogeneity in adoption rates between high- and low-income households. Starting in 2024, we implement different policy mixes and compare the consequences for the adoption process to a situation with no climate policy. We always compare transition paths 25 years into the future and impose that each policy mix must have a balanced budget for the current population over the transition path, so that subsidies for green commitment goods must be financed by taxes. Comparing the transition paths for different policy mixes, we find that a policy of a percentage subsidy for the green commitment good increases the speed of adoption the most and generates a majority of winners if it is financed by a progressive income tax. Non-progressive taxes instead redistribute from a majority of low-income households to high-income households, with the worst distributional consequences of a carbon tax that is falling disproportionately on low-income households as they are slowest in adopting the green commitment good. The quantitative effects in terms of redistribution across policy mixes are substantial. The policy that combines a percentage subsidy on green commitment goods with a carbon tax reduces emissions the most, but leads to negative net transfers for low-income households of up to 450 euros per year and net transfers for high-income households of up to 650 euros per year. A less redistributive policy combining a lump-sum subsidy for green commitment goods with a linear income tax leads to positive net transfers for the majority of households in today’s economy, but at the cost of almost 20 percent less reduction in carbon emissions at the end of the transition period. The percentage subsidy financed by a progressive tax will lead to a strong reduction in emissions with one out of five households adopting the green carbon-neutral consumption good at the end of the transition period compared to less than one out of ten households without any climate policy. Importantly, the progressive financing will avoid net transfers from low-income to high-income households and will therefore lead to a majority of households supporting this policy. We also study a policy that is popular in the public debate and that combines a carbon tax to increase the user cost of commitment consumption with transfer payments to counteract redistributive effects from higher taxes on carbon emissions. When we compare this policy to the other policy mixes with explicit subsidies, we find that it yields similar distributional outcomes as the progressive tax financing but leads to an order of magnitude smaller reduction of carbon emissions. To match the same reduction in carbon emissions, the tax has to be 2.7-times higher than in the baseline case and will yield annual transfers of 2,000 Euros per household or 82 billion Euros at the level of the German macroeconomy. Such an high carbon tax would also have effects on inflation rates. We find that the price level would increase on average by 4.9pp and by 5.3pp for low-income households in case of the high carbon tax. By contrast, the percentage subsidy will lower the average price level by 0.2pp.

This paper contributes to three strands of literature. First, we contribute to the literature on consumption commitments, building on Chetty and Szeidl (2007) and Chetty and Szeidl (2016). They show that consumption commitments constitute a considerable share of household's consumption and are important to explain their consumption behavior. Other papers have examined the impact of commitment goods on wage rigidities (Postlewaite et al., 2008), housing consumption (Shore and Sinai, 2010), marriage behavior (Santos and Weiss, 2016), and unemployment insurance (Segovia, 2021). We contribute by first documenting as a novel fact that consumption commitments are highly carbon-intensive and thus key to the study of policies to reduce carbon emissions. Second, we contribute by developing a quantitative life-cycle model to study the trade-off between reducing carbon emissions and redistributive consequences of different climate policies with consumption commitments.

Second, there is a large literature measuring environmental footprints for different countries and subgroups (Duarte et al., 2012; Hardadi et al., 2021; Isaksen and Narbel, 2017; Kerkhof et al., 2008; Miehe et al., 2016; Perobelli et al., 2015; Wiedenhofer et al., 2017). A key finding of this literature is that carbon emissions increase along the income distribution. Most important for our work is Hardadi et al. (2021). We rely on their approach of linking consumption categories and emissions data to compute carbon footprints. Relative to the literature, we add the distinction between commitment and non-commitment consumption and document that consumption commitments and their complements contribute a substantial share to household emissions. We evaluate the consequences and trade-offs of this heterogeneity for policy based on a structural model.

Finally, there are several studies that assess the distributional consequences of carbon pricing. An overview of the empirical literature is provided by Ohlendorf et al. (2021). Känzig (2021) examines this question using institutional features of the EU ETS and high-frequency data. In particular, he shows that poor households are more affected by increases in carbon taxes than richer ones. Glaeser et al. (2022) shows that gasoline taxes are regressive and are likely to become even more so in the future as richer households buy more electric cars. 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 the optimal policy differs substantially between the two groups. Households in the current steady state prefer uniform, lump-sum rebates, while households in the future steady state prefer reducing existing distortionary taxes. Relatedly, Fried et al. (2022) study the question of the optimal return of carbon tax revenues to households from an efficiency perspective. They find that using two-thirds of the carbon tax revenues to reduce the distortionary tax on capital income is welfare-maximizing. Cavalcanti et al. (2020) provide a rich unified framework, integrating worker heterogeneity within a multi-sectoral general equilibrium model with input-output linkages to study the aggregate and distributional consequences of carbon taxes across and within countries. For the United States they find that aggregate output would decrease by at most 0.8 percent when increasing carbon taxes to achieve its original Paris Agreement goal of reducing emissions, while in China output would decrease by at most 3.7 percent. Within countries, they find that workers with a comparative advantage in dirty energy production experience the largest welfare losses, while those working in the green energy sector benefit from a carbon tax. Related to our work in terms of economic mechanism is Lanteri and Rampini (2023) who study the adoption of clean technologies by heterogeneous firms and find that clean technologies require larger down payments, leading financially constrained, smaller firms to optimally invest in dirtier and older capital than unconstrained, larger firms. We contribute to this literature in two ways. First, we highlight the role of consumption commitments for household carbon emissions. Second, we explicitly account for consumption commitments and their differences in adjustment patterns across households when studying a rich set of policy mixes combining different subsidies and financing instruments.

The remainder of the paper is structured as follows. In Section 2.2, we describe the data for the empirical analysis and present our empirical results. In Section 2.3, we introduce the structural model, describe the calibration, and discuss the model fit. In Section 2.4, we conduct the policy experiments and quantify the reduction-redistribution trade-off. We also summarize our extensive sensitivity analysis that we provide in the Appendix 2.B. Section 2.5 concludes.

2.2 Data and empirical results

For our analysis, we combine data from two different sources to study the distribution of carbon emissions at the household level. First, we use the German Income and Consumption Survey (*Einkommens- und Verbrauchsstichprobe*, EVS). The EVS data provide repeated cross sections on consumption expenditures of households similar to the U.S. *Consumer and Expenditure Survey* (CEX). The EVS provides detailed information on around 43,000 households (0.1 percent of the German households) and sample weights allow to construct representative statistics for the entire German population. It is collected every five years and is used as the source for the consumption basket of the German CPI. We employ the most recent wave with data from 2018.

As a second data source, we use the EXIOBASE v3.6 in order to quantify the carbon emissions generated by different consumption goods. This dataset is compiled from multi-regional input-output tables and differentiates between 44 countries and five rest of the world regions, 163 industries, and 200 products.[1] We consider total emissions of consumption as the sum of direct emissions, e.g. emissions from driving a car, and indirect emissions, e.g. emissions from transporting a banana from South America to Germany (Hardadi et al., 2021). For direct emissions, we take aggregate emissions data from the German Statistical Office and distribute them to households based on their consumption expenditures. For indirect emissions, we follow Hardadi et al. (2021) and impute carbon emissions to consumption expenditures by linking the consumption categories of the EVS to those of the EXIOBASE. Our imputation differs from Hardadi et al. (2021) in two minor dimensions. First, they estimate carbon footprints for an average household and for eleven income groups. We impute carbon emissions of consumption at the household level which allows for a flexible aggregation of households. Second, they correct for expenditure underreporting in the EVS data. We also compute results corrected for expenditure underreporting as robustness but find differences to be negligible for our analysis. We therefore abstain from this adjustment in our baseline analysis.[2]

1. For more information see Stadler et al. (2018).

2. Adjusting consumption for underreporting increases carbon footprints along the entire income distribution. Carbon emissions increase on average by 11 percent but changes are hump-shaped along the income distribution with an increase at the bottom and the top of 7 percent and 8 percent respectively. The share of consumption commitments increases on average from 37 percent to 40 percent when accounting for underreporting what further increases the role of consumption commitments for emissions.

We will rely on the EVS 2018 data as our main data for the empirical analysis and for calibrating the model. For the calibration, we will supplement the EVS data with data from the *RWI-GRECS: German Residential Energy Consumption Survey*, short GRECS.[3]

In our empirical analysis, we distinguish between commitment and other consumption goods. This concept of consumption commitments was studied in a series of papers by Chetty and Szeidl (Chetty and Szeidl (2007) and Chetty and Szeidl (2016)). While their definition includes shelter, cars (excluding gas and maintenance), apparel, furniture, appliances, and health insurance, we depart from this definition in two ways. First, we focus on those consumption commitments which are mostly affected by climate policies, for example, cars and heating systems. Second, we add the complements of these consumption goods, like gasoline for cars and natural gas or oil for heating systems to commitment consumption. This definition captures the specific commitment property of these goods that households need to consume a certain amount of the complements in order to make use of the commitment good itself. Specifically, we consider the expenditure for consumption commitments with carbon emissions including cars, motor bikes, fuels, gas, liquid fuels, coal, wood, and other solid fuels.[4]

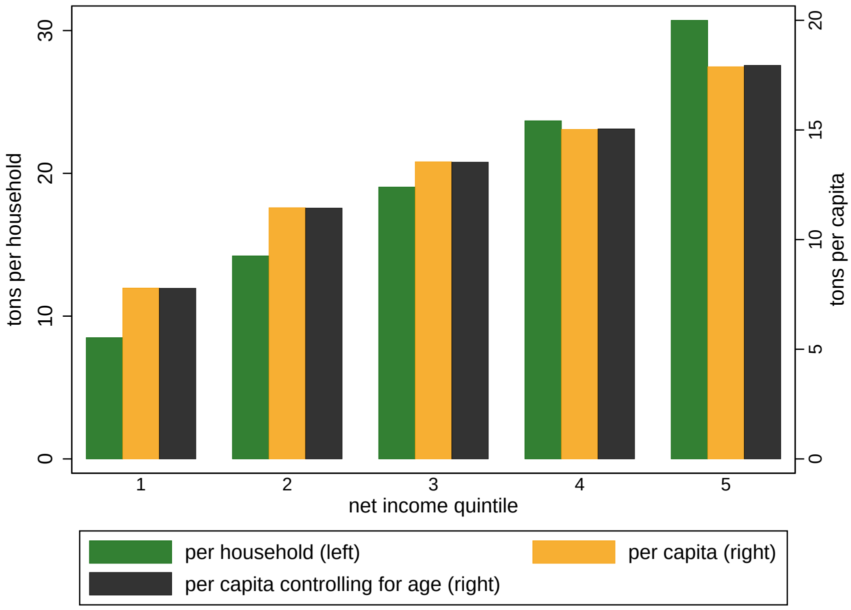
Figure 2.2.1 depicts the carbon footprint of households along the net household income distribution in Germany in 2018. The figure corroborates the finding from the empirical literature that carbon footprints are increasing along the income distribution (green bars).[5] We find that a household in the first quintile emits around 8 tons of carbon each year while a household in the fifth quintile emits around 31 tons, an increase by a factor of almost four. This difference is partly explained by richer households having on average more family members. But even when we consider per-capita equivalent emissions (yellow bars), carbon footprints still increase substantially along the income distribution. Households in the first quintile consume per capita around 8 tons, whereas a member of a household in the fifth quintile emits more than twice as much. The imputation of carbon emissions at the household level allows us further to control for potential life-cycle effects. But after taking out age effects, we find only a negligible effect on per-capita emissions (black bars).

3. The GRECS data are provided by the RWI - Leibniz-Institut für Wirtschaftsforschung. For more information see RWI and Forsa (2015).

4. There is no separate information in the EVS data on expenditures for heating systems but they are subsumed in housing investments. As buying a new heating system is very infrequent, we abstract from the expenditures for heating systems in our empirical analysis. Our results constitute therefore a lower bound on the expenditure of commitment consumption.

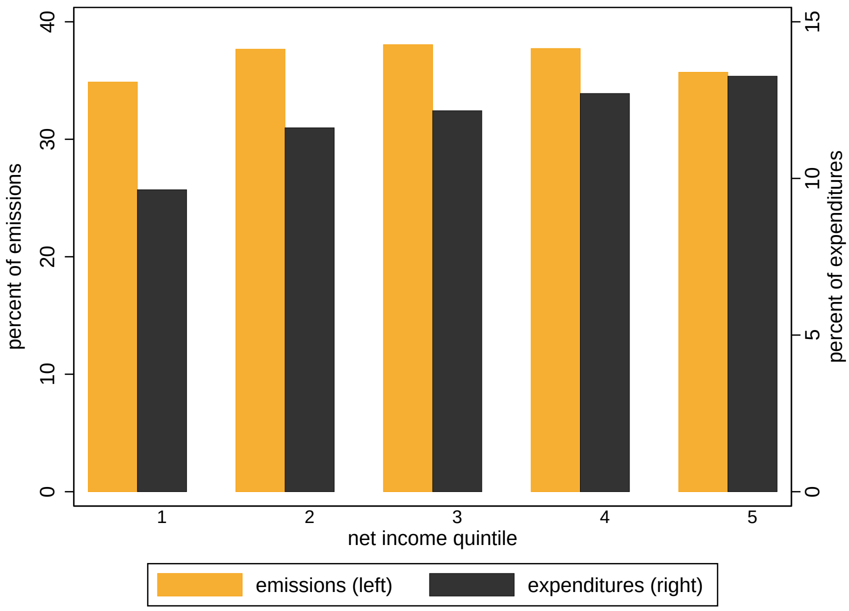
5. This observation has been shown for Germany (Hardadi et al., 2021; Miehe et al., 2016), as well as for other European (Duarte et al., 2012; Isaksen and Narbel, 2017; Kerkhof et al., 2008) and non-European countries (Perobelli et al., 2015; Wiedenhofer et al., 2017).

Figure 2.2.1. Annual household carbon emissions along the income distribution (in tons)



Notes: This figure depicts the average level of carbon emissions of households for different income quintiles. Per capita measures are computed based on the modified OECD scale. Household size is computed as the sum of weights of household members. The first adult member has a weight of 1.0, the second adult member of 0.5, and each child has a weight of 0.3. The results control for age, remove the effect of a quadratic age polynomial and are based on 2018 EVS data.

Figure 2.2.2. Share of emissions and expenditures from consumption commitments by income



Notes: This figure shows the share of total emissions and total expenditures for consumption commitments by income quintile. See text for details on the definition of consumption commitments. Results are based on 2018 EVS data.

Figure 2.2.2 explores the role of consumption commitments for the carbon emissions of households from Figure 2.2.1. We find that on average around 35 percent of total household emissions are generated by commitment goods (yellow bars), while consumption commitments account for only 10 to 13 percent of household expenditures (black bars). Hence, consumption commitments account for three times their expenditure share in emissions. This high emissions per Euro of expenditure make them a prime candidate for policies aiming at reducing carbon emissions of households. This fact of high carbon emissions per Euro of expenditure is robust along the income distribution, which is remarkable given the high degree of heterogeneity in total carbon footprints across income groups.

In Table 2.2.1, we look at emission shares of households by income groups by reporting the shares in total emissions. The numbers are striking and point to the key reduction-redistribution trade-off. We find that the top 10% of the income distribution account for 17.2 percent of total emissions and the top 25%, account for almost 40 percent of all emissions. By contrast, the bottom 25% of households account for only 12 percent of total emissions and thereby for less than a third of the emissions of the top 25% of households. A policy to reduce carbon emissions will, therefore, be particularly effective in reducing emissions if it provides incentives for high-income households to adjust their consumption. Yet, if subsidies for high-income households to adjust their consumption are financed with taxes on all households, then the distributional consequences of such policies will lead to redistribution from a majority of poorer households to high-income households. This redistribution will be further exacerbated if high-income households adopt the subsidized carbon-neutral technologies earlier in the transition process. We will discuss the empirical evidence that provides support for this fact of faster adoption with income in the calibration section (Section 2.3.3).

Table 2.2.1. Income and emission shares

	bottom 25%	25%-50%	50%-75%	top 25%	top 10%
emission share	12.0	20.9	28.5	38.6	17.2
income share	8.9	17.3	26.7	47.1	24.5
		no college	college		
income share		53.6	46.4		
population share		65.8	34.2		
emission level (in tons)		17.7	21.9		

Notes: Income shares and emission shares for different households groups. Upper part of the table shows income and expenditure shares for different income groups. Lower part shows income and expenditure shares for college and non-college households and the level of emissions in tons. Results are based on 2018 EVS data.

Table 2.2.1 also reports differences in carbon emissions by (permanent) income by looking at households with different educational attainment of the household head. We split households by educational attainment into college and non-college households. In the quantitative model, we will use education as an observable characteristic to group households by permanent income into high- and low-income households. Consistent with this idea, Table 2.2.1 shows that although college households account for only about a third of the population, they receive almost half of all income. Regarding emissions, the high-income college households emit around 22 tons per household and therefore almost 25 percent more carbon than low-income non-college households with less than 18 tons per household. Emissions of 22 tons put college households on average in the fourth quintile of the income distribution (Figure 2.2.1).

It is important to note that our grouping of households by education to capture permanent income differences is conservative as there is still substantial overlap in terms of income between the two education groups. Our quantitative results therefore likely constitute a lower bound of the redistributive effects of climate policies as they will rely on the proxy of educational attainment to describe (permanent) income differences.

2.3 Model

This section develops a quantitative life-cycle model with commitment goods and ex-ante permanent income heterogeneity of households. We will calibrate this model to today's economy and use it to simulate the transition process over 25 years to compare different climate policies in their ability to support the adoption process to green commitment goods and with respect to their distributive effects. We will provide an extensive sensitivity analysis with respect to key modelling choices.

2.3.1 Environment

We describe the model environment for a single household. Each household will be a member of a cohort of households that consists of a continuum of measure one of households. A household enters the economy and starts working at age $j = 1$ and lives for J periods. Households differ ex ante in their permanent productivity type z and face idiosyncratic productivity risk while working. Financial markets are incomplete as households can only trade a single risk-free financial asset a with per period return r that is subject to a no borrowing constraint ($a \geq 0$). The idiosyncratic income of a household of type z at age j is given by $y_{zj} = z_j \times \exp\left(\tilde{y}_j\right)$ where z_j is the deterministic life-cycle component that differs across the two ability types and $\tilde{y}_j$ is the stochastic idiosyncratic component that consists of a persistent and a transitory element, denoted η and ν, respectively:

$$\begin{aligned} \tilde{y}_j &= \eta_j + \nu_j, \\ \eta_j &= \rho\eta_{j-1} + \gamma_j \text{ with } \eta_0 = 0, \end{aligned} \tag{2.3.1}$$

where $\nu_j \sim \mathcal{N}\left(0, \sigma_\nu^2\right)$ and $\gamma_j \sim \mathcal{N}\left(0, \sigma_\gamma^2\right)$ are the idiosyncratic i.i.d. shocks and ρ denotes the persistence parameter. To simplify notation, we combine the realizations of η_j and ν_j in a vector $\tilde{\boldsymbol{y}}_j$.

Households derive utility from three types of consumption goods. First, there is a standard consumption good, denoted c, which households can freely adjust in every period. Additionally, there are two commitment goods, a brown and a green commitment good, denoted x^b and x^g, respectively. Households can in each period only consume the brown or the green commitment good. All commitment goods generate utility with utility weight μ. Green commitment goods generate additional utility which consist of two parts. The first part is that green commitment goods are luxury goods and yield utility as bequests in De Nardi et al. (2010). The parameters governing the luxurious good utility are θ^g and ψ^g. This luxurious good utility aligns the model with the empirical literature that finds that green commitment goods are consumed to a much higher extent by high-income households (Axsen et al., 2018; Figenbaum and Kolbenstvedt, 2016; Hardman et al., 2016; Hardman and Tal, 2016; Westin et al., 2018). The second utility component is a size-independent utility flow μ_x from the green consumption commitment good that we further discuss below. The period utility of a household from consuming c_t and x_t^i with $i \in \{b, g\}$ is

$$u(c_t, x_t^i) = \frac{[c_t/\lambda_j]^{1-\sigma}}{1-\sigma} + \mu\frac{[x_t^i/\lambda_j]^{1-\sigma}}{1-\sigma} + \phi\left[\theta^g\frac{[x_t^g + \psi^g]^{1-\sigma}}{1-\sigma} + \mu_x\right] \tag{2.3.2}$$

where λ_j captures household size and is age specific and ϕ describes whether a household consumes a green ($\phi = 1$) or a brown ($\phi = 0$) commitment good.

Both commitment goods require per-period flow costs κ proportional to the stock of the commitment good x that households commit to when buying the good. We allow the price of the green commitment good to differ from the price of the brown commitment good. Initially, we assume that the price of the green commitment good is higher than the price of the brown commitment good. We denote this price premium by ω. We will let this price premium change during the transition period capturing technological progress. Regarding per-period costs, we assume that green commitment goods have lower flow costs. The reduction is denoted by δ, so that flow costs for a level x of the green commitment good are $(1-\delta)\kappa x$ and κx for the brown commitment good. These committed flow costs for consuming the good distinguish the commitment good from durable consumption goods that are also long lasting but are not associated with user costs. Both assumptions are motivated by empirical studies which we employ for calibrating these parameters.

Thus, the budget constraint of a household who does not adjust its level of the commitment good is

$$y_t + (1+r)a_t \ = \ c_t + a_{t+1} + (1-\phi\delta)\kappa x_t$$

where c_t denotes consumption for the standard consumption good, y_t denotes current income, a_t wealth in period t, and the last term on the right-hand side denotes the flow costs for commitment good x_t depending on whether it is a green ($\phi = 1$) or brown commitment good ($\phi = 0$). For a household adjusting the commitment good, the budget constraint becomes

$$y_t + (1+r)a_t \ = \ c_t + a_{t+1} + (1-\phi\delta)\kappa x_t + E_i \qquad i \ \in \ \{b, g\}$$

where E_i denotes the net costs associated with adjusting the commitment good that differ depending on whether the household buys a brown $i = b$ or a green $i = g$ commitment good. Net costs comprise the costs of the purchased commitment good net of the resale value of the previously owned commitment good x. The resale value of the green commitment good is $\rho_{rs}\omega x$, i.e., if $\phi = 1$, and of the brown commitment good it is $\rho_{rs}x$ ($\phi = 0$) with $\rho_{rs} \in (0,1)$ being the discount factor for the resale value relative to the purchasing price. The net costs are then

$$\begin{aligned} E_b &= (1-\phi)(\tilde{x}' - \rho_{rs}x) + \phi(\tilde{x}' - \rho_{rs}\omega x) \\ E_g &= (1-\phi)(\omega\tilde{x}' - \rho_{rs}x) + \phi\omega(\tilde{x}' - \rho_{rs}x) \end{aligned}$$

where $\tilde{x}'$ denotes the purchased quantity of the commitment good. Finally, we allow for depreciation shocks to the commitment good so that the law of motion becomes

$$x' \ = \ x - \xi_\phi \qquad \text{and} \qquad x' \ = \ \tilde{x}' - \xi_\phi \qquad \phi \ \in \ \{b, g\}$$

with depreciation shock ξ_ϕ that hits with probability p_ϕ and it is zero otherwise. The size of the positive shock ξ_ϕ differs for the brown and green commitment good $\phi \in \{b, g\}$. The depreciation shock happens after adjusting the commitment good so that the adjusted commitment good $\tilde{x}'$ is still subject to the shock. In case of no adjustment, it is the current stock x of the commitment good that is subject to the shock.

We abstain from explicitly modelling retirement and bequests. To match life-cycle wealth accumulation, we add a reduced-form utility of wealth in retirement with the following functional form

$$v(w) \ = \ \theta\frac{(w+\Omega)^{1-\sigma}}{1-\sigma}$$

where w denotes wealth at entry into retirement that is the sum of household's financial wealth and the resale value of the commitment good the household owns in the last period. The parameter θ determines the strength of the life-cycle savings motive and the parameter Ω governs the importance of social security wealth for retirement.[6] Both parameters will be calibrated to match life-cycle wealth accumulation.

2.3.2 Recursive formulation of the dynamic decision problem

Each period the household makes a consumption-saving decision and an adjustment decision for its commitment good. Hence, households can either choose to not adjust the commitment good, to adjust and purchase the brown commitment good, or to adjust and purchase the green commitment good. We denote the value functions by V^{NA} (non adjusting), V^{BA} (adjusting to brown commitment good), and V^{GA} (adjusting to green commitment good). The value function V^{NA} is the solution to the following dynamic programming problem

$$\begin{aligned} V^{NA}(z,a,x,\phi,\tilde{y},j) &= \max_{\{a'\geq 0\}} \quad u(c,x) + \beta\,\mathbb{E}\left[V(z,a',x',\phi,\tilde{y}',j+1) \mid \tilde{y}\right] \\ s.t. &\quad y + (1+r)a = c + a' + (1-\phi\delta)\kappa x \\ &\quad x' = x - \xi_\phi \text{ and } \phi' = \phi \end{aligned}$$

The value function for adjusting to the brown commitment good V^{BA} is the solution to the following dynamic programming problem

$$\begin{aligned} V^{BA}(z,a,x,\phi,\tilde{y},j) &= \max_{\{\tilde{x}',a'\geq 0\}} \quad u(c,x) + \beta\,\mathbb{E}\left[V(z,a',x',\phi',\tilde{y}',j+1) \mid \tilde{y}\right] \\ s.t. &\quad y + (1+r)a = c + a' + (1-\phi\delta)\kappa x + E_b \\ &\quad E_b = (1-\phi)(\tilde{x}' - \rho_{rs}x) + \phi(\tilde{x}' - \rho_{rs}\omega x) \\ &\quad x' = \tilde{x}' - \xi_b \text{ and } \phi' = 0 \end{aligned}$$

and the value function for adjusting to the green commitment good V^{GA} is

$$\begin{aligned} V^{GA}(z,a,x,\phi,\tilde{y},j) &= \max_{\{\tilde{x}',a'\geq 0\}} \quad u(c,x) + \beta\,\mathbb{E}\left[V(z,a',x',\phi',\tilde{y}',j+1) \mid \tilde{y}\right] \\ s.t. &\quad y + (1+r)a = c + a' + (1-\phi\delta)\kappa x + E_g \\ &\quad E_g = (1-\phi)(\omega\tilde{x}' - \rho_{rs}x) + \phi\omega(\tilde{x}' - \rho_{rs}x) \\ &\quad x' = \tilde{x}' - \xi_g \text{ and } \phi' = 1. \end{aligned}$$

We further assume that the individual adjustment decision of each household depends on two preference shocks, denoted ϵ_a and ϵ_x. For tractability, we assume that shocks are logistically distributed with mean μ_a (μ_x) and standard deviation

6. The functional form follows De Nardi et al. (2010) who use it to model utility from bequests. The parameter Ω could therefore alternatively be interpreted as determining the strength of a bequest motive.

σ_a (σ_x). While the first shock ϵ_a determines whether or not the household adjusts its commitment good consumption, the second shock ϵ_x determines whether the household buys a green commitment good conditional on adjusting. In case of adjusting to the green commitment good, the household will receive the flow utility μ_x permanently while consuming the green good (see equation (2.3.2)). Note, that households do not know the realization of ϵ_x when deciding whether or not to adjust. The decision process of each period consists therefore of four stages. First, households enter the period with their state variables from last period, observe the realizations of the transitory and persistent income shocks and solve the contingent consumption-saving decision problem for all three possible adjustment decisions. Second, households observe the first preference shock ϵ_a and decide whether or not to adjust the commitment good. If households decide to adjust the commitment good, they enter the third stage, observe ϵ_x, and decide if they adjust to the brown or green good. Thus, the two discrete choice problems of the household are

$$\begin{aligned} V(z,a,x,\phi,\tilde{y},j) &= \max\{\mathbb{E}\left[V^{NA}(z,a,x,\phi,\tilde{y},j)\right],\mathbb{E}\left[V^{A}(z,a,x,\phi,\tilde{y},j)\right]+\epsilon_a\} \\ V^{A}(z,a,x,\phi,\tilde{y},j) &= \max\{\mathbb{E}\left[V^{BA}(z,a,x,\phi,\tilde{y},j)\right],\mathbb{E}\left[V^{GA}(z,a,x,\phi,\tilde{y},j)\right]+\epsilon_x\}, \end{aligned}$$

where expectations are with respect to the income process, the depreciation shock, and, in the first case, also with respect to the second preference shock ϵ_x. At the final stage consumption takes place.

2.3.3 Calibration

The goal of the calibration is to provide a quantitative laboratory to explore the reduction-redistribution trade-off of different climate policy mixes. The model is calibrated to match the current status quo and we demonstrate its consistency with available evidence on household adjustment patterns for commitment goods. We set some parameters externally and calibrate a second set of parameters internally.

We set one period in the model to match one year in the data. Households enter the economy at age 25 and live for 40 years until they exit the model with certainty at age 64 ($J = 40$). Households enter the economy without any wealth but they are endowed with the lowest level of their parents' commitment good that can be brown or green and is changing during the transition period. Through the lens of the model, this initial endowment can be interpreted as receiving an inter-vivo transfer or inheriting a used commitment good. The coefficient of relative risk aversion and the interest rate are set to standard values $\sigma = 1.5$ and $r = 2\%$. The two ability types z are calibrated to education groups as two observable permanent income types in the EVS data. We assign a household to an education group depending on whether the main earner of a household has a college degree. The share of college households is 34.2 percent and we calibrate the deterministic life-cycle profile of income $\{z_j\}_{j=1}^{J}$ to net household income. Average household income in the model provides a normalization and is set to 48,609 Euro in line with the EVS data. For the idiosyncratic shock process, we use estimates from Fehr et al. (2013) for the persistence parameter ρ and the variance of the transitory shock σ_{γ}^2.[7] We calibrate the variance of the persistent shock σ_{ν}^2 to match the Gini coefficient for net household income.

We use a grid for the commitment good with five logarithmic spaced grid points. In line with the empirical analysis, we interpret the commitment good as a composite of cars and heating systems. As around two-thirds of all commitment adjustments are car purchases and since two-thirds of total flow costs generated by commitment goods are caused by cars, we use a weight of two-thirds for cars and one-third for heating systems. For the price premium ω, we use evidence from Holland et al. (2021) for the US car market for a premium of 63 percent. This estimate is well in line with other studies looking at European countries, including Germany (Lévay et al., 2017). For heating systems, estimates from German heating installing firms suggest a price difference for brown and green systems with a price of 10,000 Euro for brown heating systems (oil, gas) and 28,125 Euro for green systems (heat pump) (Statista, 2023). Combining these price premia for cars and heating systems of 63 percent and 181 percent and taking into account adjustment frequencies results in a price premium parameter $\omega = 1.84$.[8] While the price premia for electric cars are relatively homogeneous across countries, the operating costs vary substantially. For Germany, Lévay et al. (2017) estimate a reduction in fuel costs of 25 percent for battery electric vehicles (BEV) and of 3 percent for plug-in hybrid electric vehicles (PHEV) relative to traditional internal combustion engine (ICE) vehicles. These reductions are relatively small compared to other European countries and are the result of the high electricity prices in Germany. Since the number of BEVs and PHEVs are roughly the same in Germany, we take the average of both estimates to arrive at an estimate of 14 percent for the reduction in flow costs when using electric cars. For heating systems, a large price comparison portal for energy reports a cost reduction of 39 percent (Verivox, 2023). Combining the two estimates, we get $\delta = 0.226$. For the resale value of the commitment good, we follow Gilmore and Lave (2013) who find average resale values for cars of around 40 percent. Assuming that heating systems do not have any resale value, we set $\rho_{rs} = 0.262$. As the grid for the commitment good is

7. Fehr et al. (2013) estimate parameters for three income groups. As we assume the idiosyncratic part to be independent of the ability type, we take their estimate for the middle income group for both types.

8. In order to match the overall adjustment costs, we need to not only take into account the adjustment costs for each item but also the adjustment frequency. Hence, we weight cars and heating systems by both components to derive the aggregate price premium. Using the average adjustment frequency of 12 years for cars and 23 years for heating systems, we arrive at an effective weight for cars of 82 percent and heating systems of 18 percent.

logarithmically spaced, combining the relative difference between two grid points of 32 percent with the annual depreciation rates found in Schloter (2022) gives us annual depreciation probabilities of $p_b = 0.325$ and $p_g = 0.435$, respectively.

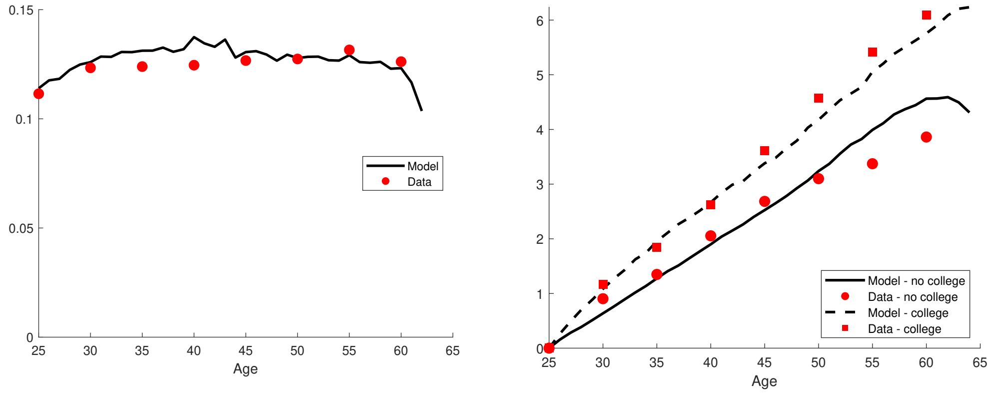
The remaining eleven parameters are calibrated within the model to match corresponding data moments. Six of these parameters, μ, κ, θ^g, β, Ω, and θ are calibrated to the initial steady state in 2018. The weight on utility from commitment consumption μ is calibrated to match the share of carbon emissions from consumption commitments generated by college households relative to all households. In the 2018 EVS data, the share of carbon emissions from consumption commitments from college households is 36.6 percent. The flow cost parameter κ is calibrated to match the share of flow costs to the total expenditures for commitment consumption also from the EVS data. To calibrate the weight on the luxurious good utility for the green commitment good θ^g, we target the costs (purchase price and flow costs) of the commitment good as share of total household expenditure. We calibrate the time discount factor β and the parameters of the utility function of wealth in retirement Ω and θ to match the average wealth-to-income ratio, the average difference between college and non-college households of the wealth-to-income ratio, and the average wealth-to-income ratio at the end of working life ($J = 40$) from the EVS data. Figure 2.3.1 shows the model fit for life-cycle profiles of two dimensions of the consumption-saving decision. Figure 2.3.1a shows the expenditure share for commitment goods over the life cycle from model and data. In both cases, we see little life-cycle variation around the mean. Figure 2.3.1b shows the wealth-to-income ratios for low- and high-income households. The calibration matches the average life-cycle profile, the unconditional income-group difference, and the figure shows that the model mechanism also matches closely the untargeted life-cycle evolution of both income groups.

The remaining five parameters, μ_a, μ_x, σ_a, σ_x, and ψ^g are calibrated to match the parameters of the adjustment process to green commitment goods using the most recent evidence for 2023. The means of the preference shocks μ_a and μ_x are calibrated to match the share of households who adjust their commitment consumption over the life-cycle and the share of adjustments to green goods. As corresponding data moments, we use data from the German Federal Motor Transport Authority (*Kraftfahrtsbundesamt*) for cars and the Federal Association of the Heating Industry (*Bundesverband der Deutschen Heizungsindustrie*) for heating systems. The parameters governing the variance of the preference shocks σ_a and σ_x are set to match the price elasticities of green and brown commitment goods. Fridstrøm and Østli (2021) provide estimates for own-price and cross-price elasticities of cars with different powertrains. We target their estimates for battery electric vehicles and plug-in hybrid vehicles in Norway in 2016 for the own-price elasticity of the green commitment good in the model. Norway in 2016 is very comparable to Germany in 2022 regarding the market share of electric cars, the cumulative

Figure 2.3.1. Life-cycle profiles from consumption-saving decision

(a) Commitment consumption expenditure share

(b) Wealth-to-income ratio



Notes: The figure shows the model fit for the consumption commitment expenditure share and the wealth-to-income profiles for college and non-college households. Data shown as red dots and squares in 5-year age bins. Model simulation shown as black lines. Consumption commitment expenditure share shown as fraction of total household expenditure. Data from 2018 EVS data.

market shares of battery electric vehicles and plug-in hybrid vehicles was 29 percent in Norway in 2016 very similar to 31 percent in Germany in 2022. Fridstrøm and Østli (2021) estimate the elasticities of battery electric and plug-in hybrid vehicles to be -0.99 and -1.72, respectively. We average these estimates to compare them to the model. To compute the model equivalent, we mimic their strategy and simulate a 10 percent price increase for the green commitment good holding all other prices constant. We find that our model matches the targeted elasticity of -1.4 exactly.[9] Lastly, we calibrate the curvature of the luxurious utility function for green commitment goods ψ^g to the ratio of green adjustments made by high-income households (college households) relative to low-income households (non-college households). For this target, we rely on estimates for Norway in 2016 (Figenbaum and Kolbenstvedt, 2016) for electric cars and own estimates using the GRECS dataset for heat pumps. Figenbaum and Kolbenstvedt (2016) report that 77 percent of electric cars are bought by college graduates and we find in the GRECS data that college households are around 58 percent more likely to buy a heat pump. Our estimate of a smaller gradient in income for heat-pumps relative to electric cars is also consistent with evidence in Davis (2023) for the US.

9. Another widely used measure in the literature is the percentage increase in purchases for green commitment goods if prices decrease by 1,000 Euro. We find that purchases would increase by around five percent, which is well in line with the literature. Studying 32 European countries between 2010 and 2017 Münzel et al. (2019) find that sales shares for electric vehicles increase by five to seven percent and Clinton and Steinberg (2019) find an increase of around seven percent in electric vehicle registrations per capita in the United States between 2010 and 2014. We take this as further support for our calibration.

The calibration target is the combined estimate from Figenbaum and Kolbenstvedt (2016) for electric cars and the estimate based on the GRECS data for heat pumps. We get a ratio of green commitments bought by college - relative to non-college households of 2.7. Our calibration matches this target exactly. We summarize the calibrated model parameters in Table 2.3.1.

Table 2.3.1. Calibrated parameters

Symbol	Description	Value	Source/Target
σ	Risk aversion	1.5	
r	Interest rate	0.02	
ϕ_{col}	Share of college graduates	0.342	EVS (2018)
ω	Price premium green good	1.84	See text
δ	Cut in flow costs with green good	0.226	See text
ρ_{rs}	Resale value	0.262	See text
p_b	Prob. depreciation brown good	0.3254	Schloter (2022)
p_g	Prob. depreciation green good	0.4349	Schloter (2022)
ρ	Persistence of income shock	0.957	Fehr et al. (2013)
σ_γ^2	Variance transitory income shock	0.084	Fehr et al. (2013)
	Internally calibrated parameters		
σ_ν^2	Variance of persistent income shock	0.025	Gini-coefficient net household income
μ	Weight commit. consumption	0.29	Share emissions college
κ	Share flow costs commitment size	0.171	Share flow costs to total commit. costs
θ_g	Weight green commit. consump.	0.89	Share commit. to total consumption
β	Discount rate	0.986	Average WTI-ratio
Ω	Importance of social security wealth	11	Diff. bequests college/non-college
θ	Life-cycle savings motive	61	Average WTI-ratio at death
μ_a	Mean of first preference shock	-0.769	Share of households adjusting
μ_x	Mean of second preference shock	0.813	Share of green to total adjustments
σ_a	Scale parameter first pref. shock	0.31	Elasticity of brown good
σ_x	Scale parameter second pref. shock	0.35	Elasticity of green good
ψ_g	Curvature green commit. consump.	1.4	Ratio green good college/non-college

Notes: This table presents the calibrated model parameters. The upper part shows parameters set based on external sources. The lower part shows internally calibrated parameters. Column *symbol* reports the parameter and column *value* the calibrated value.

In our calibration, we target the average own-price elasticities. The moment of interest for the redistributive effects of climate policies are, however, the semi-elasticities of the green consumption good as they determine the adjustment level in response to a price change, for example, from introducing a subsidy. A larger semi-elasticity means that more households will adjust to the green commitment good and receive subsidies.[10] If there is heterogeneity in the semi-elasticities,

10. Most of the adjustment will happen at the extensive margin given that only very few households have green commitment goods at the start of the transition.

this implies that the group with the larger semi-elasticity will receive more of a newly introduced subsidy because of a stronger adoption of the green commitment good. Table 2.3.2 reports the semi-elasticities for different income and age groups. Regarding the variation with age, we find that the semi-elasticities are increasing with age for high-income households and that they are hump-shaped in age for low-income households. The on average higher elasticities among older households imply that there will be a redistribution from the currently young households to older households during a transition period after a subsidy will be introduced. Conditional on age, we find that high-income households are more price sensitive. More importantly, there is hardly any overlap between low- and high-income households regarding the range of semi-elasticities. Older low-income households show about the same semi-elasticity as high-income young households. This pattern implies that there will be redistribution of climate policies from low- to high-income households once the government introduces subsidies for adopting the green commitment good.

Table 2.3.2. Model heterogeneity

Age (years)	30	30	45	45	55	55
Income group	low	high	low	high	low	high
Semi-elasticity of green good	0.01	0.05	0.07	0.12	0.05	0.12

Notes: This table shows the semi-elasticity in percentage points for the green commitment good for different age and income groups. Semi-elasticity reported as the percentage point increase of households purchasing the green commitment good after a one percent decrease in the price of the good. First row reports age of household in the model, second row reports permanent income group z, and bottom row the value for the semi-elasticity from the model.

A further important moment for redistribution during a transition period is the average adjustment age to green technologies. We therefore evaluate whether our model is able to match at which age households adjust to the green commitment good. There is only limited data on the age profile of households with green commitment goods. For electric cars, empirical studies find the average age for electric car buyers to be between 43 and 53 years (Figenbaum and Kolbenstvedt, 2016; Lee et al., 2019; Westin et al., 2018). For heat pumps, the RWI data suggest that owners are on average around 42 years old. This evidence suggest that most of the green commitment goods are bought by middle-aged household heads. In our model, the average age among those households who adjust to the green commitment good is around 49, which is in line with what the empirical literature suggests. In the next section, we will use the calibrated model as laboratory to quantify the effects of different climate policies.

2.4 Policy experiments

We will now use the calibrated model to study different policy mixes with respect to their reduction-redistribution trade-off, this means their ability to support the adoption process to green commitment goods (reduction) and with respect to their allocation of net transfers (redistribution). The empirical analysis of Section 2.2 suggests that increasing the speed of the transition to low carbon emissions requires that high-income households with larger carbon footprints receive sufficiently strong financial incentives for adjusting. On the redistribution side, because of heterogeneous adoption rates, such a policy is likely to result in net transfers from low-adjusting low-income households to high-adjusting high-income households. Our policy analysis will therefore explore different policy mixes of subsidies for green technologies and financing options. We will quantify the present value of net transfers at the household level for the different policy mixes as our measure of political support for a policy to see which policy mixes satisfy the political economy constraint that they find majority support among today's electorate (support of the median voter).

Our policy experiments start from an initial steady state in which only the brown commitment good exists and which we calibrate to the year 2018.[11] From this steady state, we compute a transition of 25 years during which the green commitment good is available. For the first five years, we assume no governmental policy, thereafter, in year 2024, we assume that the government introduces a climate policy mix of a subsidy and a financing instrument. We rule out anticipation effects and simulate the economy for 20 years (until 2043) with a constant policy mix in place. We will always focus the analysis on the group of households that are (economically) alive when the policy is introduced and follow these households over time. In Appendix 2.B.4, we show how transition dynamics are affected if young (newborn) households enter the economy during the transition period. Although we find that the dynamics will change quantitatively, the conclusions of the policy analysis will remain unchanged. We opt for the focus on the currently alive households to allow for an informative comparison of policy mixes. Including newborn households will lead to intergenerational transfers that will differ across policy mixes and that will, therefore, render the comparison of the policy mixes uninformative.

After the introduction of the green commitment good, we also allow for technological progress that will lead to a relative price decline of the green commitment good. This relative price decline will result in a decrease of the price differences ω between the green and the brown commitment good. A lower relative price of

11. The share of electric cars and heat pumps on the stock of all cars and heating systems in 2018 were around 0.2 percent and 2.0 percent, respectively.

the green commitment good will further speed up the adoption of the green good. For our baseline economy, we follow the literature and assume that the price of the green commitment good will converge over time to the price of the brown commitment good (Holland et al., 2021). We take actual price developments for electric cars and heat pumps until 2022 and forecasts from 2023 onward until the end of the transition period. For electric cars, we take actual data and forecasts by the car rental company nextmove (Nextmove, 2023). For heat pumps, we observe no price changes until 2022. From there onward, we take as our baseline scenario the forecasts from LCP Delta who estimate prices to drop by 40 percent within 10 years (LCP Delta, 2021). We extrapolate this percentage price reduction over the entire transition period. We also compute a second more conservative price scenario with slower price convergence based on price forecasts for electric cars by Holland et al. (2021). For heat pumps, we also take the more conservative price scenario by LCP Delta of a reduction of 25 percent within 10 years. As before, we weight variables for electric cars and heat pumps to a composite good. Appendix Figure A4 shows the baseline price scenario for the green composite commitment good, as well as the slower convergence scenario. Appendix Figure A5 shows the price scenarios for cars and heat pumps separately. We report the results of the analysis for the more conservative price scenario in Appendix 2.B.2.

In the first step, we compare different specifications of price subsidies for the green commitment good. Specifically, we consider a percentage subsidy on the purchase price and a lump-sum subsidy for the purchase of the green commitment good. In both cases, the government imposes a linear income tax to finance the subsidy. In the second step, we will consider different financing options. These taxes will then be set such that the government has a balanced budget over the transition period. Hence, we rule out policies with transfers from or to future (unborn) generations as, in particular, any debt-financed policy for the current generation (transfers from future generations) could make a majority of households support any policy. Under this assumption, the government's budget constraint for the linear income tax with the percentage subsidy reads

$$\sum_{t=2024}^{2043} \frac{1}{(1+r)^{t-2024}} \tau_y \int_i y_{i,t} di = \sum_{t=2024}^{2043} \frac{1}{(1+r)^{t-2024}} \pi_1 \int_i \zeta_{i,t} \tilde{x}_{i,t+1} di \qquad (2.4.1)$$

where $\zeta_{i,t}$ is an indicator function that is one if household i buys a green commitment good in period t and τ_y and π_1 represent the linear income tax and the percentage subsidy, respectively. In case of the lump-sum tax, the budget constraint changes to

$$\sum_{t=2024}^{2043} \frac{1}{(1+r)^{t-2024}} \tau_y \int_i y_{i,t} di = \sum_{t=2024}^{2043} \frac{1}{(1+r)^{t-2024}} \pi_2 \int_i \zeta_{i,t} di \qquad (2.4.2)$$

where π_2 denotes the lump-sum tax for buying a green commitment good ($\zeta_{i,t} = 1$). As now the subsidy is lump sum, the right-hand side becomes independent of the size of the green commitment good $x_{i,t}$.

In the second step, we compare on the financing side a linear income tax, a progressive income tax, a consumption tax, and a tax on the flow cost of the brown commitment good (carbon tax). By raising the user cost of the brown commitment good, the carbon tax will on top of the subsidy for the green good further increase the speed of adopting the green commitment good. We will also consider as a further and widely discussed policy option the introduction of a carbon tax that increases the user cost of the brown commitment good but that will not be used to finance a subsidy for adopting the green commitment good but where tax revenues will be redistributed as lump-sum transfers. In this case, the reduction of carbon emissions will only result from higher user costs of the brown commitment good and redistribution comes from the lump-sum transfer of tax revenue of the carbon tax.

For each policy mix, we quantify the adoption of green commitment goods and the financial consequences in terms of net transfers for the two permanent income groups and between age groups over the transition period. Looking at the distribution of net transfers, we will ask if any of the policy mixes has a majority of households with positive net transfers so that it would find majority support. By looking only at financial transfers, we abstract from any direct or indirect welfare costs of climate change that are important but that are challenging to quantify at the level of the individual household.

2.4.1 Subsidies for carbon reduction

Subsidies for the green commitment good change the costs of adjusting to the green commitment good E_g. We get in case of the proportional price subsidy π_1

$$E_g^P = (1-\phi)[(1-\pi_1)\omega x' - \rho_{rs}x] + \phi[\omega((1-\pi_1)x' - \rho_{rs}x)]$$

and in case of the lump-sum subsidy π_2, we get

$$E_g^L = (1-\phi)[\omega x' - \rho_{rs}x] + \phi[\omega(x' - \rho_{rs}x)] - \min\{\pi_2, \omega x'\}$$

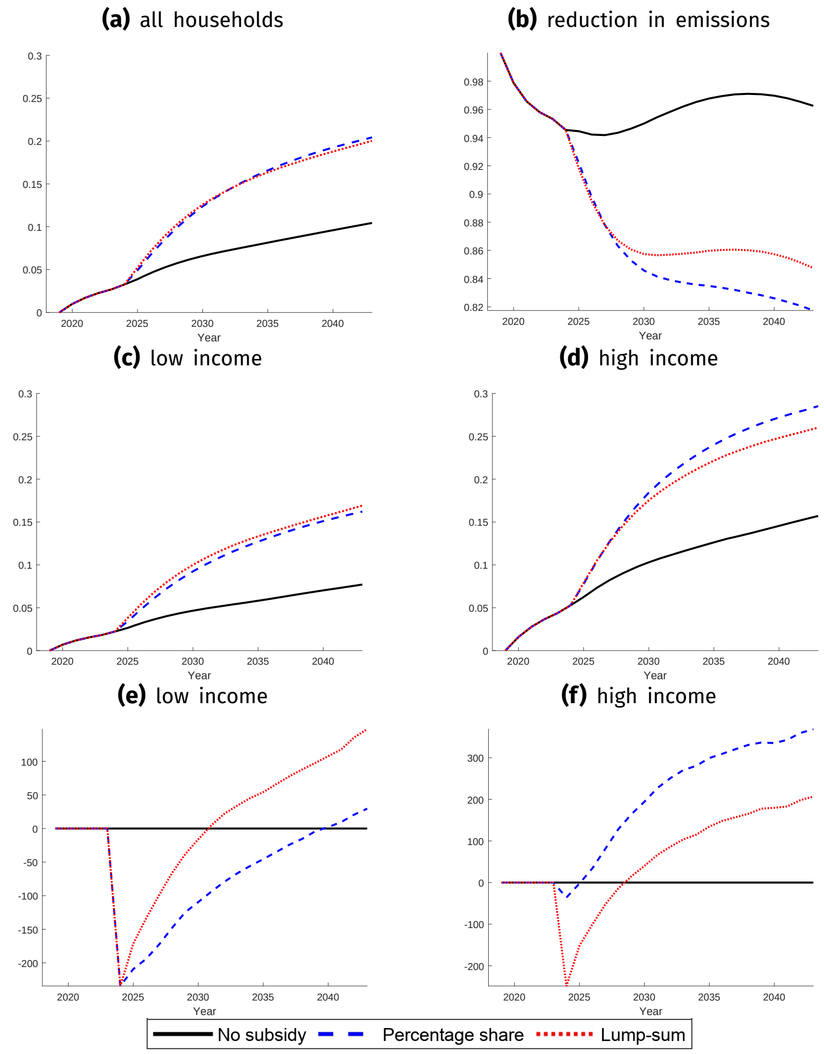
where we rule out that the subsidy π_2 exceeds the costs of the new commitment good $\omega x'$. In both cases, the subsidy is financed by a linear income tax τ_y on labor income, so that net labor income becomes $(1-\tau_y)y$. In case a household does not adjust or adjusts to the brown commitment good, the budget constraints for this household only changes on the income side with labor income being $(1-\tau_y)y$. To determine the level of subsidies, we use recently introduced subsidies in Germany for electric cars and heat pumps that set the lump-sum subsidy to a maximum of $\pi_2 = 12,795$ Euros.[12] We then determine the linear income tax τ_y so that the government runs a balanced budget over the entire transition period (equation (2.4.2)). This approach yields a tax rate $\tau_y = 0.011$. To make the proportional subsidy comparable, we set $\pi_1 = 0.253$ which implies again that the government runs a balanced budget at the same income tax rate (equation (2.4.1)).

Figure 2.4.1a shows the share of households consuming the green commitment good along the transition for three scenarios. First, the scenario without any subsidy, where we get that around 10 percent of households have a green commitment good at the end of the transition in 2043.[13] Second, in case of a lump-sum subsidy, we find a substantial increase of the adoption rate to around 20 percent at the end of the transition. We find a similar household share in case of the proportional subsidy. Figure 2.4.1b shows that the two subsidy policies differ however in their implied reduction of emissions over time. The reduction of emissions only depends on the size of the brown commitment consumption of an adopting household as we assume that the green commitment good has zero emissions independent of its size. Hence, the larger the brown commitment good of the household adjusting to the green commitment good, the larger is the reduction in carbon emissions. For the lump-sum subsidy, we now find with 15 percent a roughly 3pp smaller reduction in emissions compared to the 18 percent reduction of the percentage subsidy. By contrast, without any subsidy the reduction is only 4 percent. We observe that the reduction paths for the lump-sum subsidy and the no-subsidy case become non-monotone around 2030 and that the percentage subsidy case flattens out. The reason are the life-cycle dynamics of the cohort of households alive at the beginning of the transition period. As the households become older, they want to consume larger commitment goods. As only a fraction of households will buy the green good, many will still buy the brown commitment good, thereby, exerting upward pressure on the consumption level of the brown commitment good and the associated emissions over time.

12. We take subsidies of 4,500 Euro and 10,000 Euro for electric cars and heat pumps, respectively, and aggregate them with the respective weights. Note that the subsidy for the composite good is higher than the individual subsidies. This is due to the difference in adjustment frequencies that enter also our aggregation of cars and heating systems. We aggregate the sum of all subsides received over an average adjustment period so that we get a sum that is higher than the two individual subsidies. We proceed equivalently for the aggregation throughout. The level of the subsidy constitutes a free parameter that we discipline in this way and results will not depend on its exact level.

13. The scenario without a subsidy allows us to further validate the quantitative predictions of the model regarding the speed of adjustment and therefore justify its use for a quantitative policy analysis. The general challenge is that the available evidence on adjustment paths is necessarily scarce. In Appendix Figure A1, we compare the first four years of the transition from 2019 to 2022 for which data exist. We find that the model matches the speed of adoption well. Both model and data yield a roughly 0.5pp annual adoption rate of the green commitment good after 2020. We take this evidence as further support for the quantitative predictions of the model.

Figure 2.4.1. Share of households with green consumption commitment good, reduction of emissions, and annual net transfers by income group



Notes: Panel (a) shows the share of households with green commitment goods along the transition path for percentage and lump-sum subsidy and in the case with no subsidy. Panel (b) shows the reduction in carbon emissions along the transition for percentage and lump-sum subsidy and in the case with no subsidy. Carbon emissions only come from brown consumption commitment goods and are assumed to be proportional to the size of the brown commitment good. Panels (c) and (d) show the share of households with a green consumption commitment good from panel (a) for low- and high-income households. Panels (e) and (f) show the annual net transfers along the transition period for the different subsidy specifications and for low- and high-income households. Net transfers are the difference between subsidies and taxes paid and are in Euros per year.

Two observations explain the difference between the change in households adopting the green good and the change in emissions. First, the emission reduction initially exceeds the share of households adopting the green commitment good as high-income households who more strongly adopt had higher emissions as they consume more of the brown commitment good (Section 2.2). Over time, the life-cycle effect leads to increasing average emissions even at constant shares of adjusting households as all households consume larger commitment goods in an aging population. Second, the percentage subsidy is more attractive for high-income households in general because they consume larger commitment goods and therefore adjust more under a percentage price subsidy. This stronger adjustment of high-income households shifts the composition of adjusting households towards high-income households which leads to a stronger reduction of emissions under the percentage subsidy compared to the lump-sum subsidy.

The difference in adoption rates between income groups can be seen in Figures 2.4.1c and 2.4.1d that show the share of households with green commitment goods among low- and high-income households. Two observations are important from this comparison. First, we see that the share of households with a green commitment good is higher and increases more in its level for high-income households consistent with existing empirical estimates (Axsen et al., 2018; Figenbaum and Kolbenstvedt, 2016; Hardman et al., 2016; Hardman and Tal, 2016; Westin et al., 2018). This implies that also a larger fraction of the subsidy will go to high-income households. Second, the difference between the adoption rates with the price and lump-sum subsidy reverses between high-income and low-income households. Whereas low-income households adopt more under the lump-sum subsidy, high-income households react more to the percentage subsidy as their expenditure for the commitment good are on average higher. This stronger adoption of high-income, high-emission households makes the percentage subsidy the more effective policy for reducing carbon emissions.

The differences in the adoption of the green commitment good under the two subsidy policies also implies that the policies will differ in their distributional consequences. We compute the average net transfers for both policies in each year of the transition as the average subsidies net of the average income taxes paid for high- and low-income households. Figures 2.4.1e and 2.4.1f show that for the percentage subsidy high-income households are on average typically net-transfer recipients, while low-income households are on average typically net contributors to the policy. For the lump-sum subsidy, the pattern is less clear. Both income groups have a steeply increasing net transfer profile over time that flips sign in the middle of the transition period. As we will show below, these time paths are such that their present values are negative for a majority of households. Hence, they will not satisfy the political economy constraint of having a majority of net recipients.

In general, we see for both policies that net transfers increase along the transition path. This increase is driven by the falling price path of the green commitment good along the transition, which increases the share of households consuming the green commitment good and thus the share of households receiving the subsidy. The increase in net transfers is stronger for lump-sum subsidies as their level is independent of the price of the green commitment good, i.e., transfers stay constant over the transition period. Quantitatively, the annual net transfers per household are sizeable and amount to up to positive or negative 300 Euros in some years, which corresponds to 0.6 percent of annual net household income.

2.4.2 Different financing schemes

The results show that both subsidy policies lead to large net transfers and therefore potential redistribution along the transition if they are financed by a linear income tax. In the next step, we focus on the percentage subsidy that is more effective in reducing emissions and consider different financing schemes to explore if there is a policy mix with a similar reduction of emissions and redistribution pattern that will find majority support among households. In Appendix 2.B.1, we present the corresponding results for the lump-sum subsidy. For this analysis, we fix the percentage subsidy on the green commitment good at $\pi_1 = 0.253$ and solve for each of the tax instruments for the tax rate to finance the subsidy with a balanced budget over the transition. The baseline is the case of a linear income tax. Second, we consider a progressive income tax. For the progressive tax, we introduce two tax rates for low- and high-income households and set the difference of tax rates to match the empirical observation that the low-income group accounts for 16 percent of total labor income tax revenues in Germany. Third, we consider a consumption tax on all consumption goods. For the consumption tax, the budget constraint in case of adjusting the commitment good becomes

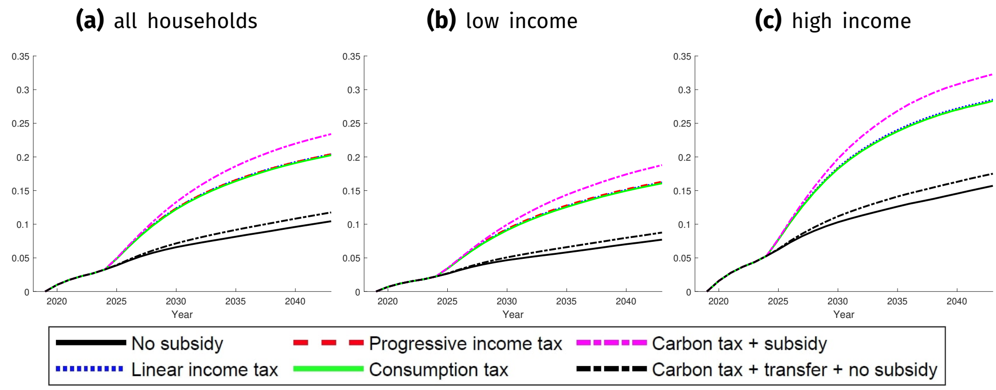
$$\begin{aligned} y + (1+r)a &= (1+\tau_c)c + a' + (1+\tau_c)((1-\phi)\kappa x + \phi(1-\delta)\kappa x) + E_i^P \quad i \in \{b,g\} \\ E_b^P &= (1-\phi)((1+\tau_c)\tilde{x}' - \rho_{rs}x) + \phi((1+\tau_c)\tilde{x}' - \rho_{rs}\omega x) \\ E_g^P &= (1-\phi)((1+\tau_c)(1-\pi_1)\omega\tilde{x}' - \rho_{rs}x) + \phi\omega((1+\tau_c)(1-\pi_1)\tilde{x}' - \rho_{rs}x) \end{aligned}$$

and differs depending on if the adjustment is to the brown commitment good associated with costs E_b^P or to the green commitment good associated with costs E_g^P. If there is no adjustment of the commitment good E_i^P drops from the constraint. The consumption tax τ_c applies to consumption c, flow expenditures κx, and new commitment goods $\tilde{x}'$. Finally, we consider a tax on the user cost of the brown commitment good, which is a carbon tax through the lens of the model. The flow cost in case of consuming the brown commitment good ($\phi = 0$) are $(1+\tau_b)\kappa x$ where τ_b denotes the carbon tax and user costs are $(1-\delta)\kappa x$ in case of the green commitment good ($\phi = 1$) where no tax needs to be paid.

Setting each of the four tax rates such that the government runs a balanced budget over the transition period implies a linear tax rate of $\tau_y = 0.011$, a progressive tax of $\tau_y^l = 0.005$ and $\tau_y^h = 0.018$ for low-income (τ_y^l) and high-income (τ_y^h) households respectively, a consumption tax $\tau_c = 0.012$, and a carbon tax $\tau_b = 0.215$.[14] For the carbon tax, we also evaluate a policy mix where instead of financing a subsidy for the green commitment good the tax revenue from the carbon tax will be redistributed as a lump-sum transfer among all households (Carbon tax + transfer + no subsidy).

In the first step, we explore how, in the case of the percentage subsidy, the different financing policies affect the adoption of the green commitment good. Figure 2.4.2a shows the adoption of the green commitment good across all households. On average, we find differences across financing schemes to be small. An exception is the financing of the subsidy by a carbon tax (carbon tax + subsidy) that further speeds up the adoption by 3pp at the end of the transition period. In the case of the carbon tax financing transfers but no subsidy, we only get 1.3pp more households adopting the green consumption good relative to the baseline without any policy. Looking across income groups in Figures 2.4.2b and 2.4.2c, we find that for low-income households the consumption tax leads to the least adjustment

Figure 2.4.2. Share of households with green consumption commitments



Notes: This figure shows the share of households with the green commitment good along the transition path for different policy mixes. The left panel shows the share among all households, the middle panel shows the share for low-income households, and the right panel shows the share for high-income households. The policy mix is the combination of a percentage subsidy on the green commitment good in combination with different financing schemes. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

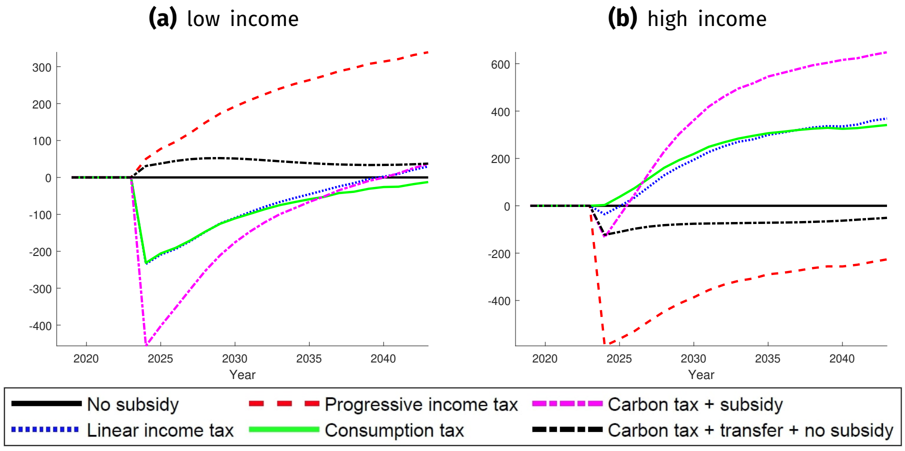
14. To translate this tax rate in a carbon price note that about 11 percent of household expenditures are for commitment goods and two-thirds of these costs are flow costs for commitment consumption. Based on the data from Section 2.2, the flow consumption of the commitment good leads to 5 tons of carbon emissions. Given average household expenditures of 40,200 Euros, the 21.5 percent tax on the flow costs therefore corresponds to a carbon price of around 127 Euros per ton of carbon emissions. A carbon price of 127 Euros is substantially higher than the current carbon price of 45 Euros in Germany in 2024.

and the carbon tax leads to the most adjustment but the difference at the end of the transition is only 2.5pp. With the exception of the carbon tax, the differences between the other financing schemes are negligible. For high-income households, the difference in adoption rates between the carbon tax and the other financing schemes is with 4pp larger. Among the other financing schemes, the progressive tax leads to the least adjustment but again the differences are negligible. If the objective function were to maximize adoption rates without political economy constraints, then a percentage subsidy financed by a carbon tax would be the best policy across the considered policy mixes but as we will see this policy does not satisfy the political economy constraint that a majority of households support it because of its redistributive consequences.

Finally, when we look at the policy where the carbon tax finances lump-sum transfers to households, we find that adoption rates are an order of magnitude smaller than with any of the subsidy policies. The reason is that in case of the carbon tax, it is only the differences in user costs that will induce households to change consumption and there is no additional incentive from subsidies for acquiring the green commitment good. At the end of the transition period, the carbon tax that increases the user costs for the brown commitment good by 22 percent leads to only 12 percent of households consuming the green commitment good in contrast to the case with a percentage subsidy where the share is almost twice as high. The reason for the low adoption rate under the carbon tax is not simply its low level. The 22 percent tax on the expenditures for the flow costs of the brown commitment good corresponds to a carbon price of 127 Euros per ton of emissions (see footnote 14). This price is about three times the current carbon price in Germany and within the range of estimates for carbon prices in the EU by 2030. Yet, the user cost are still small compared to the purchase price. The tax increases the flow user cost only by 4pp which provides a weaker incentive than a direct subsidy for the purchase of the green commitment good. The policy taxes the consumption of most households that still consume the brown commitment good but does not provide targeted incentives for substitution. A large part of the reduction in emissions will consequently not come from households buying green goods but from consuming less of the brown commitment good. In Appendix 2.B.3, we study a policy mix with even higher carbon taxes that are rebated back as transfers. We find that in this case the effect of lower consumption of the brown commitment good accounts for over two-thirds of the emission reduction from the policy.

While the effects on the emission reduction of the different financing schemes are overall modest, Figure 2.4.3 shows that the differences in redistribution vary strongly across the different financing schemes. Most strikingly, the direction of redistribution for the progressive tax flips the sign relative to the other financing schemes. Only the carbon tax that finances lump-sum transfers also yields a redis-

Figure 2.4.3. Annual net transfers



Notes: This figure shows the annual net transfers of different policy mixes. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros per year. The different policy mixes combine a percentage subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

tribution pattern that aligns qualitatively with that of progressive taxation but at a lower level. Except for these two policies, all other financing policies typically result in positive net transfers for high-income households and negative net transfers for low-income households along the transition. The reason for the increasing time path of net transfers is the falling price path of the green commitment good over time. In terms of transfer levels, we get net transfers to low-income households for the progressive tax in the final years of the transition that exceed on average 330 Euros per year. By contrast, high-income households receive negative net transfers under this policy because of its progressive financing. In the year of the introduction, their negative net transfer is almost 600 Euros. Over time, their net transfer reduces but remains sizable and negative at 230 Euros per year at the end of the transition period.

The polar opposite is the carbon tax to finance the percentage subsidy. Now, it is low-income households who mainly finance the policy. They are slower to adopt the green commitment good and consequently they have to pay more of the carbon tax. They buy smaller commitment goods and they buy the green commitment good less often and, therefore, also receive less of the subsidy. Hence, they are worse off in both dimensions of a policy mix of a percentage subsidy with carbon taxes. In the year of the introduction, their negative net transfer is over 450 Euros, it declines quickly over time and only towards the end of the transition period, it turns positive. High-income households are the receivers of these net transfers.

Except for the initial periods when still many of them own the brown commitment good and therefore have to pay carbon taxes, they receive positive transfers that increase to more than 640 Euros on average at the end of the transition period.

The policy mix of the carbon tax financing transfers leads to the least redistribution across income groups of all policies. For most of the transition, low-income households receive positive net transfers of less than 100 Euros and high-income households contribute with roughly similar negative net transfers. Hence, the policy has the qualitative redistribution pattern as the progressive tax financing option. In Appendix 2.B.3, we show that increasing the carbon tax will lead to higher transfers and the redistribution pattern further converge.

We find consistently that net transfers increase over the transition period. By assumption, we restrict all policy mixes to have a balanced budget for the initial cross section of households so that net transfers across income groups net out to zero in the first period of the transition. This budget constraint rules out transfers across generations. Any debt-financed policy could make the current generation financially better off by financing transfers by higher debt levels as in our framework Ricardian equivalence does not hold. The time path of net transfers shows, however, that all policies tend to yield surpluses today that will be spent in the later part of the transition period when prices have fallen and more households adjust to the green commitment good. This time path therefore highlights a potentially important role also for intergenerational financial redistribution of climate policies.

2.4.3 Distributional effects

So far, the analysis has shown that subsidizing the adoption of carbon-neutral commitment consumption goods can lead to a doubling of the reduction of carbon emissions relative to a baseline without policy. Yet, we have also seen that different financing options differ strongly in their net transfers across income groups. To assess the support for different policy mixes, we quantify in a final step the present value of net transfers of the different policy mixes. The budget-balance requirement for the government implies that the sum of net transfers across all households at the introduction of the policy is zero so that we get a direct measure of redistribution within the electorate from the policy when considering the differences of present values across households. We assume that households who receive a positive net transfer support a policy mix whereas households with a negative present value of net transfers will not support it. Hence, we consider a policy to find support if a majority of households or the median voter has a positive present value of transfers.

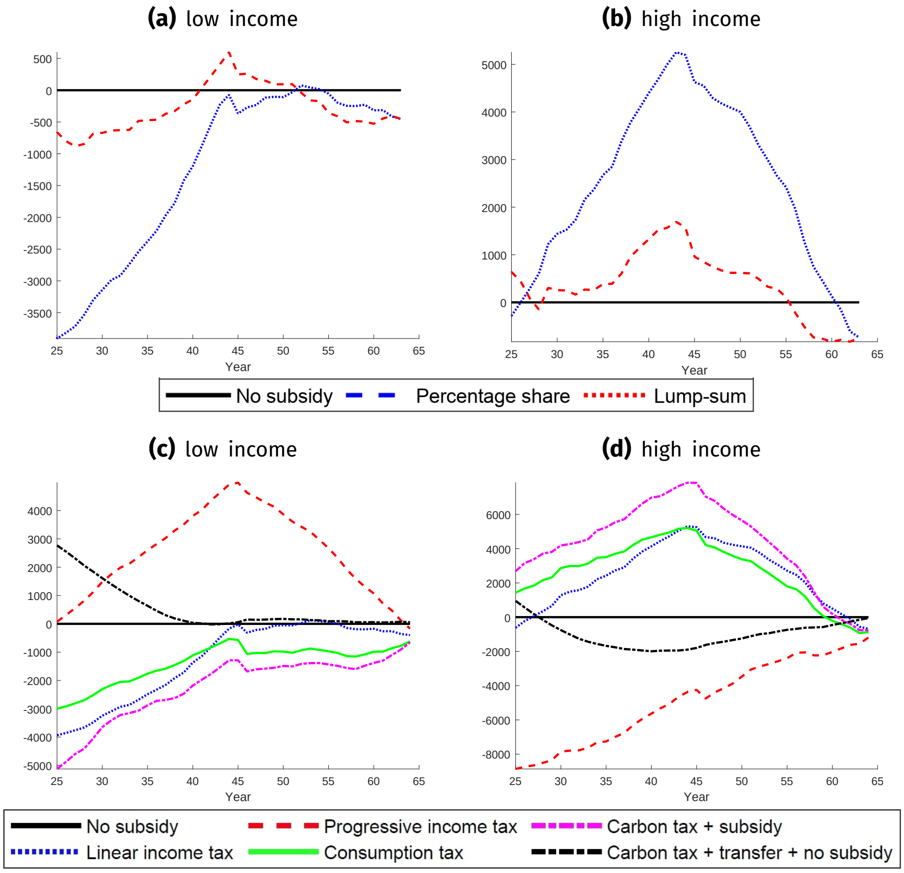
Importantly, these net transfers are not the entire welfare effect of the different policies as they abstract from any other gains or losses associated with climate change. We abstain from including these additional welfare effects as they are hard to quantify at the household level. Instead, we focus here on the economic decisions and transfers directly attributable to the individual household. Furthermore, we only consider the support of the policy among currently alive households and rule out intergenerational transfers, for example, by debt financing. We restrict the policy mixes in this way as otherwise intergenerational transfers across policy mixes can and will differ. Such different intergenerational transfers to the current generation will render a direct comparison of the different policies mixes uninformative.

We compute net transfers for all households over the transition period. Households who are at most 45 years old when the policy is introduced (born 1978 or later) will live for the whole transition period. For the remaining households, we only consider the transfers until they leave the model for retirement. We report results by age and for the two permanent income groups. We proceed as before and first compare the policy mixes of the percentage and lump-sum subsidy with the linear income tax and in the second step, we compare the percentage subsidy with the different financing schemes. In this second step, we also discuss the carbon-tax-and-transfer policy.

The top row of Figure 2.4.4 shows the age profile separately for low- and high-income households of the present value of net transfers for the linear income tax in combination with the two subsidy policies. Annual net transfers in Figure 2.4.1 did not yet allow for a direct conclusion on the distributional consequences of the policy mix especially with lump-sum subsidy because they show an increasing time path of net transfers with a flipping sign in the middle of the transition. Looking at the net present value, the lump-sum subsidy (red dashed line) shows qualitatively similar pattern for low- and high-income households. We find that the age profiles of the net present values increase up to age 45 and decrease afterwards. The levels differ however across income groups. Whereas the present value is except for few age groups around age 45 always negative for low-income households, it is mainly positive for high-income households except for households 55 and older. In terms of net transfer levels, the youngest low-income households have the most negative net present value of transfers of about 900 Euros and high-income middle-age households receive a positive present value of net transfers of up to 1,700 Euros. Aggregating support across households, i.e. summing across households with positive net present value across and within age groups, Table 2.4.1 shows that this policy mix will not find a majority with only 45 percent of households having a positive present value of net transfers.[15]

15. We assume a uniform age distribution and the calibrated population shares of college and non-college households for the high- and low-income households.

Figure 2.4.4. Present value of net transfers of policy mixes across age and income groups



Notes: This figure shows the present value of net transfers of the different policy mixes by age and income group. Left panels show transfers for low-income households and right panels show transfers for high-income households. Transfers are in Euros and have been discounted at the interest rate *r*. Top row show policy mix of a linear income tax and a percentage and lump-sum subsidy for the purchase of the green commitment good. Bottom row shows policy mixes that combine the percentage subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

Looking at the age profiles for the percentage subsidy in Figure 2.4.4 (blue dotted line), we find them to differ qualitatively and quantitatively. Young low-income households experience the largest negative net transfers and low-income households, in general, have on average negative net transfers. For the youngest low-income households, with the most negative transfers the present value is almost 4,000 Euros. By contrast, the present value of net transfers is for almost all age groups of high-income households on average positive and it is substantial with up to 5,200 Euros for middle-age households. These results show that the percentage subsidy that reduces carbon emissions most effectively will not be supported by most low-income households if financed by a linear income tax. Table 2.4.1 shows that only 7.7 percent of low-income households will support the policy and in total the policy will find support only from about a third of the electorate. Hence, the distributional consequences of a policy undermine the support for this climate policy despite its effectiveness in reducing emissions.

The bottom row of Figure 2.4.4 shows the age profiles of net transfers for the different financing schemes from the previous section. It also shows the policy mix of a carbon tax financing a lump-sum transfer but no subsidy. Qualitatively, we find the same distribution patterns as for the annual net transfers in Figure 2.4.3. A financing of the percentage subsidy by a progressive income tax and the carbon-tax-and-transfer policy lead to positive transfers for low-income households and negative transfers for high-income households even if we take the entire transition path into account. By contrast, the linear tax, the consumption tax, and the carbon tax financing a percentage subsidy all lead to a negative present value of net transfers for low-income households. Given that low-income households account for two-thirds of the population, these average numbers already suggest that these policies will not find support by a majority of households. It is mainly high-income households who support these policies as they benefit from the percentage subsidy but contribute less to its financing under these financing schemes so that the present value of net transfers is on average positive (except for some of the oldest households).

Table 2.4.1 shows the results for the support of the different policy mixes when aggregated across households. As expected, we find that all policy mixes that lead on average to negative net transfers for low-income households also do not have a majority supporting them. The least support exists for the consumption and carbon taxes as financing tools. Less than a third of households support these policy mixes. The linear income tax has support of only slightly above one third. By contrast, the progressive income tax finds broad support with almost two-thirds of households supporting this policy. As we have seen, these are mainly low-income households who will adjust less to the green commitment good but who will now also contribute little to the financing of the subsidy. As a consequence, we find that almost all low-income households support this policy mix. Strikingly, we find that no high-income household will support the progressive financing option. On the other hand, no low-income household will support the carbon tax or consumption tax financing option. The other policy mix that finds broad support is the carbon tax financing transfers. Figure 2.4.4 shows that this policy, too, leads typically to positive present values of net transfers for low-income households and negative values for high-income households. Although the policy finds support by a majority of households, we have seen in Figure 2.4.2 that it will lead to little adoption of the green commitment good and consequently is very ineffective in reducing carbon emissions.

Table 2.4.1. Share of households with positive present value of transfers from different policy mixes

Subsidy	Tax	low income	high income	total
Percent	income, linear	7.7%	87.2%	34.9%
Lump-sum	income, linear	28.2%	76.9%	44.8%
Percent	income, progressive	97.4%	0.0%	64.1%
Percent	consumption	0.0%	87.2%	29.8%
Percent	carbon tax	0.0%	89.7%	30.6%
Transfer	carbon tax	94.9%	7.7%	65.1%

Notes: Share of households with positive present value of net transfers for different policy mixes. The shares are computed using the empirical shares of the two income groups of 34.2 percent (high income) and 65.8 percent (low income) and for a uniform age distribution. First column reports specification of subsidy, second column specification of financing instrument of the considered policy mix. The subsidy case *transfer* indicates the case when tax revenues are rebated back as lump-sum transfers. Columns *low income* and *high income* report shares among low-income and high-income households and column *total* shows aggregated share among all households.

A further policy-relevant dimension of climate policies is their effect on inflation. A carbon tax will increase the price of the flow consumption costs for all households who consume the brown commitment good whereas subsidies decrease the price of the green commitment good.[16] A concern for monetary policy will therefore be the different effects of the policy mixes on inflation. We find that the carbon-tax-and-transfer policy will lead to a 1.8pp increase in the price level whereas the percentage subsidy will lead to a 0.2pp decline of the price level. The effect on the price level will be with 4.9pp substantially larger if we consider carbon taxes that reduce emissions as much as the percentage subsidy (Appendix 2.B.3). We also find heterogeneity of the price increase across households. For the carbon-tax-and-transfer policy, we find an increase of 2pp for low-income households and of 1.6pp for high-income households. The difference increases to 1pp in case of the higher carbon tax with a price increase of 5.3pp for low-income households and 4.3pp for high-income households. We also find differences across income groups for the percentage subsidy but they are smaller with price level declines of 0.1pp and 0.2pp for low-income and high-income households, respectively.

In summary, our analysis of the reduction-redistribution trade-off shows that different financing schemes for a percentage subsidy have modest effects on adoption rates, but that there are large differences in the present value of net transfers. We abstract from any welfare gains from carbon reduction for the macroeconomy or

16. We consider a one-time increase of the carbon tax which will have one-time effect on the price level. A gradual introduction would lead to a persistent effect on inflation.

specific groups of households, but our analysis provides an explanation for why some policy mixes may find little support among large segments of the electorate although they could be effective in reducing emissions. Our results thus highlight the political economy constraints of climate policy when considering the transition period with heterogeneous adoption rates. High-income households are, on average, early adopters and thus net recipients of subsidies. To avoid deteriorating support for climate policy, the financing side of the policy must take heterogeneous adoption rates into account by relying on financing that redistributes to low-income households, such as a progressive income tax.

2.4.4 Sensitivity analysis

The current analysis considers already a variety of different policy mixes and studies their reduction-redistribution trade-offs. For the analysis, we restrict the set of policy mixes and have to make specific assumptions on the transition path over the next 25 years. In Appendix 2.B, we provide an extensive analysis with respect to alternative policy mixes and assumptions on the transition path. We first demonstrate that the same conclusions about the reduction-redistribution trade-off arise when we consider the lump-sum subsidy instead of the percentage subsidy. We focus on the percentage subsidy in the main part as it is more effective in reducing carbon emissions as more high-income households adopt the green commitment good under the percentage subsidy. We also discuss and show different assumptions on the price convergence of the green commitment good over the transition period. In the main part, we consider a fast price convergence scenario but we find that the speed of convergence does not have any effect on the key conclusions of the reduction-redistribution trade-off. The results for the slower price convergence scenarios highlight however the important role of technological progress and innovations for the reduction of carbon emissions as they are quantitatively typically more important than policy interventions. We also study a policy mix of the carbon-tax-and-transfer policy with substantially higher carbon taxes. We set the carbon tax to achieve the same reduction of carbon emissions during the transition as the percentage subsidy with progressive taxes. The reduction of emissions are then identical by construction and we find that the redistributive effects also become more similar. Two important differences between the policy mixes however remain. The policy with the subsidy for buying the green commitment good achieves the reduction of emissions by substituting consumption from the brown to the green commitment good. The high carbon tax reduces emissions mainly by reducing consumption of the brown commitment good and has much lower adoption rates of the green commitment good. Hence, the reduction in emissions comes mainly from lower consumption of brown goods whereas it comes from substitution towards green consumption goods in the case of the subsidy. The second difference is the fiscal budget of the two programs. The higher carbon tax implies annual lump-sum transfers of 2,000 Euros per year or almost 82 billion Euros at the level of the macroeconomy for the 41 million German households. The policy with the subsidy for the green commitment good is also a large program but subsidies in the first year will account for less than a quarter with 19 billion Euros. Finally, we demonstrate how the inclusion of newborn generations will affect the distributional dynamics. In the main part of the analysis, we focused on the distributional dynamics only for households alive at the introduction of the policy. The reason is that the focus on this group allows for informative comparison across policy mixes. In general, we find that the conclusions from the main part regarding the reduction-redistribution trade-off are robust to alternative assumptions on policy mixes and transitional dynamics.

2.5 Conclusions

Policies to mitigate climate change are high on the policy agenda of governments around the world. Policies targeting households are of particular interest because the consumption of the household sector accounts for about two-thirds of total carbon emissions. We highlight that a key issue for any climate policy is its distributional consequences. We provide novel empirical facts on the importance of consumption commitments for carbon emissions of households and their heterogeneity in the population. Guided by this empirical evidence, we develop a quantitative life-cycle model with permanent income heterogeneity for the transition period after the introduction of green, carbon-neutral consumption goods. We use the model to evaluate a variety of different policy mixes with respect to their ability to reduce carbon emissions and their distributional consequences. We find that different policy mixes vary little in their ability to reduce carbon emissions, but differ widely in their distributional consequences. We find that widely advocated carbon taxes have strong redistributive consequences, as low-income households are slower and less likely to adjust to green consumption commitments. Progressive financing of a percentage price subsidy offers a policy mix that mitigates the redistributive consequences while still allowing for rapid adoption of carbon-neutral green consumption goods. The main advantage of the percentage price subsidy is that it provides high incentives for high-income households with large carbon footprints to adopt green consumption goods, but the progressive tax financing avoids the large fiscal burden on slowly adopting low-income households of other financing schemes, especially a carbon tax.

References

Axsen, Jonn, Josh Cairns, Nichole Dusyk, and Suzanne Goldberg. 2018. "What drives the Pioneers? Applying lifestyle theory to early electric vehicle buyers in Canada." *Energy Research & Social Science* 44: 17–30.

Cavalcanti, Tiago, Zeina Hasna, Cezar Santos, et al. 2020. *Climate Change Mitigation Policies: Aggregate and Distributional Effects.* JSTOR.

Chetty, Raj, and Adam Szeidl. 2007. "Consumption commitments and risk preferences." *Quarterly Journal of Economics* 122 (2): 831–77.

——, 2016. "Consumption commitments and habit formation." *Econometrica* 84 (2): 855–90.

Clinton, Bentley C, and Daniel C Steinberg. 2019. "Providing the Spark: Impact of financial incentives on battery electric vehicle adoption." *Journal of Environmental Economics and Management* 98: 102255.

Davis, Lucas W. 2023. "The Economic Determinants of Heat Pump Adoption." Working Paper 31344. National Bureau of Economic Research. DOI: 10.3386/w31344. URL: http://www.nber.org/papers/w31344.

De Nardi, Mariacristina, Eric French, and John B Jones. 2010. "Why do the elderly save? The role of medical expenses." *Journal of political economy* 118 (1): 39–75.

Duarte, Rosa, Alfredo Mainar, and Julio Sánchez-Chóliz. 2012. "Social groups and CO2 emissions in Spanish households." *Energy policy* 44: 441–50.

Fehr, Hans, Manuel Kallweit, and Fabian Kindermann. 2013. "Should pensions be progressive?" *European Economic Review* 63: 94–116.

Figenbaum, Erik, and Marika Kolbenstvedt. 2016. "Learning from Norwegian battery electric and plug-in hybrid vehicle users."

Fridstrøm, Lasse, and Vegard Østli. 2021. "Direct and cross price elasticities of demand for gasoline, diesel, hybrid and battery electric cars: the case of Norway." *European Transport Research Review* 13 (1): 1–24.

Fried, Stephie, Kevin Novan, and William B Peterman. 2018. "The distributional effects of a carbon tax on current and future generations." *Review of Economic Dynamics* 30: 30–46.

——, 2022. "Understanding the Inequality and Welfare Impacts of Carbon Tax Policies." Report. Working Paper.

Gilmore, Elisabeth A, and Lester B Lave. 2013. "Comparing resale prices and total cost of ownership for gasoline, hybrid and diesel passenger cars and trucks." *Transport Policy* 27: 200–8.

Glaeser, Edward L, Caitlin S Gorback, and James M Poterba. 2022. "How Regressive are Mobility-Related User Fees and Gasoline Taxes?" Working Paper 30746. National Bureau of Economic Research. DOI: 10.3386/w30746. URL: http://www.nber.org/papers/w30746.

Hardadi, Gilang, Alexander Buchholz, and Stefan Pauliuk. 2021. "Implications of the distribution of German household environmental footprints across income groups for integrating environmental and social policy design." *Journal of Industrial Ecology* 25 (1): 95–113.

Hardman, Scott, Eric Shiu, and Robert Steinberger-Wilckens. 2016. "Comparing high-end and low-end early adopters of battery electric vehicles." *Transportation Research Part A: Policy and Practice* 88: 40–57.

Hardman, Scott, and Gil Tal. 2016. "Exploring the decision to adopt a high-end battery electric vehicle: role of financial and nonfinancial motivations." *Transportation Research Record* 2572 (1): 20–27.

Holland, Stephen P, Erin T Mansur, and Andrew J Yates. 2021. "The electric vehicle transition and the economics of banning gasoline vehicles." *American Economic Journal: Economic Policy* 13 (3): 316–44.

Isaksen, Elisabeth T, and Patrick A Narbel. 2017. "A carbon footprint proportional to expenditure-A case for Norway?" *Ecological Economics* 131: 152–65.

Känzig, Diego R. 2021. "The unequal economic consequences of carbon pricing." *Available at SSRN 3786030*,

Kerkhof, Annemarie C, Henri C Moll, Eric Drissen, and Harry C Wilting. 2008. "Taxation of multiple greenhouse gases and the effects on income distribution: A case study of the Netherlands." *Ecological Economics* 67 (2): 318–26.

Lanteri, Andrea, and Adriano A Rampini. 2023. "Financing the Adoption of Clean Technology."

LCP Delta. 2021. "Heat pump costs projected to fall by 40 percent." URL: https://delta.lcp.com/press-release/heat-pump-costs-projected-to-fall-by-40/.

Lee, Jae Hyun, Scott J Hardman, and Gil Tal. 2019. "Who is buying electric vehicles in California? Characterising early adopter heterogeneity and forecasting market diffusion." *Energy Research & Social Science* 55: 218–26.

Lévay, Petra Zsuzsa, Yannis Drossinos, and Christian Thiel. 2017. "The effect of fiscal incentives on market penetration of electric vehicles: A pairwise comparison of total cost of ownership." *Energy Policy* 105: 524–33.

Miehe, Robert, Rene Scheumann, Christopher M Jones, Daniel M Kammen, and Matthias Finkbeiner. 2016. "Regional carbon footprints of households: a German case study." *Environment, Development and Sustainability* 18: 577–91.

Münzel, Christiane, Patrick Plötz, Frances Sprei, and Till Gnann. 2019. "How large is the effect of financial incentives on electric vehicle sales?–A global review and European analysis." *Energy Economics* 84: 104493.

Nextmove. 2023. "Preisverfall bei E-Autos?" URL: https://nextmove.de/preisverfall-bei-e-autos/?privacy=updated.

Ohlendorf, Nils, Michael Jakob, Jan Christoph Minx, Carsten Schröder, and Jan Christoph Steckel. 2021. "Distributional impacts of carbon pricing: A meta-analysis." *Environmental and Resource Economics* 78 (1): 1–42.

Perobelli, Fernando Salgueiro, Weslem Rodrigues Faria, and Vinicius de Almeida Vale. 2015. "The increase in Brazilian household income and its impact on CO2 emissions: Evidence for 2003 and 2009 from input–output tables." *Energy Economics* 52: 228–39.

Postlewaite, Andrew, Larry Samuelson, and Dan Silverman. 2008. "Consumption commitments and employment contracts." *Review of Economic Studies* 75 (2): 559–78.

RWI and Forsa. 2015. "The German Residential Energy Consumption Survey 2011-2013." *RWI Projektberichte*,

Santos, Cezar, and David Weiss. 2016. ""Why not settle down already?" a quantitative analysis of the delay in marriage." *International Economic Review* 57 (2): 425–52.

Schloter, Lukas. 2022. "Empirical analysis of the depreciation of electric vehicles compared to gasoline vehicles." *Transport Policy* 126: 268–79.

Segovia, Javier Lôpez. 2021. "Consumption Commitments and Unemployment Insurance."

Shore, Stephen H, and Todd Sinai. 2010. "Commitment, risk, and consumption: do birds of a feather have bigger nests?" *Review of Economics and Statistics* 92 (2): 408–24.

Stadler, Konstantin, Richard Wood, Tatyana Bulavskaya, Carl-Johan Södersten, Moana Simas, Sarah Schmidt, Arkaitz Usubiaga, José Acosta-Fernández, Jeroen Kuenen, Martin Bruckner, et al. 2018. "EXIOBASE 3: Developing a time series of detailed environmentally extended multi-regional input-output tables." *Journal of Industrial Ecology* 22 (3): 502–15.

Statista. 2023. "Vergleich der Anschaffungskosten verschiedener Heizsysteme in Deutschland im Jahr 2022." URL: https://de.statista.com/statistik/daten/studie/380742/umfrage/anschaffungskosten-verschiedener-heizsystem-in-deutschland/.

Verivox. 2023. "Heizkostenvergleich: Wärmepumpe bis zu 39 Prozent günstiger als Erdgas." URL: https://www.verivox.de/strom/nachrichten/heizkostenvergleich-waermepumpe-bis-zu-39-prozent-guenstiger-als-erdgas-1119298/.

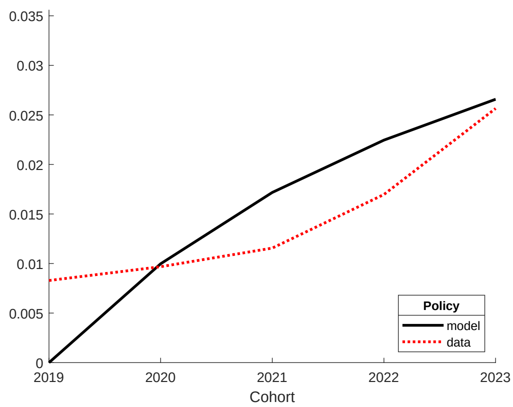
Westin, Kerstin, Johan Jansson, and Annika Nordlund. 2018. "The importance of socio-demographic characteristics, geographic setting, and attitudes for adoption of electric vehicles in Sweden." *Travel Behaviour and Society* 13: 118–27.

Wiedenhofer, Dominik, Dabo Guan, Zhu Liu, Jing Meng, Ning Zhang, and Yi-Ming Wei. 2017. "Unequal household carbon footprints in China." *Nature Climate Change* 7 (1): 75–80.

Appendix 2.A Additional results

Figure A1 compares the adoption rates for the green commitment good after its introduction in the model and compares the path to the data. The model starts at a share of households with the green commitment good of zero in 2019. Empirically, the share is already slightly positive by 2019. By 2020, we get, however, that the model has already converged to the adoption rate in the data and that after 2020 model and data show a close alignment in adoption rates increasing by about half a percentage point per year. We take this close alignment of adoption rates as further supporting evidence that the model provides a good framework to study the adoption dynamics of the green commitment good.

Figure A1. Comparison of adoption of green commitment good with data



Notes: This figure shows the adoption of the green commitment good after its introduction relative to data for the time period from 2019 to 2023.

Appendix 2.B Sensitivity analysis

For the policy analysis in the main part of the paper, we focus on policy mixes that combine the percentage subsidy with different financing schemes. Here, we present the same policy experiments as in the main part for other policy mixes and different assumptions on price paths of the green commitment good. In Section 2.B.1, we report results for the lump-sum subsidy in combination with different financing schemes. In Section 2.B.2, we show the reduction-redistribution trade-off for alternative assumptions on the price convergence of the green commitment good. In the main part of the paper, we discuss a price scenario of fast convergence of prices. In Section 2.B.2.1, we present the results for slower price convergence of the green commitment good and in Section 2.B.2.2, we show the case without any price convergence of the green commitment good. Section 2.B.3 discusses a policy mix of a carbon tax that finances transfers as in Section 2.4 (carbon tax + transfer + no subsidy) but instead of determining the tax to yield the same fiscal budget as in the case of the proportional subsidy, we now target the emission reduction by adjusting the carbon tax. In the main part, we saw that the carbon tax with the same fiscal budget yields only a small reduction in emissions. Tax receipts will as before be reimbursed lump-sum to households. Finally, we consider in Section 2.B.4 the effect on the transition path if newborn cohorts enter the economy during the transition period and under the same policy that is in place for households initially alive. Importantly, policies will now no longer have a balanced budget and imply for entering cohorts that they are net recipients or contributors to the system depending on the specific policy. We discuss the results because of their macroeconomic relevance for the evolution of emissions but highlight the problem of comparability of policies with non-balanced budgets.

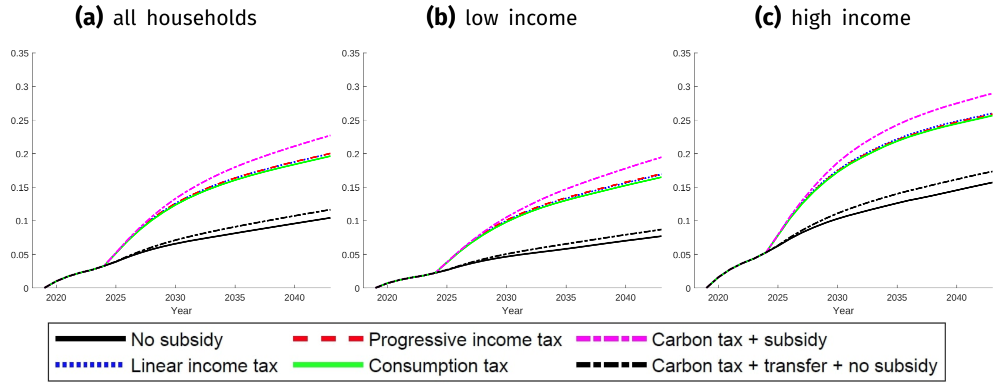
2.B.1 Results for lump-sum subsidy

In this section, we consider the policy experiment from Section 2.4.2 but now combine the lump-sum subsidy with different financing schemes. As in the main part, we first show the effect on adoption rates (reduction) and then discuss the distributional consequences (redistribution).

Figure A1 shows the adoption rates. We find that average adoption rates look very similar to the case of the percentage subsidy but they are on average lower. The combination with the different financing schemes yield the same pattern as in the case of the percentage subsidy. The financing of the subsidy by a carbon tax leads to the most adoption as the carbon tax provides additional substitution incentives. The results for the carbon-tax-and-transfer policy remain unaffected as no subsidy is paid for the green commitment good. When looking across income groups, we see that the lower adoption rates mainly stem from the high-income households. Their adoption rates go down because of the smaller incentive to buy large green commitment goods when the subsidy is lump-sum rather than proportional to the purchase price.

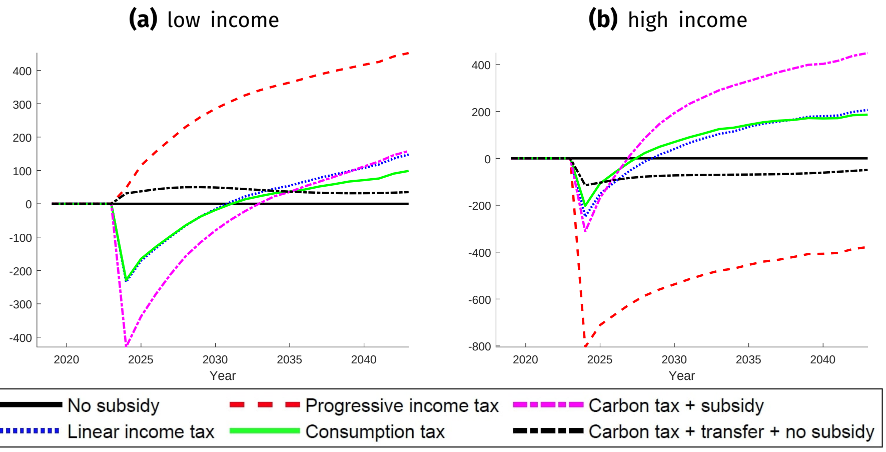
When we look at the annual net transfers during the transition, Figure A2 shows similar patterns as in the case of the percentage subsidy but levels of net transfers change and in particular net transfers increase for low-income households and decline for high-income households. In case of the linear income tax, we find that when combined with the percentage subsidy that low-income households have during the entire transition period with the exception of few years in the end of the transition negative net transfers. In case of the lump-sum subsidy, it becomes relatively more attractive for them to purchase the green commitment good so that they receive more transfers and we find that already after 8 years of the transition period, their transfers turn positive. Yet, as we will see below the net present value remains negative for most of the households from this policy. If we look at the progressive income tax as a financing instrument, we find consistently

Figure A1. Share of households with green consumption commitments with lump-sum subsidies



Notes: This figure shows the share of households with the green commitment good along the transition path for different policy mixes. The left panel shows the share among all households, the middle panel shows the share for low-income households, and the right panel shows the share for high-income households. The policy mix is the combination of a lump-sum subsidy on the green commitment good in combination with different financing schemes. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

Figure A2. Annual net transfers with lump-sum subsidies



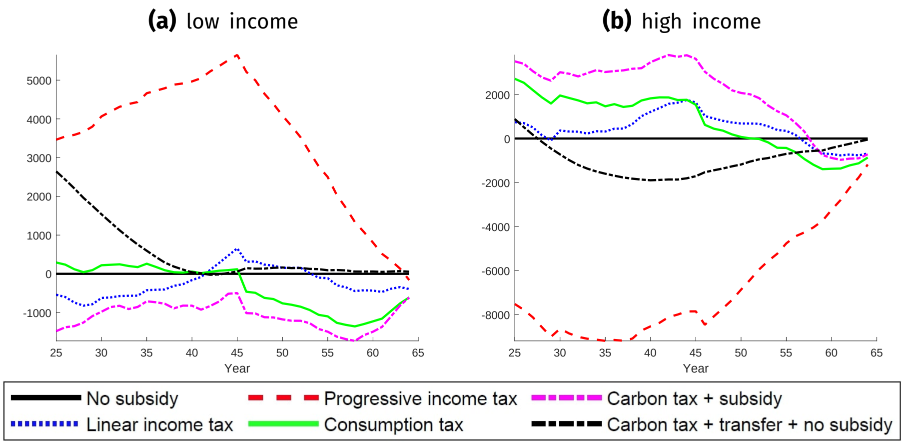
Notes: This figure shows the annual net transfers of different policy mixes. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros per year. The different policy mixes combine a lump-sum subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

that with the lump-sum subsidy high-income households receive less subsidies so that there are transfers from high-income to low-income households. In the year

2030, the negative net transfer with the lump-sum subsidy is almost 40 percent larger than in the case of the percentage subsidy.

In Figure A3, we report the present value of net transfers from the different policy mixes with the lump-sum subsidy. As before, results for the carbon-tax-and-transfer policy will not change relative to the results in the main part of the paper. Qualitatively, we get very similar conclusions compared to the case with the percentage subsidy. Yet, we find again that the lump-sum subsidy favors low-income households. We see this now most strongly for younger low-income households. For a 30-year-old low-income household, the average present value of net transfers in the case of a linear income tax is roughly cut by more than 80 percent from about 3250 Euros to around 620 Euros. We have seen in the main part that a progressive tax financing of the subsidy will lead to positive transfers for low-income households even if the subsidy is proportional to the value of the green commitment good. If the subsidy becomes lump-sum, this further benefits the low-income households as their transfers increase. Yet, this comes at the cost of lower adoption rates as we have seen before. Hence, we find that generally the results for the reduction-redistribution trade-off are robust to what kind of subsidy is used but the percentage subsidy is more effective in increasing adoption rates and decreasing emissions as more of the high-income households with a large carbon footprint adjust their consumption choices.

Figure A3. Present value of net transfers of policy mixes across age and income groups - lump sum subsidy



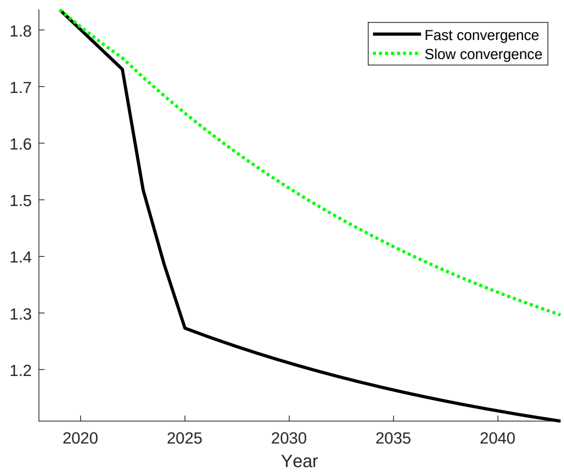
Notes: This figure shows the present value of net transfers of the different policy mixes by age and income group. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros per year and have been discounted at the interest rate r. The different policy mixes combine a lump-sum subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

2.B.2 Results for different price convergence paths

This section presents the results for different convergence paths of the price premium for green commitment goods over the transition period. We first discuss the different price convergence scenarios including the price convergence path for our baseline results from Section 2.4. In Section 2.B.2.1, we then show a sensitivity analysis with results for a slow price convergence path following price projections for electric vehicles in Holland et al. (2021) and in Section 2.B.2.2, we show results for a scenario without any price convergence over time.

Figure A4 shows the aggregated path for the price premium of the composite commitment good in the model that underlies the policy experiment in Section 2.4. We see that the fast convergence path shows a particularly strong convergence of prices until the year 2025 (black solid line). The reason for this fast convergence is that prices for electric cars are predicted to converge very quickly so that there will be no price premium for electric cars after 2025 (see below). The non-zero price premium and the ongoing convergence after 2025 is only a result of the convergence of the price for heating systems. The green dotted line shows the alternative scenario of a slow price convergence over time that we consider in Appendix 2.B.2.1.

Figure A4. Price for green relative of brown commitment goods - composite good

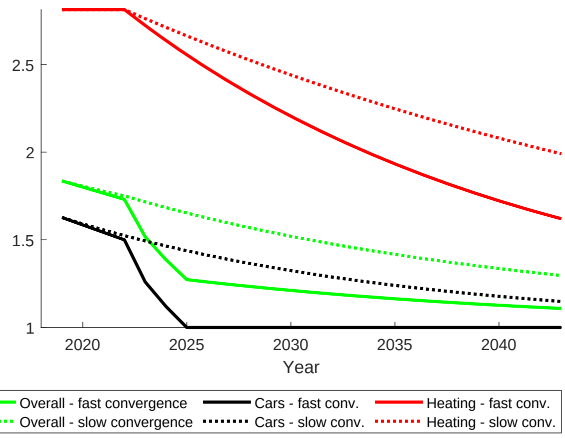


Notes: This figure plots the price paths for green commitment good relative to brown commitment good. The solid black line shows the baseline scenario that is used in the main part of the paper. The green dotted line shows the slower convergence path for which results are shown in Appendix Section 2.B.2.1.

Figure A5 decomposes the composite price dynamics and shows the separate paths for price premia for electric cars and heating systems that we aggregate to the price premium ω in Figure A4. Aggregation weights combine expenditure shares and adjustment frequency to get a composite commitment good (see footnote

8). We show for electric cars and heating systems a slow and fast convergence scenario that we aggregate accordingly for the composite commitment good. For electric cars, we observe that under the fast convergence scenario the price premium for cars has disappeared by 2025. This convergence explains the kink in the aggregated time series in Figure A4 in the year 2025.

Figure A5. Price for green relative of brown commitment goods - cars and heating systems



Notes: This figure shows the price paths for the green commitment goods relative to brown commitment goods separately for cars and heating system and for the aggregated composite good. The solid lines describe the baseline scenario that is used in the main part of the paper. The dotted lines show the slower convergence scenario for which results are shown in Appendix Section 2.B.2.1.

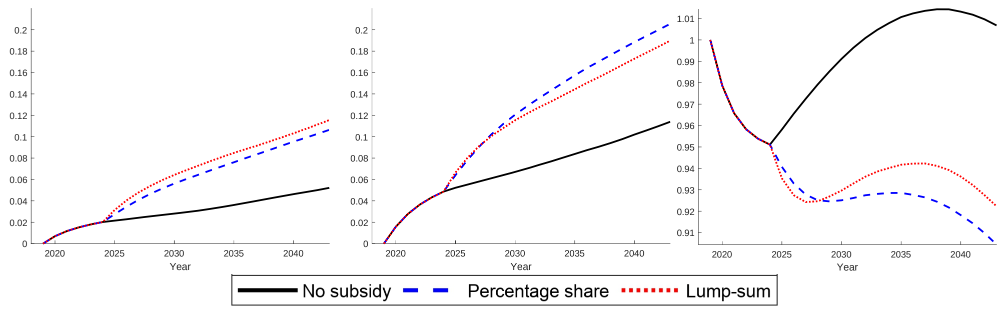
Green heating systems start with a substantially higher initial price premium and price convergence is predicted to be much slower compared to cars so that even at the end of the transition period, there is still a large price premium of the green over the brown commitment good.

2.B.2.1 Slow price convergence

Figure A6 presents results for the three policy scenarios from Section 2.4.1 under the slow price convergence scenario. It shows the share of households with green commitment goods for the low- and high-income group, as well as the reduction in emissions along the transition path. As prices for green commitment good convergence at a slower rate to those of the brown commitment good, we find that the share of households with a green commitment good to be smaller and consequently the reduction in carbon emission to be lower compared to the baseline scenario. We find that on average adoption rates are about two-thirds of our baseline scenario but that there are no qualitative differences in transition paths if the price convergence is slower. Looking at the reduction of emissions, we find that the slower price convergence is too weak to counteract the life-cycle effect of the aging cohort that arises in the model as we are following the initial cohort of households. With a lower price reduction, their life-cycle increase of consumption of the brown commitment good leads even to an increase of emissions over time. We see this effect also for the cases with the subsidy in place but the subsidy mitigates the effect and leads only in the case of the lump-sum subsidy to a non-monotonicity starting in year 2030.

Figure A6. Share of households with green commitment good by income and reduction in carbon emissions for slow price convergence - subsidy side

(a) low income **(b)** high income **(c)** Reduction in emissions



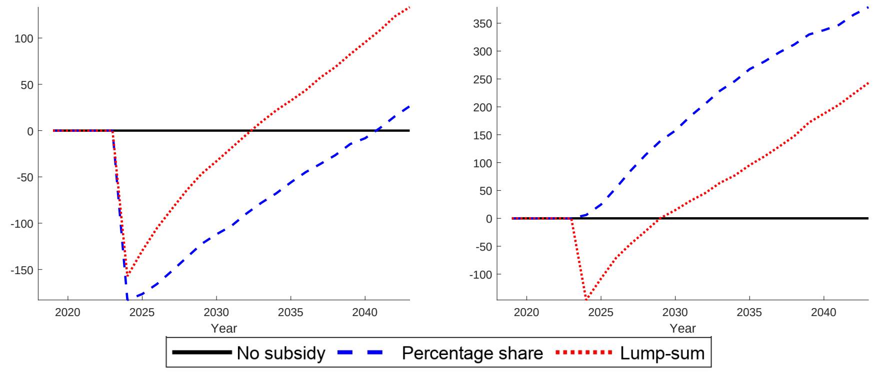
Notes: Panels (a) and (b) show the share of households with green commitment goods along the transition path for percentage and lump-sum subsidy and in the case with no subsidy for low- and high-income households for slow price convergence. Panel (c) shows the reduction in carbon emissions along the transition for percentage and lump-sum subsidy and in the case with no subsidy for slow price convergence. Carbon emissions only come from brown consumption commitment goods and are assumed to be proportional to the size of the brown commitment good.

Figure A7 shows the annual net transfers under the slow price convergence scenario. We find qualitative the same pattern as in Section 2.4.1. There will be redistribution from low-income to high-income households and the redistribution is stronger under the percentage subsidy. On average, there is less redistribution because fewer green commitment goods are bought so that fewer subsidies are paid out. Figure A8 shows the corresponding present value of net transfers for low- and high-income households by age in the case of slower price convergence of the green commitment good. Qualitatively, we find the same results as under the fast convergence scenario. Quantitatively, we get that the heterogeneity of the present values of transfers across age groups is smaller than in the fast price convergence scenario.

As in the analysis in the main part of the paper, we combine in the next step the percentage subsidy with different financing seems to further explore the reduction-redistribution trade-off. Figures A9, A10, and A11 present the corresponding results to Section 2.4.2 for the financing side under the slow price convergence scenario. Qualitatively, we find results to have similar redistribution patterns and that the differences in the speed of adjustment under slow price convergence mainly affects results quantitatively. Most notably, we find that the present value

Figure A7. Annual net transfers for slow price convergence - subsidy side

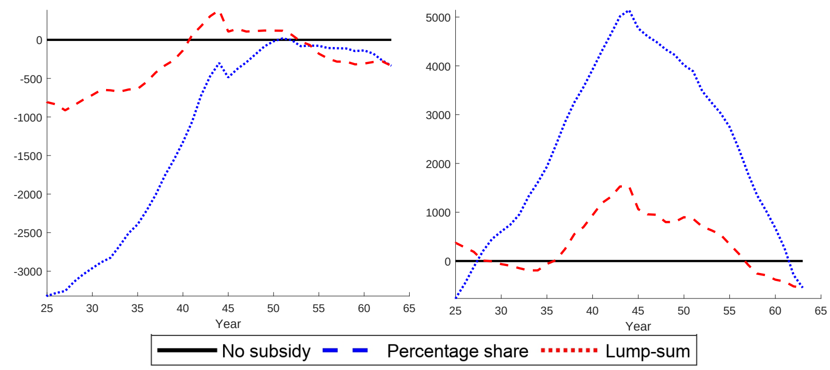
(a) low income **(b)** high income



Notes: This figure shows the annual net transfers along the transition period for the different subsidy specifications and for low- and high-income households in case of slow price convergence of the green and the brown commitment good. Net transfers are the difference between subsidies and taxes paid and are in Euros per year.

Figure A8. Present value of net transfers for different age groups and subsidies for slow price convergence - subsidy side

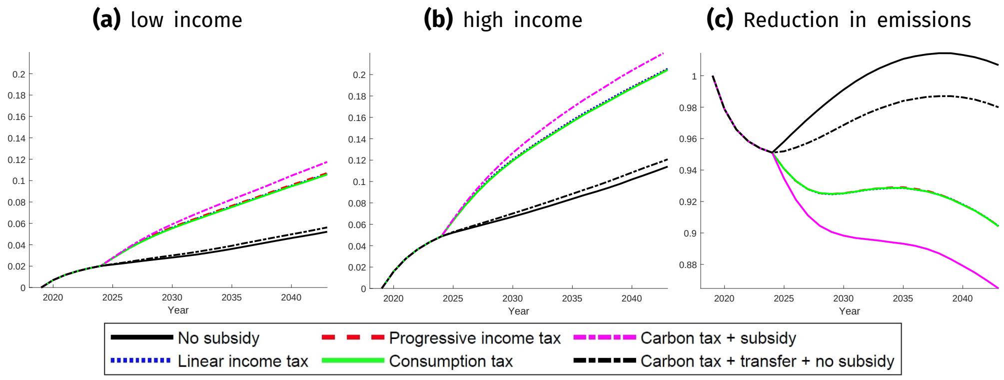
(a) low income **(b)** high income



Notes: This figure shows the present value of net transfers of the different policy mixes by age and income group in the case of slow price convergence. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros and have been discounted at the interest rate r. The policy mixes combine a linear income tax with a percentage and lump-sum subsidy for the purchase of the green commitment good. The subsidies for both policy mixes are set to have a balanced budget over the transition period.

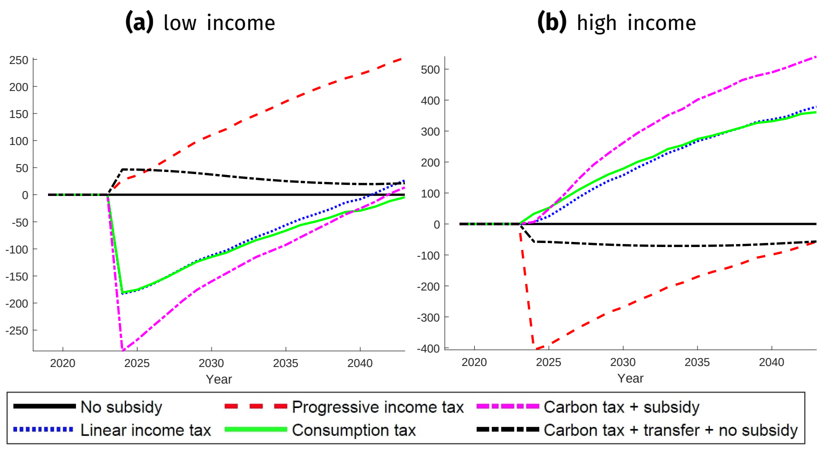
of net transfers becomes less negative for high-income mid-age households under progressive financing with slower price convergence. The reason is that with a smaller program size overall because of lower adoption rates, also tax rates decline so that there will be less redistribution. Based on these results, we conclude that our findings on the reduction-redistribution trade-off are robust to the assumptions on the speed of price convergence.

Figure A9. Share of households with green commitment good by income and reduction in carbon emissions for slow price convergence - financing side



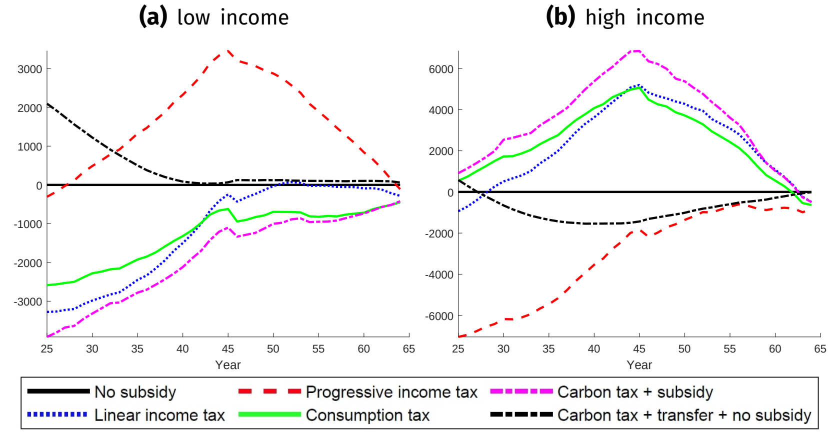
Notes: This figure shows for the case of slow price convergence the share of households with the green commitment good along the transition path for different policy mixes and the reduction in carbon emissions. The left panel shows the share for low-income households and the middle panel shows the share for high-income households. The right panel shows the reduction in emissions. Carbon emissions only come from brown consumption commitment goods and are assumed to be proportional to the size of the brown commitment good. The policy mix is the combination of a percentage subsidy on the green commitment good in combination with different financing schemes. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

Figure A10. Annual net transfers for slow price convergence - financing side



Notes: This figure shows for the case of slow price convergence the annual net transfers of different policy mixes. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros per year. The different policy mixes combine a percentage subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

Figure A11. Present value of net transfers of policy mixes across age and income groups for slow price convergence - financing side



Notes: This figure shows the present value of net transfers of the different policy mixes by age and income group in the case of slow price convergence. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros and have been discounted at the interest rate *r*. The different policy mixes combine a percentage subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

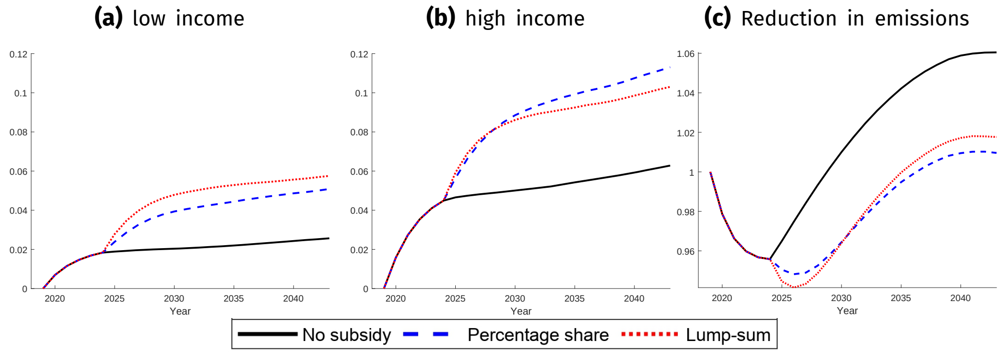
2.B.2.2 No price convergence

Finally, we also report results for a scenario without any price convergence between the green and the brown commitment good. We consider this an unlikely scenario given the available data on price dynamics, yet, we think it is an instructive scenario to study as it takes out all effects of exogenous price dynamics for the transition period. In the case without a relative price decline, we will still see that there are positive adoption rates of the green commitment good. There are two reasons for these positive adoption rates. First, there will always be adoption of the green commitment good after its introduction in the model in 2019 because of its different utility value (equation (2.3.2)) and the life-cycle dynamics of consumption. Second, if additional subsidies are introduced, then this will further increase demand for the green commitment good at a constant price differential to the brown commitment good.

Figure A12 presents the share of households with green commitment goods and the reduction in emissions under the no price change scenario. Not surprisingly, we find that the share of households with green commitment goods and the reduction in emissions is smaller than in the fast and the slow price convergence scenario. Despite the constant price difference between the green and the brown commitment good, we find a reduction of emissions at the end of the transition period of 8 percent. The reduction is 15 percent under the slow convergence scenario and

25 percent under the fast convergence scenario. The adoption rate of 8 percent in the no price convergence scenario in contrast to the 25 percent adoption rate in the fast price convergence scenario shows that competition and technological progress are important drivers of adoption rates over time and policy will only act on top of these developments.

Figure A12. Share of households with green commitment good by income and reduction in carbon emissions for no price convergence - subsidy side

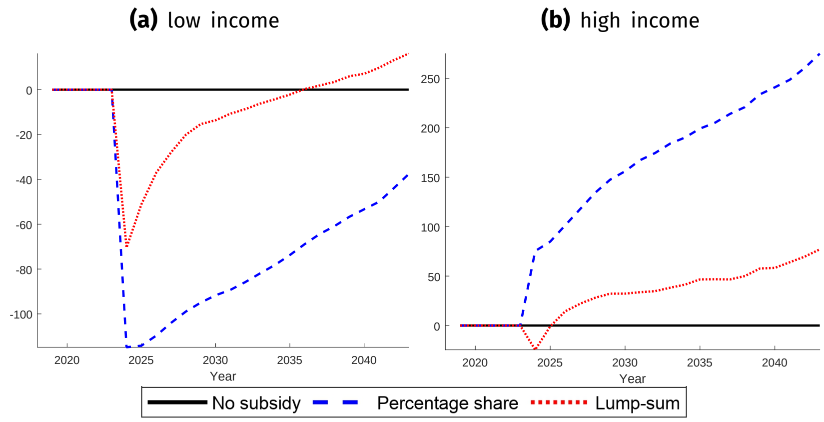


Notes: Panels (a) and (b) show the share of households with green commitment goods along the transition path for percentage and lump-sum subsidy and in the case with no subsidy for low- and high-income households for no price convergence. Panel (c) shows the reduction in carbon emissions along the transition for percentage and lump-sum subsidy and in the case with no subsidy for no price convergence. Carbon emissions only come from brown consumption commitment goods and are assumed to be proportional to the size of the brown commitment good.

Figures A13 and A14 depict the annual net transfers and the present value of net transfers of the two subsidies. We find that annual transfers are negative for most of the transition period for low-income households and positive for most of the transition period for high-income households. This is different to the price scenarios before where net transfers in case of the lump-sum subsidy turned positive for both groups much earlier in the transition process. Absent falling prices, adoption rates for low-income households remain however low. For low-income households, the present value of net transfers remains negative in the case of the lump-sum subsidy around age 40 and until age 50 for the percentage subsidy. After these ages, the values remain at zero or only slightly above. For high-income households, we find that even in the absence of price convergence adoption rates are high enough to lead to substantial positive present values of net transfers at most ages. For both subsidies, the present value is highest between age 40 and 45 and only negative in the first 5 years respectively 10 years of the life cycle depending on the subsidy specification.

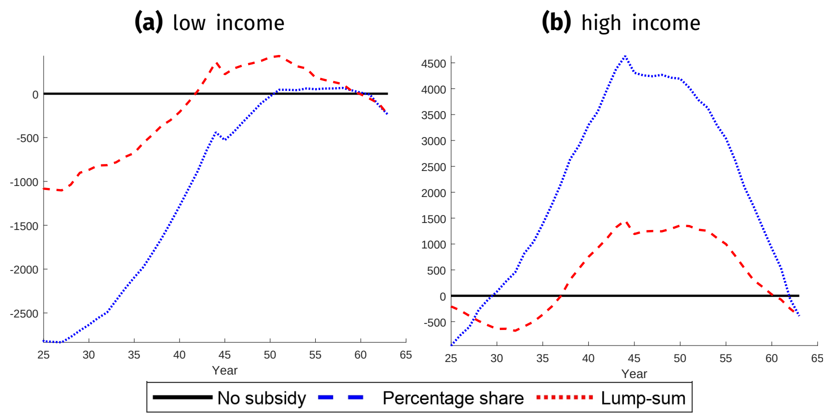
Figures A15, A16, and A17 show the results for the percentage subsidy with different financing instruments in the case of no price convergence. Looking at the share of households with the green commitment good in Figure A15, we find that adoption rates vary only little with the financing instrument. The only financing instrument that makes a difference is the carbon tax that provides an additional incentive to buy the green commitment good.

Figure A13. Annual net transfers for no price convergence - subsidy side



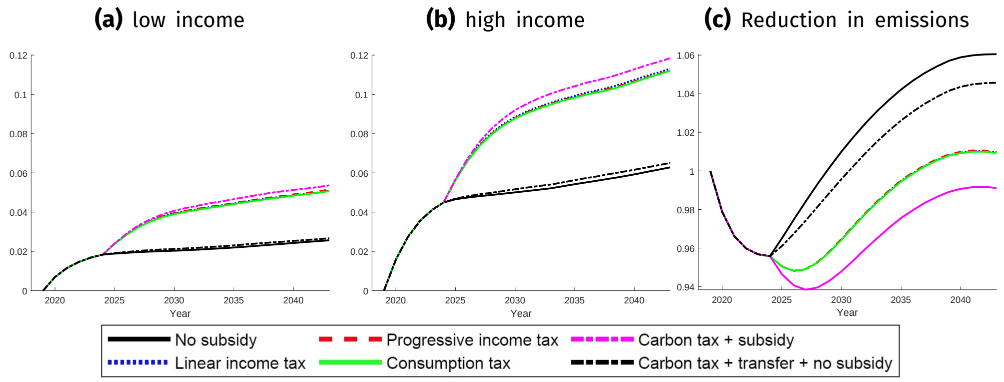
Notes: This figure shows the annual net transfers along the transition period for the different subsidy specifications and for low- and high-income households in case of no price convergence of the green and the brown commitment good. Net transfers are the difference between subsidies and taxes paid and are in Euros per year.

Figure A14. Present value of net transfers for different age groups and subsidies for no price convergence - subsidy side



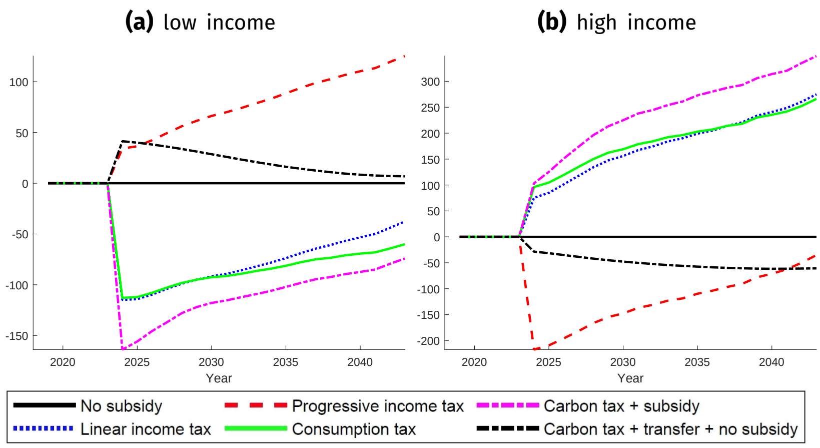
Notes: This figure shows the present value of net transfers of the different policy mixes by age and income group in the case of no price convergence. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros and have been discounted at the interest rate r. The policy mixes combine a linear income tax with a percentage and lump-sum subsidy for the purchase of the green commitment good. The subsidies for both policy mixes are set to have a balanced budget over the transition period.

Figure A15. Share of households with green commitment good by income and reduction in carbon emissions for no price convergence - financing side



Notes: This figure shows for the case of no price convergence the share of households with the green commitment good along the transition path for different policy mixes and the reduction in carbon emissions. The left panel shows the share for low-income households and the middle panel shows the share for high-income households. The right panel shows the reduction in emissions. Carbon emissions only come from brown consumption commitment goods and are assumed to be proportional to the size of the brown commitment good. The policy mix is the combination of a percentage subsidy on the green commitment good in combination with different financing schemes. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

Figure A16. Annual net transfers for no price convergence - financing side

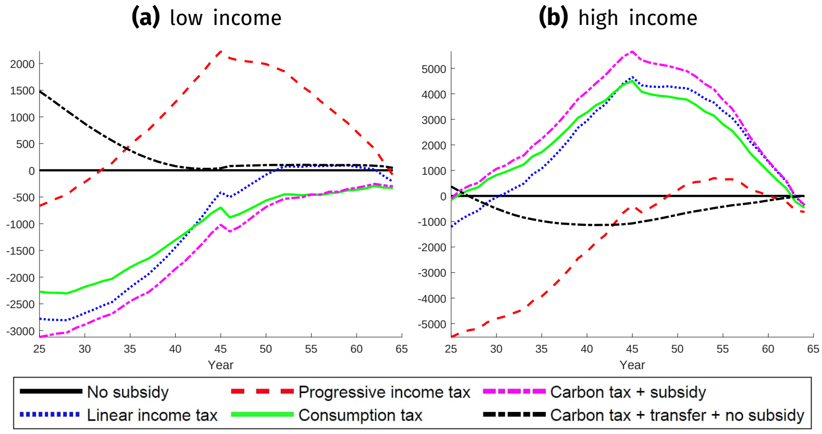


Notes: This figure shows for the case of no price convergence the annual net transfers of different policy mixes. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros per year. The different policy mixes combine a percentage subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

Figure A16 shows the annual net transfers for the different policy mixes in case of no price convergence. The key difference to the baseline experiment is that adoption rates are lower as the green commitment good maintains a higher price premium. We observe that the absolute size of annual transfers are smaller compared to the two price scenarios with price convergence, yet, we also see that the qualitative results remain unchanged. Only the financing of the subsidy by a progressive income tax or the carbon-tax-and-transfer policy without a subsidy yield positive net transfers for low-income households. The other policy mixes all lead to positive net transfers to high-income households. The time trend in transfers results from the life-cycle effect as we are only considering the cohort of households alive at the introduction of the policy.

Figure A17 shows the net present value of transfers by age of the different policy mixes. We find our key results to be robust. The only policy that offers subsidies and thereby substantially increases adoption rates and that also implies positive net transfers for most low-income households is the policy mix with the progressive tax as a financing instrument.

Figure A17. Present value of net transfers of policy mixes across age and income groups for no price convergence - financing side

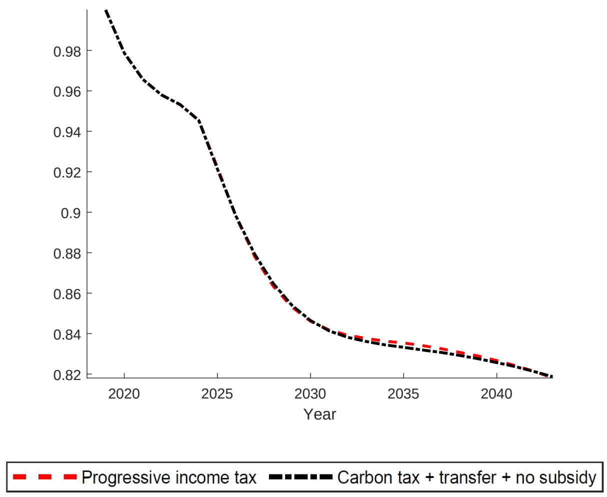


Notes: This figure shows the present value of net transfers of the different policy mixes by age and income group in the case of no price convergence. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros and have been discounted at the interest rate r. The different policy mixes combine a percentage subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

2.B.3 Results for higher carbon taxes

In Section 2.4, we construct all policy mixes so that they imply a balanced budget over the transition period for a given percentage subsidy. If we use the receipts of the carbon tax to finance lump-sum transfers instead of a subsidy, we find that only few households adjust to the green commitment good (carbon tax + transfer + no subsidy). In this section, we therefore consider a carbon tax that we set to match the same reduction in carbon emissions as in the case of the percentage subsidy with progressive taxation. To match a 18 percent reduction of emissions, we need a carbon tax that is substantially higher. In Section 2.4, the carbon tax was 22 percent and it has to be increased to 58 percent to match the same reduction in emissions, hence, more than 2.5 times as high. This higher carbon tax corresponds to a carbon price of 342 Euros per ton that is six times its current level and the annual transfer per household that the tax finances are about 2,000 Euros per year. Figure A18 shows the reduction in carbon emissions with progressive tax and the percentage subsidy from Section 2.4 and the higher carbon tax.

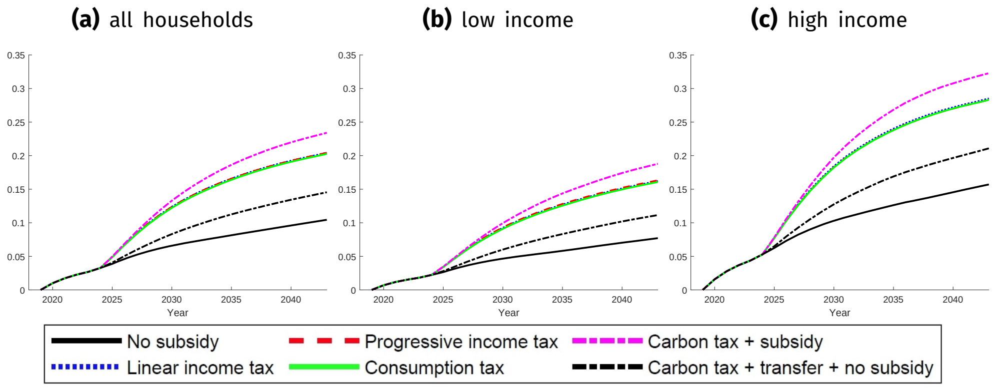
Figure A18. Emission reduction with higher carbon taxes



Notes: This figure depicts the reductions in carbon emissions when a progressive income tax finances a percentage subsidy and when a carbon tax revenues are rebated back to households as lump-sum transfers.

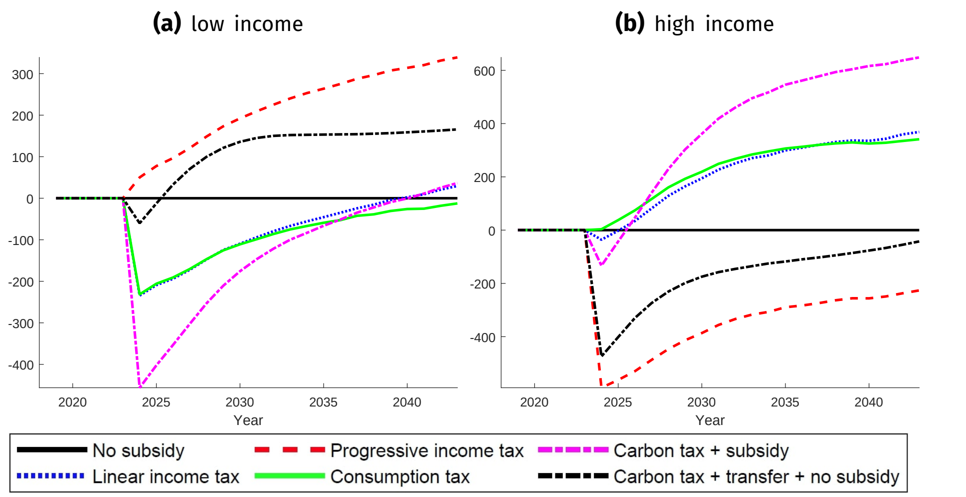
Figure A19 shows the share of households with the green commitment good under the policies as in Section 2.4 and in case of the higher carbon tax (carbon tax + transfer + no subsidy). Although the carbon tax has been set to match the same reduction in emissions, the share of households with the green commitment good increases only modestly over the no subsidy case. Surprisingly, the adoption rate remains low compared to the policies that yield the same reduction in emissions. The reason is that an important part of the reduction in emissions comes from households who still consume the brown commitment good but who consume less of the good so that emissions fall because of less consumption of the brown commitment good rather than substitution to the green good. Compared to the

Figure A19. Share of households with green consumption commitments with higher carbon tax



Notes: This figure shows the share of households with the green commitment good along the transition path for different policy mixes. The left panel shows the share among all households, the middle panel shows the share for low-income households, and the right panel shows the share for high-income households. The policy mix is the combination of a percentage subsidy on the green commitment good in combination with different financing schemes. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but a higher carbon tax where the tax revenues are rebated back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

Figure A20. Annual net transfers with higher carbon tax



Notes: This figure shows the annual net transfers of different policy mixes. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros per year. The different policy mixes combine a percentage subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but a higher carbon tax where the tax revenues are rebated back to households as lump-sum transfers. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

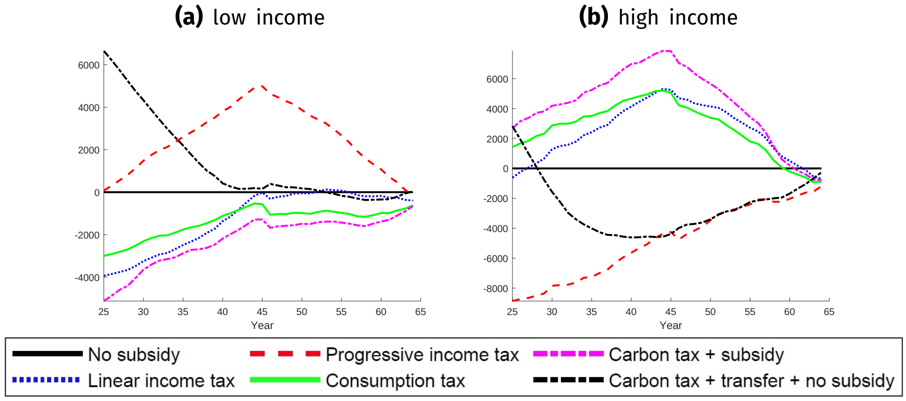
no policy scenario, the reduction of emissions with higher carbon taxes is 14pp of which 10pp are accounted for by smaller commitment goods and only 4pp because of higher adoption rates.

Figure A20 shows the annual net transfers of the different policy mixes from Section 2.4 and for the case of the higher carbon tax. We find that the net transfers of the policy mix with the higher carbon tax converge to the policy mix of the progressive income tax with the percentage subsidy. The lump-sum transfer financed by the higher carbon taxes increases the progressivity of the tax and transfer system similar to the progressive tax system. While the two policy mixes appear similar with respect to the time path of average net transfers, we find that they still differ substantially in their distributional effects across age groups.

Figure A21 shows the present value of net transfers by age group. Comparing the carbon-tax-and-transfer policy without a subsidy to the progressive income tax with percentage subsidy shows very different distributional consequences by age among low-income households. The same qualitative pattern already arises in the case of the lower carbon tax but at a substantially smaller scale (Figure 2.4.4). We find the progressive income tax with a percentage subsidy to be particularly attractive for mid-age low-income households who adopt to the green commitment good and receive the subsidy but pay low taxes. By contrast, the carbon-tax-and-transfer policy is most attractive for young low-income households who consume little of the brown commitment good, pay little carbon taxes, and receive the full lump-sum transfer. Hence, the carbon-tax-and-transfer policy redistributes mainly to households who consume little of the commitment good or reduce their consumption whereas the subsidy policy redistributes to households who change to consuming the green commitment good. Hence, whereas the carbon tax policy reduces consumption for most households because of the increase in user costs, the policy of a progressive tax to finance a subsidy leads to more substitution because of increased substitution incentives.

For high-income households, we find the corresponding pattern. The carbon-tax-and-transfer policy leads to the largest negative present values for mid-age households who consume the brown commitment good. The youngest high-income households receive slightly positive net transfers as they reduce their consumption of the brown commitment good, pay little carbon taxes, and receive the transfers financed by the carbon tax. With the progressive income tax to finance a subsidy, we find that the present value is always negative but that net transfers are the least negative for those households who are most likely to adopt to the green commitment good, the older high-income households. The group with the largest negative present value are the high-income young households as they receive little of the subsidy as they are buying less of the green commitment good but they contribute to the financing of the subsidy program by paying the higher progressive tax rate.

Figure A21. Present value of net transfers of policy mixes across age and income groups with higher carbon tax



Notes: This figure shows the present value of net transfers of the different policy mixes by age and income group. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros per year and have been discounted at the interest rate r. The different policy mixes combine a percentage subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but a higher carbon tax where the tax revenues are rebated back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

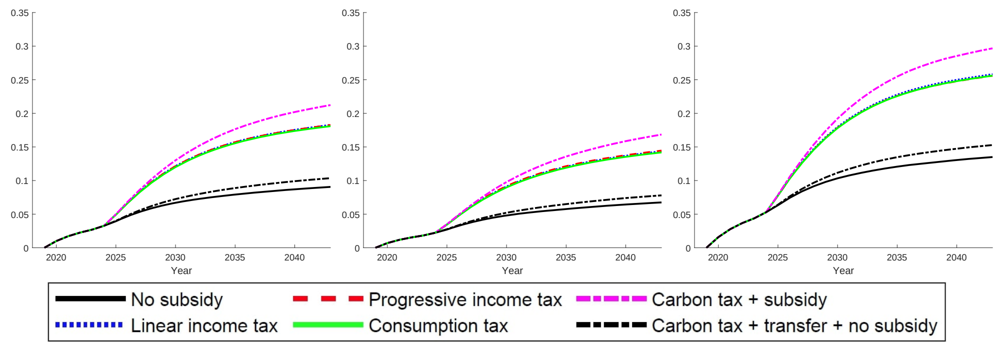
In summary, a substantially higher carbon tax that is rebated as lump-sum transfer could be an alternative to a progressive tax policy financing a percentage subsidy. The policies differ however in the mechanism how the reduction of emissions is achieved. Whereas the higher carbon tax achieves a large part of the reduction by reducing consumption of the brown commitment good by higher user costs, the subsidy policy financed by a progressive tax provides incentives for substitution so that higher adoption rates of the green commitment good lead to the reduction of emissions. These differences in mechanism show up in the very different distributional consequences along the age dimension of these policies. Importantly, the two policies also differ in their fiscal budget. The higher carbon tax policy will at the level of the macroeconomy lead to transfers of about 82 billion Euros per year given 41 million households in Germany. This budget corresponds to 20 percent of the current German federal budget. The progressive tax policy is substantially smaller but would still be a large fiscal program with about 19 billion Euros of subsidies in the first year of the program.

2.B.4 Entering newborn cohorts during the transition

In Section 2.4, we discuss the transition dynamics for the group of households alive a the introduction of the policy. We abstract from young cohorts entering the model at later points during the transition to allow for a transparent comparison. Here, we show results with newborn households entering the model during the transition. We keep the taxes, transfers, and subsidies as before what implies that the policies typically do not have a balanced budget over the transition period but that the newborn cohorts are either net recipients or net contributors. Figure A22 shows the adoption rates with newborn households. The key qualitative difference is that the entry of new cohorts will remove the life-cycle effect on the transitional dynamics as now the age structure remains constant over the transition period. As young households are less likely to buy the green commitment good, we find that there is a negative effect on adoption rates but the effects are overall very small. In case of the percentage subsidy financed by a progressive tax, the average adoption rate at the end of the transition period declines by 2pp from 20 percent to 18 percent.

Figure A22. Share of households with green consumption commitments by income and reduction in carbon emissions with newborn cohorts

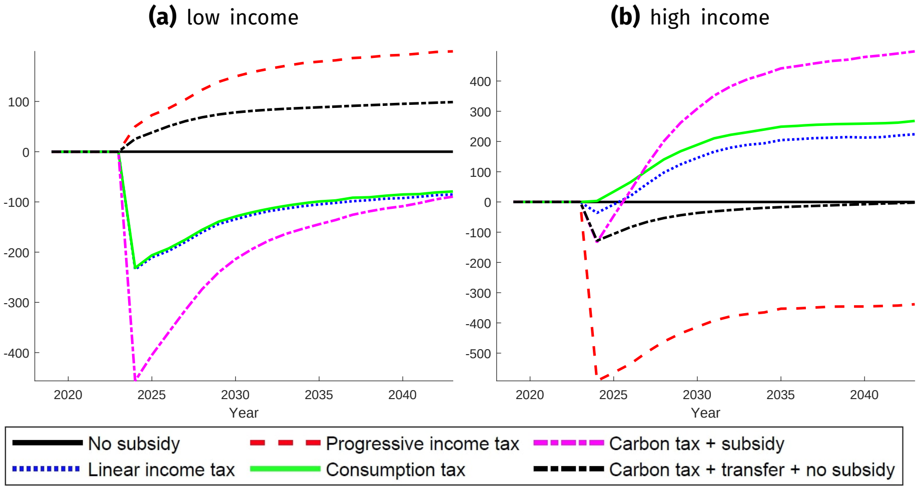
(a) all households **(b)** low income **(c)** high income



Notes: This figure shows for the case with newborn cohorts the share of households with the green commitment good along the transition path for different policy mixes and the reduction in carbon emissions. The left panel shows the share for low-income households and the middle panel shows the share for high-income households. The right panel shows the reduction in emissions. Carbon emissions only come from brown consumption commitment goods and are assumed to be proportional to the size of the brown commitment good. The policy mix is the combination of a percentage subsidy on the green commitment good in combination with different financing schemes. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

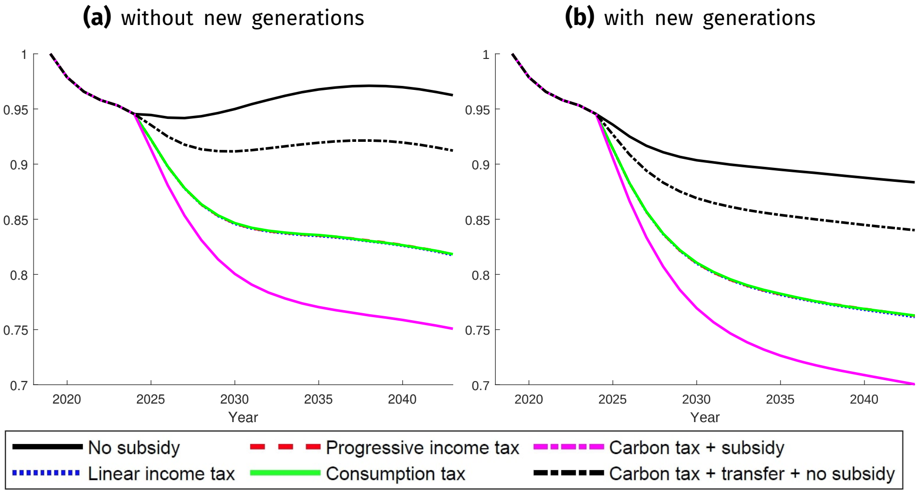
Figure A23 shows the time path of net transfers. We find overall effects to be small. In the first years of the transition period, the effect on average transfers is negligible. At the end of the transition, when the life-cycle effect in the baseline model becomes strongest, we find that including newborn generations stabilizes the redistribution pattern around their level of 2035.

Figure A23. Annual net transfers with newborn cohorts



Notes: This figure shows for the case with newborn cohorts the annual net transfers of different policy mixes. Left panel shows transfers for low-income households and right panel shows transfers for high-income households. Transfers are in Euros per year. The different policy mixes combine a percentage subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

Figure A24. Reduction in emissions with newborn cohorts



Notes: This figure shows the reduction in carbon emissions along the transition for different policy mixes. Left panel shows the case without newborn cohorts and right panel shows the case with newborn cohorts. The different policy mixes combine a percentage subsidy for the purchase price of the green commitment good with different financing instruments. The carbon tax + transfer + no subsidy policy mix includes no subsidy for the green commitment good but rebates tax revenues back to households as lump-sum transfer. Tax rates for all policy mixes are set to have a balanced budget over the transition period.

Finally, Figure A24 compares the reduction of emissions from Section 2.4 to the reduction of emissions if also young households enter during the transition period. The life-cycle effect in the case without new generations leads to higher emissions in the second half of the transition period. When new generations enter during the transition period, we find a smooth decline of emissions for all policy mixes.

References

Holland, Stephen P, Erin T Mansur, and Andrew J Yates. 2021. "The electric vehicle transition and the economics of banning gasoline vehicles." *American Economic Journal: Economic Policy* 13 (3): 316–44.

Chapter 3

Spatial Redistribution of Carbon Taxes

3.1 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 green 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 green 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 green technologies. I examine the impact of a carbon tax on the distributional consequences across income groups and regions along the transition. Furthermore,

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.

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 green 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 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 *brown* and *green*.[3] Green 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 green technologies is done by the firm sector, which consists of three firms. First, there is a construction firm that builds brown and green housing and converts brown houses into green 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 green technologies.[4] I introduce green 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 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

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 internal combustion engines or battery electric vehicles.

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.

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 3.4.4 and provide all figures and results in Appendix 3.C.2.

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 green houses.

I evaluate these different policy scenarios along the transition to green technologies, which takes about 100 years. The speed of the transition to green 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 green 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 green 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, green 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 green houses relative to the prices for brown houses in the initial stationary equilibrium, jump, upon introducing the green technologies, to 10 and 9 percent in rural and urban regions, respectively. The prices for brown houses remain unchanged. As the construction firm builds new green houses and renovates brown houses into green houses, the prices of green and brown houses converge over time. If the carbon tax revenues are spent on lump-sum transfers, the initial increase in the price premium for green houses is 15 percent, 5 percentage points higher than without policy intervention. In addition, the prices for brown houses fall by 5 and 2 percent, respectively, relative to the initial steady state for rural and urban regions. This decrease results from 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 green housing price premium by about 2 percentage points relative to the scenario with lump-sum transfers due to an increased supply of green 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 green cars and green houses rises to 93 and 96 percent, respectively. Because green 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 green 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 green 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 green 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 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

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

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 level of heterogeneity in 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 effects 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 3.2 introduces the data used and presents the empirical results. Section 3.3 presents the model and explains the calibration strategy. Finally, Section 3.4 introduces the policy experiments and presents the results, before Section 3.5 concludes.

3.2 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.

3.2.1 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 five 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]

3.2.2 Spatial heterogeneity in energy consumption

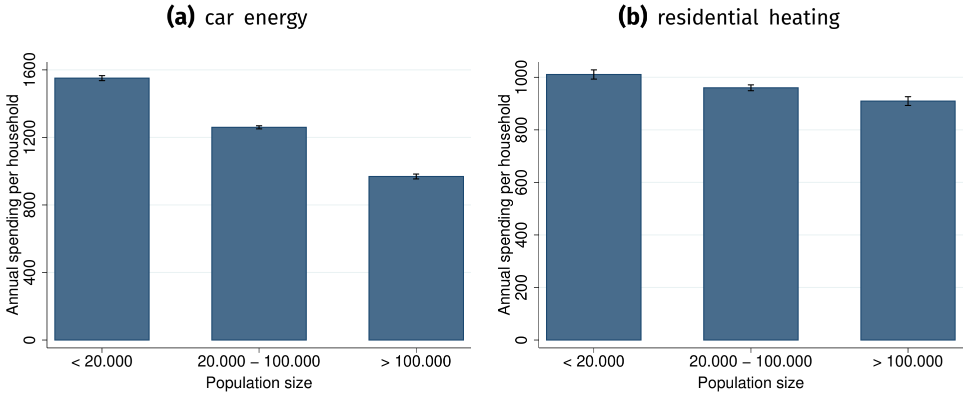
To analyze the heterogeneity in energy consumption patterns of households living in rural and urban regions, I focus on car energy and residential heating consumption. These two consumption goods are not only considered to be of key importance for carbon footprints, as they account for about a third 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 3.2.1 shows the resulting predicted annual expenditures for comparable households depending on where they live. Figure 3.2.1a 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

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 3.A.1.

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 3.2.1b 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.

Figure 3.2.1. Annual energy expenditures across regions (in Euro)

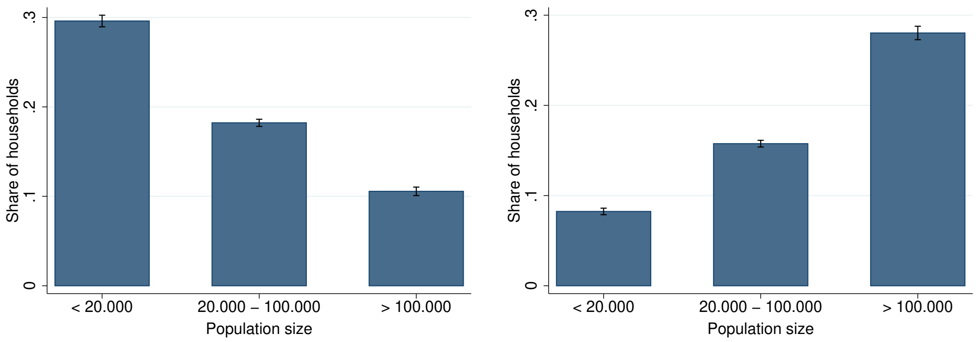


Notes: Panel (a) shows the predicted annual household expenditures in Euro for car energy for an average household with respect to age, net disposable income, and household size living in a region of one of the three city sizes. Panel (b) shows the same statistic on residential heating, where the household additionally has an average heating technology. All regression specifications and results are shown in Appendix 3.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 3.2.2 shows that the share of households using oil and district heating differs significantly. Figure 3.2.2a indicates that 30 percent of rural households use oil heating, while only around 11 percent of urban households use this technology. Figure 3.2.2b 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 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 green technologies.

Figure 3.2.2. Heating technologies across regions

(a) oil heating **(b)** district heating



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 3.A.1.

3.2.3 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]

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

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.

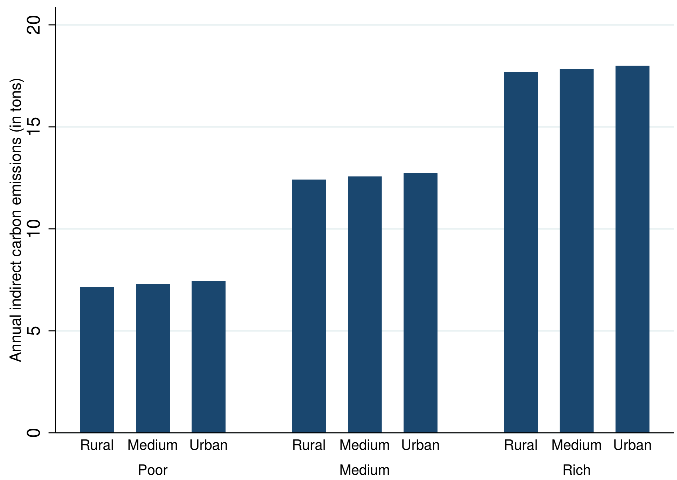
Figure 3.2.3 shows the results for indirect and direct emissions.[12] First, for both types of emissions, I corroborate the finding in the literature that carbon emissions increase with income (Hardadi et al., 2021; Kuhn and Schlattmann, 2024; Wiedenhofer et al., 2017). Moving from the bottom to the top third of the net income distribution increases indirect and direct carbon footprints by a factor of 2.5 and 2, respectively. Second, Figure 3.2.3a 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 3.2.3b 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.

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.

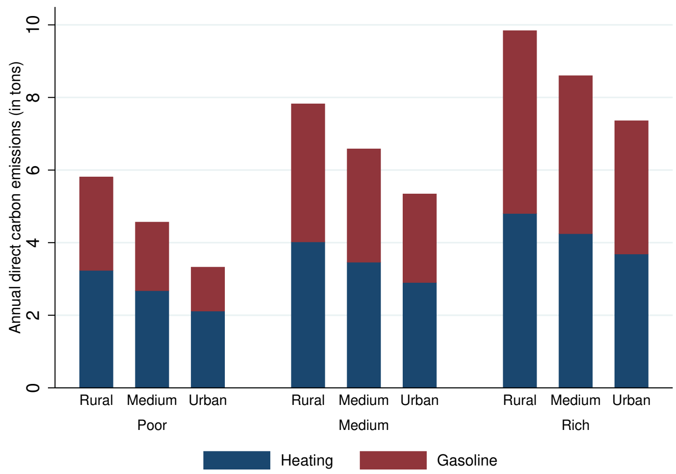
12. More details on the estimation and all regression results can be found in Appendix 3.A.2.

Figure 3.2.3. 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 3.A.2.

3.3 Model

This section develops a quantitative general equilibrium model with two regions and two types of technologies for cars and housing units, one is green and does not emit carbon, the other one is brown 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.

3.3.1 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 green and brown housing, denoted by $H^{r,g}$, $H^{r,b}$ and $H^{u,g}$, $H^{u,b}$, respectively. Time is discrete.

3.3.1.1 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 whether the housing stock or the car is brown, denoted by $j = b$ or green, denoted by $j = g$.[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]

$$u(x,h,e^h,e^c,l) = \frac{1}{1-\sigma}\left(\tilde{x}^{\gamma}\tilde{h}^{1-\gamma}\right)^{1-\sigma} + l\kappa$$

$$\tilde{x} = \left(\mu_x x^{\frac{\nu_x-1}{\nu_x}} + (1-\mu_x)\left[\left(1+\phi^{c,j}\right)(e^c - \underline{e^{c,l}})\right]^{\frac{\nu_x-1}{\nu_x}}\right)^{\frac{\nu_x}{\nu_x-1}}$$

$$\tilde{h} = \left(\mu_h h^{\frac{\nu_h-1}{\nu_h}} + (1-\mu_h)\left[(1+\phi^{h,j})e^h\right]^{\frac{\nu_h-1}{\nu_h}}\right)^{\frac{\nu_h}{\nu_h-1}}$$

13. Figures 3.A.6 and 3.A.5 in Appendix 3.A.2 show that the empirical results hardly change when only including tenants.

14. I calibrate these parameters according to empirical estimates in the literature as described in more detail in Section 3.3.4.5.

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.

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.

3.3.1.2 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

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

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]

3.3.1.3 Budget constraint

Besides their labor income y, households may receive two types of government transfers. First, the government extracts the construction firm's profits which it returns to households within regions as lump-sum transfers T^π. Second, if the government imposes carbon taxes, 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 green and brown technology, respectively. The rent is endogenous and is determined on one of the four segmented rental markets, for each combination of the two regions and housing technologies. If a household lives in a green 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

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.

regions.[17] If a household lives in a brown house, it has to additionally 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 and higher in the rural region. The cost for car energy is modeled analogously. If a household drives a green car, denoted by $\lambda^c = 1$, it pays the economy-wide and constant exogenous price p^{ec}. Households driving a brown 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 F^j and depend on whether the household buys a car with a green $(j = g)$ or brown technology $(j = b)$. Hence, the household's budget constraint reads

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

where $F^j = p^{c,g}$, $F^j = p^{c,b}$, or $F^j = 0$ in case the household buys a green, brown, or no new car, respectively. The prices for new cars $p^{c,g}$ and $p^{c,b}$ are specified in Section 3.3.2.3.

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 brown or green 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 brown or a green 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 3.B.1. The value functions of buying a brown car (BCA) and a green car (GCA) conditional on not moving (NM) and not changing the housing type (NHA) are given by

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

$$\begin{aligned} s.t. \qquad x_t &= y_t + T_t^\pi + T_t^\tau - \rho(l_{t+1}, \lambda_{t+1}^h)h_t - [p_t^{eh} + (1-\lambda_{t+1}^h)\xi_l^h \tau]e_t^h \\ &\quad - [p^{ec} + (1-\lambda_{t+1}^c)\xi^c \tau]e_t^c - p_t^{c,b} \\ l_{t+1} &= l_t, \quad \lambda_{t+1}^c = 0, \quad \lambda_{t+1}^h = \lambda_t^h \end{aligned}$$

and

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

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

respectively. The expected value function is specified in Appendix 3.B.1.

3.3.2 Firm sector and production

There are three representative firms in the economy. First, a construction firm that builds brown and green housing and renovates brown housing into green 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.

3.3.2.1 Construction sector

The construction firm builds houses of both technologies and renovates brown houses into green 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

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

where $q^j_{l,t}$ and $I^{h,j}_{l,t}$ are the housing price and the number of housing units built for housing type j in location l in time period t. Further, $w^j_{l,t}$ is the wage for one unit of labor services, $N^j_{l,t}$ 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 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^h_l and $\psi^{h,j}_{l,t}$ 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 green housing construction is initially more costly but that, due to exogenous technological process, its productivity converges to that of brown housing construction which is assumed to be constant over time. The parameter $\Omega^h_{l,t}$, which describes this convergence of productivities over the transition period, is specified when calibrating the model in Section 3.3.4.5.

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

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

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 $\frac{\alpha^h_l}{1-\alpha^h_l}$ and thus depends only on α^h_l.

After deriving the optimal levels for brown and green 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 green housing if the selling price of one unit of green housing is higher than the selling price of one unit of brown housing, adjusted for the relative pro-

18. In equilibrium all wages in this economy are equal to one, as discussed in Section 3.3.2.3.
19. The full derivation is provided in Appendix 3.B.2.1.
20. Again, full derivations are provided in Appendix 3.B.2.1.

ductivity of constructing green housing, formally

$$q^{h,g}_{l,t} > \frac{q^{h,b}_{l,t}}{\Omega^h_{l,t}}.$$

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

$$\max_{I^{ren}_{l,t}} q^g_{l,t} I^{ren}_{l,t} - w^{ren}_{l,t} N^{ren}_{l,t} - q^b_{l,t} h^b_{l,t} \quad \text{s.t.} \quad I^{ren}_{l,t} = \Omega^{ren}_{l,t} \min\left\{ \left(N^{ren}_{l,t}\right)^{\alpha^{ren}}, h^b_{l,t} \right\}.$$

Thus, the construction firm uses brown houses, which it buys from the rental firm at the market price $q^b_{l,t}$, and labor services, for which it pays wage $w^{ren}_{l,t}$, to produce green housing of size $I^{ren}_{l,t}$, which it can sell to the rental firm for the market price $q^g_{l,t}$. I assume a Leontief production function with a TFP-parameter of $\Omega^{ren}_{l,t}$, for which I assume the same speed of the technological process as for the TFP-parameter for the construction of green houses $\Omega^h_{l,t}$. Solving this problem, the optimal level of renovations is given by[21]

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

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

3.3.2.2 Rental firm

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

21. Full derivations are provided in Appendix 3.B.2.2.

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

where $h^g_{l,t}, h^b_{l,t}$, and $h^{ren}_{l,t}$ are the number of green, brown, and renovated houses bought, $q^g_{l,t}, q^b_{l,t}$, and $q^{ren}_{l,t}$ are the respective prices, and $\rho^g_{l,t}$ and $\rho^b_{l,t}$ are the rents for green and brown housing. Finally, $H^b_{l,t}$ and $H^g_{l,t}$ 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]

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

3.3.2.3 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 within regions, all wages in this economy are equal to one.

The production function for cars of technology j is given by

$$C^j_t = \psi^{c,j}_t N^{c,j}_t, \quad \text{with} \quad \psi^{c,g}_t = \Omega^c_t \psi^{c,b}$$

where Ω^c_t describes the productivity differences between producing green and brown cars. Analogous to the construction of housing, I assume exogenous tech-

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

nological improvements for the production of green cars, while the productivity of producing brown 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.

3.3.3 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 brown 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

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

$$\begin{aligned} \text{with} \quad \pi_{u,t}^{h,g} &= q_{u,t}^g I_{u,t}^{h,g} - w_{u,t}^g N_{u,t}^g, \quad \pi_{u,t}^{h,b} = q_{u,t}^b I_{u,t}^{h,b} - w_{u,t}^b N_{u,t}^b \\ \text{and} \quad \pi_{u,t}^{ren} &= q_{u,t}^g I_{u,t}^{ren} - w_{u,t}^{ren} N_{u,t}^{ren} - q_{u,t}^b h_{u,t}^b \end{aligned}$$

and

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

$$\begin{aligned} \text{with} \quad \pi_{r,t}^{h,g} &= q_{r,t}^g I_{r,t}^{h,g} - w_{r,t}^g N_{r,t}^g, \quad \pi_{r,t}^{h,b} = q_{r,t}^b I_{r,t}^{h,b} - w_{r,t}^b N_{r,t}^b \\ \text{and} \quad \pi_{r,t}^{ren} &= q_{r,t}^g I_{r,t}^{ren} - w_{r,t}^{ren} N_{r,t}^{ren} - q_{r,t}^b h_{r,t}^b \end{aligned}$$

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

3.3.4 Calibration

I calibrate the initial stationary equilibrium of this model, in which green 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, 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*), only 0.1 and 2.2 percent, respectively, 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.

3.3.4.1 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 as I already match the overall car-energy consumption by calibrating the utility weights.

3.3.4.2 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 green 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 green cars is matched by the price premium of green cars. The scale parameter is set to match the price elasticity of green cars and yields $\sigma_{\epsilon,ct} = 0.0003$. As empirical targets, I take estimates from Fridstrøm and Østli (2021) for Norway of -1.27.

3.3.4.3 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 $\sigma_\eta^2 = 0.031$.

3.3.4.4 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 $\alpha_l^h/(1-\alpha_l^h)$. Exploiting this direct mapping, I calibrate α_l^h 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 $\alpha_r^h = 0.3986$ and $\alpha_u^h = 0.2563$. For the housing renovation elasticity, I target the overall housing supply elasticity in Beze (2023), giving me a value of $\alpha_{ren}^h = 0.333$. 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 brown housing construction, denoted $\psi^{h,b}$, can be normalized to 1. For the initial productivity of green housing construction relative to brown housing construction, I take estimates from the Bavarian Construction Association, which estimates that the construction of green housing was 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 green housing, will fall by 40 percent over 10 years (LCP 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 $\Omega_{r,2019}^{ren} = 0.955$ and $\Omega_{u,2019}^{ren} = 0.939$. For the productivity improvements of housing renovation, captured by the path of Ω_l^{ren}, 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 num-

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.

24. Figure 3.C.1b in Appendix 3.C.1 shows the technological process of green housing construction along the transition.

25. Figure 3.C.1c in Appendix 3.C.1 shows the technological process of housing renovations along the transition.

bers 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 $r = 0.03$.

3.3.4.5 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 $\xi_r^h = 0.247$ and $\xi_u^h = 0.232$ 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 brown cars is calibrated to match the expenditure share of new car purchases and is $\psi^{c,b} = 61.6$. For the production of green cars, I calibrate the productivity difference relative to brown cars and its convergence over time by matching the observed share of electric vehicles purchased in Germany until 2023. Again, I 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 green and brown 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 $\phi^{c,g} = 0.33$. 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 kWh/m^2a, respectively. Thus, the efficiency premium for green houses is $\phi^{h,g} = 2.412$. The values for the brown technologies, $\phi^{c,b}$ and $\phi^{h,b}$ are normalized to 0. All parameters, their values, targets and the calibration method are summarized in Table 3.3.1.

Table 3.3.1. 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 green housing adoption rate	SMM
$\mu_{\epsilon,c}$	Location parameter of car pref. shock	-0.00008	Share of households buying brown 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 green housing adoption rate	SMM
$\sigma^2_{\epsilon,c}$	Scale parameter of car pref. shock	0.00003	Elasticity of brown car purchases	SMM
$\sigma^2_{\epsilon,ct}$	Scale parameter of car technology pref. shock	0.0003	Elasticity of green 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
$\psi^{h,b}$	Productivity brown housing construction	1.0	Normalization	-
Ω^h_r	Techn. progress green housing constr. - rural	see 3.C.1b	See text	Literature
Ω^h_u	Techn. progress green housing constr. - urban	see 3.C.1b	See text	Literature
Ω^{ren}_r	Techn. progress housing renov. - rural	see 3.C.1c	see text	Literature
Ω^{ren}_u	Techn. progress housing renov. - urban	see 3.C.1c	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 brown car production	61.6	Average exp. car purchases	Literature
Ω^c	Technological progress green car production	see 3.C.1a	See text	SMM
$\phi^{c,g}$	Additional car energy efficiency green cars	0.33	Lévay et al. (2017)	Literature
$\phi^{c,b}$	Additional car energy efficiency brown cars	0.0	Normalization	-
$\phi^{h,g}$	Additional heating energy efficiency green houses	2.412	Taruttis and Weber (2022)	Literature
$\phi^{h,b}$	Additional heating energy efficiency brown houses	0.0	Normalization	-

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

3.3.4.6 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 3.3.2 shows the model fit for the parameters that are calibrated with a simulated method of moments.

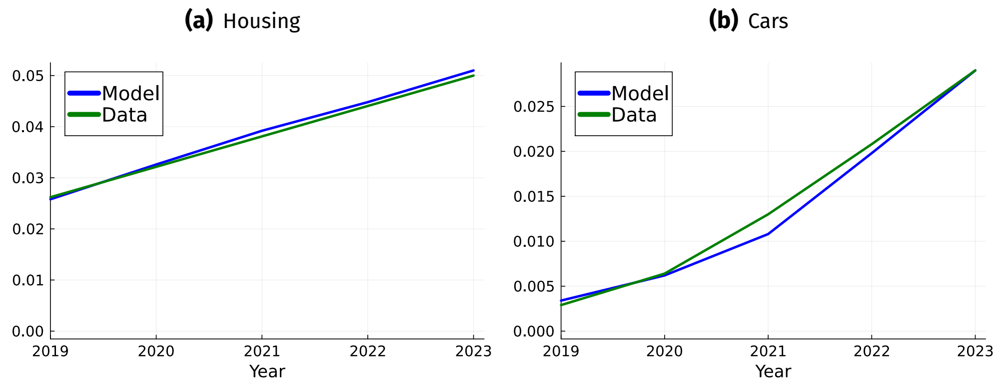
Table 3.3.2. Model fit

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 green housing adoption	see Figure 3.3.1a		$\mu_{\epsilon,h}$	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 green housing adoption	see Figure 3.3.1a		$\sigma^2_{\epsilon,h}$	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 green cars	see Figure 3.3.1b		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

Figure 3.3.1. Model fit technology adjustments



Notes: Panel (a) compares the shares of households with green 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.

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 green houses and cars, respectively. Figure 3.3.1 plots the share of households with green goods in the model, without carbon taxes, and in the data. The levels and the speed of adjustments are matched very well.

3.4 Policy experiments

Using the calibrated model, I now study the effets of introducing carbon taxes on (i) the level of redistribution across income groups and space, (ii) the speed of transitioning to green technologies and (iii) 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 brown technologies exist and introduce green technologies exogenously. Since green technologies are more efficient at converting raw car and heating energy into vehicle miles traveled and temperature, this starts a transition to green 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, I consider lump-sum transfers, which the literature has identified as a policy to avoid the regressive redistribution of carbon taxes caused by higher expenditure shares on carbon intensive goods, such as energy, by poor households. 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

$$\int_0^1 \left[e^h_{i,t}(1-\lambda^h_{i,t})(l_{i,t}\xi^h_u + (1-l_{i,t})\xi^h_r) + e^c_{i,t}(1-\lambda^c_{i,t})\xi^c \right] \tau di = T^\tau_t .$$

Second, as shown in the empirical part of this paper, carbon footprints differ substantially across space between rural and urban regions. Thus, spending carbon tax revenues on 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 across regions. This policy resembles the Austrian *Klimabonus*, a policy that was implemented in 2022 and reimburses carbon tax revenues based

26. The level of transfers along the transition is shown in Figure 3.C.2 in Appendix 3.C.1.

on whether households live in rural or urban regions. The government budget constraints for both regions read

$$\int_0^1 \left[e^h_{i,t}(1-\lambda^h_{i,t})(1-l_{i,t})\xi^h_r + e^c_{i,t}(1-\lambda^c_{i,t})(1-l_{i,t})\xi^c\right]\tau di = \int_0^1 (1-l_{i,t})T^\tau_{r,t}di$$

and

$$\int_0^1 \left[e^h_{i,t}(1-\lambda^h_{i,t})l_{i,t}\xi^h_u + e^c_{i,t}(1-\lambda^c_{i,t})l_{i,t}\xi^c\right]\tau di = \int_0^1 l_{i,t}T^\tau_{u,t}di,$$

for the rural and urban region, respectively.

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

$$\int_0^1 \left[e^h_{i,t}(1-\lambda^h_{i,t})(l_{i,t}\xi^h_u + (1-l_{i,t})\xi^h_r) + e^c_{i,t}(1-\lambda^c_{i,t})\xi^c\right]\tau di = \left[w_{l,t}N^{ren}_{r,t} + w_{l,t}N^{ren}_{u,t}\right]\psi_t,$$

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 green technologies and implicitly redistributes between early and late green 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.

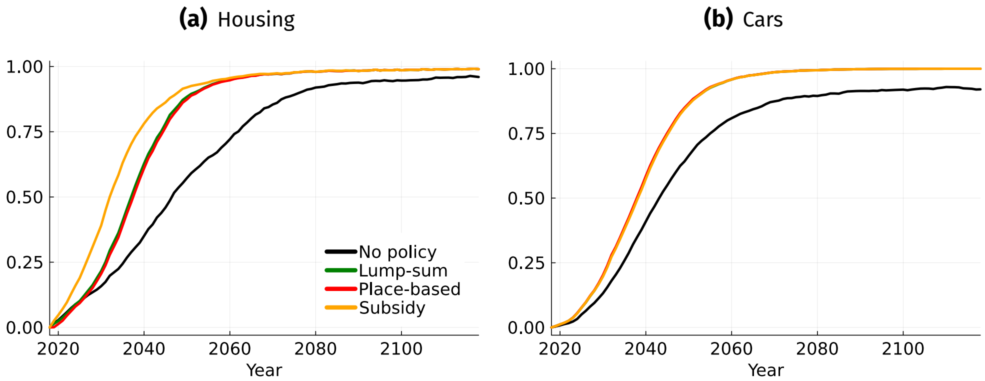
3.4.1 Results along the transition

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.

3.4.1.1 Consumption and spatial redistribution

Figure 3.4.1 shows the share of households with green houses and cars along the transition. Without any policy intervention, the share of households with green 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 green 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 green 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 green 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 green cars does not depend on how the carbon tax revenues are spent.

Figure 3.4.1. Share of green technologies along the transition



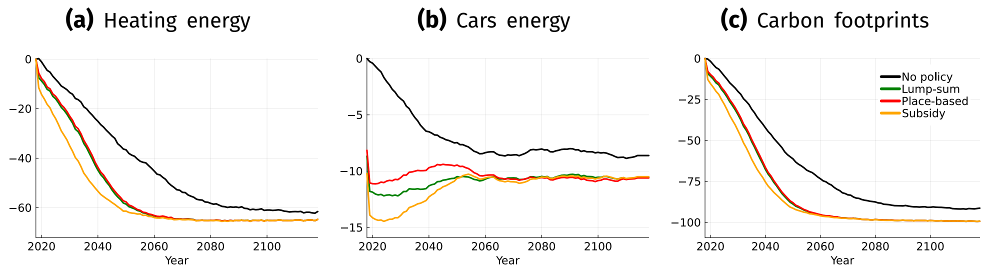
Notes: Panel (a) shows the share of households with green houses along the transition period for the different policy scenarios considered. Panel (b) shows the corresponding share of households with green cars along the transition.

As households adopt green and more efficient technologies, their raw energy consumption decreases. Figure 3.4.2 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 an-

27. Figure 3.C.4 in Appendix 3.C.1 shows the level of the subsidy along the transition period.
28. These results on migration are shown next.

other two percentage points larger due to the negative income effect of smaller direct transfers. As households move into green 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 taxes, fewer households adopt green 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.

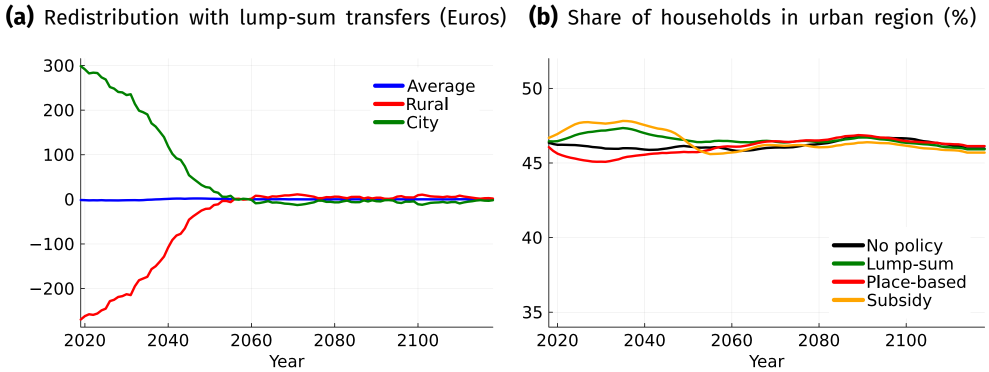
Figure 3.4.2. Percentage changes over the transition



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 3.4.3 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 3.C.5 in Appendix 3.C.1. 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 has net payments of 270 Euros. As households adopt green 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 3.C.5 in Appendix 3.C.1. 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 3.4.3. Location choices and redistribution over the transition

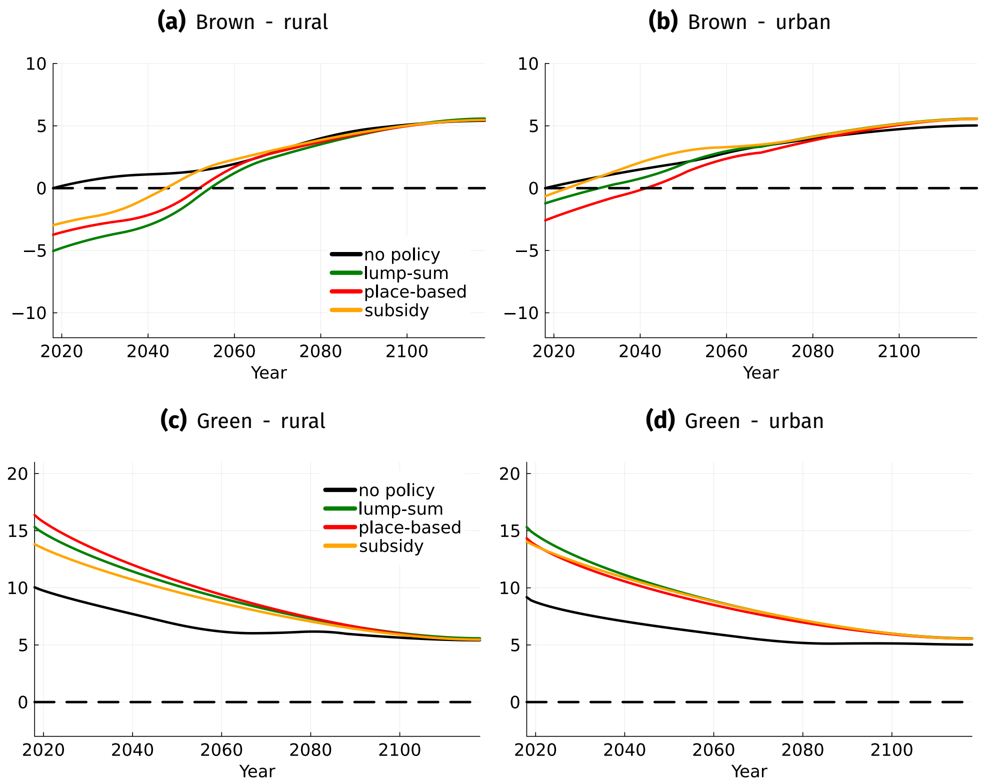


Notes: Panel (a) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers. Figure 3.C.5 in Appendix 3.C.1 shows the level of spatial redistribution for all policy scenarios. Panel (b) shows the share of the population living in the urban region along the transition for the different policy scenarios.

3.4.1.2 Housing sector

This subsection documents how housing prices and housing construction and renovation change over the transition period. Figure 3.4.4 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 green houses jumps to 10 and 9 percent for rural and urban regions, respectively, upon introducing green technologies, while the prices of brown houses remain unchanged. This price increase is slightly higher in the rural region because of higher carbon tax payments and thus higher demand for green houses. As the construction firm builds new green houses and renovates brown houses into green ones, prices for green and brown houses converge and stabilize around 6 percent higher than in the initial stationary equilibrium after around 100 years.

Figure 3.4.4. Housing price changes over the transition

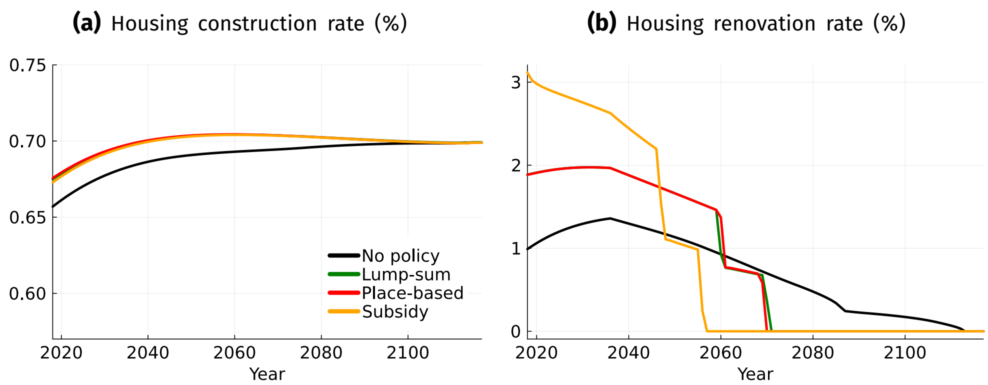


Notes: Panel (a) shows the percentage change of the housing price of brown houses in the rural region relative to the price in the initial stationary equilibrium for brown housing along the transition for the different policy scenarios. Panels (b) - (d) show the corresponding paths for brown houses in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

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 green 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 green houses as carbon taxes increase the price of heating brown houses. Prices for brown 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 quarter 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 brown into green houses, the initial price premium for green 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 green housing, which reduces prices in equilibrium.

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 3.4.5 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]

Figure 3.4.5. Housing construction and renovations over the transition



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.

Since the prices for green 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 green houses. Subfigure 3.4.5b shows that the renovation rate 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 green

29. Subfigure 3.4.5a shows the total level of newly constructed housing regardless of the technology. Figure 3.C.6 in Appendix 3.C.1 shows the construction rates of both technology types along the transition.

and brown 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 green and brown 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 3.C.4 in Appendix 3.C.1.

3.4.2 Long-run effects of carbon taxes

To assess the long-run effects of the different policy scenarios, I compare their stationary equilibria. Since the prices of green and brown 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 and ignore subsidies on green technologies. Table 3.4.1 shows the percentage changes in key variables for the different policy scenarios relative to the initial stationary equilibrium without green technologies.

Table 3.4.1. Changes from initial to final stationary equilibrium

	No policy		Lump-sum		Place-based	
	Rural	Urban	Rural	Urban	Rural	Urban
Green cars (ppts.)	92.5	93.5	100	100	100	100
Green 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.

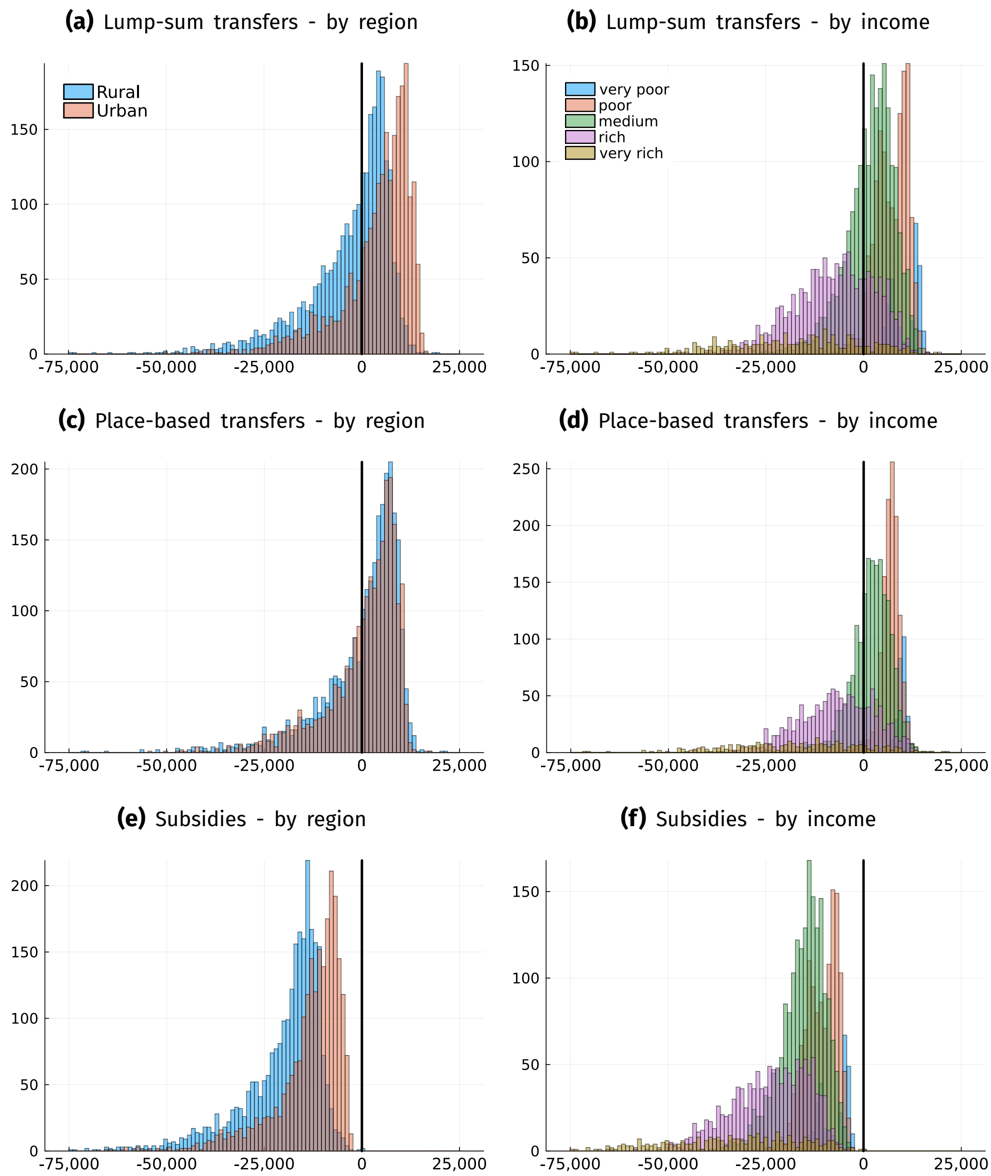
Because green technologies are more efficient in converting raw energy into temperature and vehicle miles traveled, the vast majority of households use green technologies in the final steady states. In the scenario without carbon taxes this is true for 92 to 97 percent of households and when introducing carbon taxes, this number even increases to 99 to 100 percent. As the share of green, 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, which is in line with empirical findings (Santos and Catchesides, 2005; Wadud et al., 2010). As a result of this shift to green 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 green houses and thus on average 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. 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 green 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 green 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 green, 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.

3.4.3 Distributional effects 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 effects 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 3.4.6 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 3.4.6b, 3.4.6d, and 3.4.6f 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 3.4.2 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 3.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

Figure 3.4.6. 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.

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, no household benefits.

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

Table 3.4.2. 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.

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 3.4.3 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,

30. Figure 3.C.7 in Appendix 3.C.1 plots the distributions of welfare effects.

Table 3.4.3. 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.

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.

3.4.4 Sensitivity analysis

The current analysis already considers a variety of different policy scenarios, which are evaluated in terms of their effects 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, 3.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

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

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 green 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 green 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

32. Figure 3.C.18 plots this price path over the transition period.

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 green 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 brown 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.

3.5 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 effects of carbon taxes along the transition to green 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 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 green 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 green, non-emitting houses by 5 percent and decreasing the price of brown, 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.

References

Auffhammer, Maximilian, and Edward Rubin. 2018. “Natural gas price elasticities and optimal cost recovery under consumer heterogeneity: Evidence from 300 million natural gas bills.” Report. National Bureau of Economic Research.

Bastos, Paulo, Lucio Castro, Julian Cristia, and Carlos Scartascini. 2015. “Does Energy Consumption Respond to Price Shocks? Evidence from a Regression-Discontinuity Design.” *Journal of Industrial Economics* 63 (2): 249–78.

Baum-Snow, Nathaniel, and Lu Han. 2024. “The microgeography of housing supply.” *Journal of Political Economy* 132 (6): 1897–946.

Belfiori, Maria Elisa. 2017. “Carbon pricing, carbon sequestration and social discounting.” *European Economic Review* 96: 1–17. ISSN: 0014-2921. DOI: https://doi.org/10.1016/j.euroecorev.2017.03.015. URL: https://www.sciencedirect.com/science/article/pii/S0014292117300715.

Beze, Eyayaw. 2023. “Geographic constraints and the housing supply elasticity in Germany.” *Ruhr Economic Papers* 1003:

Bilal, Adrien, and Diego R Känzig. 2024. “The Macroeconomic Impact of Climate Change: Global vs. Local Temperature.” Report. National Bureau of Economic Research.

Bilal, Adrien, and Esteban Rossi-Hansberg. 2023. “Anticipating Climate Change Across the United States.” Working Paper 31323. National Bureau of Economic Research. DOI: 10.3386/w31323. URL: http://www.nber.org/papers/w31323.

Brons, Martijn, Peter Nijkamp, Eric Pels, and Piet Rietveld. 2008. “A meta-analysis of the price elasticity of gasoline demand. A SUR approach.” *Energy economics* 30 (5): 2105–22.

Bundeskartellamt. 2020. “Jahresbericht der Markttransparenzstelle für Kraftstoffe 2020.” URL: https://www.bundeskartellamt.de/SharedDocs/Publikation/DE/Berichte/Jahresbericht_MTS-K_2020.html.

Carleton, Tamma, Amir Jina, Michael Delgado, Michael Greenstone, Trevor Houser, Solomon Hsiang, Andrew Hultgren, Robert E Kopp, Kelly E McCusker, Ishan Nath, James Rising, Ashwin Rode, Hee Kwon Seo, Arvid Viaene, Jiacan Yuan, and Alice Tianbo Zhang. 2022. “Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits*.” *Quarterly Journal of Economics* 137 (4): 2037–105. ISSN: 0033-5533. DOI: 10.1093/qje/qjac020. eprint: https://academic.oup.com/qje/article-pdf/137/4/2037/51054116/qjac020.pdf. URL: https://doi.org/10.1093/qje/qjac020.

Cischinsky, Holger, and Nikolaus Diefenbach. 2018. *Datenerhebung Wohngebäudebestand 2016: Datenerhebung zu den energetischen Merkmalen und Modernisierungsraten im deutschen und hessischen Wohngebäudebestand*. Fraunhofer IRB Verlag.

Cruz, Jose-Luis, and Esteban Rossi-Hansberg. 2024. “The Economic Geography of Global Warming.” *Review of Economic Studies* 91 (2): 899–939. ISSN: 0034-6527. DOI: 10.1093/restud/rdad042. eprint: https://academic.oup.com/restud/advance-article-pdf/doi/10.

1093 / restud / rdad042 / 49761300 / rdad042.pdf. URL: https://doi.org/10.1093/restud/rdad042. rdad042.

Davis, Lucas W, and Erich Muehlegger. 2010. "Do Americans consume too little natural gas? An empirical test of marginal cost pricing." *RAND Journal of Economics* 41 (4): 791–810.

Douenne, Thomas. 2020. "The vertical and horizontal distributive effects of energy taxes: A case study of a french policy." *Energy Journal* 41 (3): 231–54.

Douenne, Thomas, Albert Jan Hummel, and Marcelo Pedroni. 2023. "Optimal Fiscal Policy in a Climate-Economy Model with Heterogeneous Households." *Available at SSRN 4018468*,

Duarte, Rosa, Alfredo Mainar, and Julio Sánchez-Chóliz. 2012. "Social groups and CO2 emissions in Spanish households." *Energy policy* 44: 441–50.

Favilukis, Jack, Sydney C Ludvigson, and Stijn Van Nieuwerburgh. 2017. "The macroeconomic effects of housing wealth, housing finance, and limited risk sharing in general equilibrium." *Journal of Political Economy* 125 (1): 140–223.

Fehr, Hans, Manuel Kallweit, and Fabian Kindermann. 2013. "Should pensions be progressive?" *European Economic Review* 63: 94–116.

Fridstrøm, Lasse, and Vegard Østli. 2021. "Direct and cross price elasticities of demand for gasoline, diesel, hybrid and battery electric cars: the case of Norway." *European Transport Research Review* 13 (1): 1–24.

Fried, Stephie. 2024. "A Macro Study of the Unequal Effects of Climate Change." Report.

Fried, Stephie, Kevin Novan, and William B Peterman. 2018. "The distributional effects of a carbon tax on current and future generations." *Review of Economic Dynamics* 30: 30–46.

Frondel, Manuel, and Colin Vance. 2009. "Do high oil prices matter? Evidence on the mobility behavior of German households." *Environmental and Resource Economics* 43: 81–94.

Gill, Bernhard, and Simon Moeller. 2018. "GHG emissions and the rural-urban divide. A carbon footprint analysis based on the German official income and expenditure survey." *Ecological Economics* 145: 160–69.

Goebel, Jan, Markus M Grabka, Stefan Liebig, Martin Kroh, David Richter, Carsten Schröder, and Jürgen Schupp. 2019. "The German socio-economic panel (SOEP)." *Jahrbücher für Nationalökonomie und Statistik* 239 (2): 345–60.

Goetzke, Frank, and Colin Vance. 2021. "An increasing gasoline price elasticity in the United States?" *Energy economics* 95: 104982.

Hardadi, Gilang, Alexander Buchholz, and Stefan Pauliuk. 2021. "Implications of the distribution of German household environmental footprints across income groups for integrating environmental and social policy design." *Journal of Industrial Ecology* 25 (1): 95–113.

Hassler, John, and Per Krusell. 2012. "Economics and Climate Change: Integrated Assessment in a Multi-Region World." *Journal of the European Economic Association* 10 (5): 974–1000. ISSN: 1542-4766. DOI: 10.1111/j.1542-4774.2012.01082.x. eprint: https://academic.oup.com/jeea/article-pdf/10/5/974/10314609/jeea0974.pdf. URL: https://doi.org/10.1111/j.1542-4774.2012.01082.x.

Hsiang, Solomon, Robert Kopp, Amir Jina, James Rising, Michael Delgado, Shashank Mohan, Daniel J Rasmussen, Robert Muir-Wood, Paul Wilson, Michael Oppenheimer, et al. 2017. "Estimating economic damage from climate change in the United States." *Science* 356 (6345): 1362–69.

IINAS, International Institute for Sustainability Analysis, and Strategy. 2021. "GEMIS report version 5.0." URL: https://iinas.org/en/downloads/gemis-downloads/.

Isaksen, Elisabeth T, and Patrick A Narbel. 2017. "A carbon footprint proportional to expenditure-A case for Norway?" *Ecological Economics* 131: 152–65.

Kalkuhl, Matthias, Maximilian Kellner, Tobias Bergmann, and Karolina Rütten. 2023. "CO2-Bepreisung zur Erreichung der Klimaneutralität im Verkehrs- und Gebäudesektor: Investitionsanreize und Verteilungswirkungen."

Känzig, Diego R. 2021. "The unequal economic consequences of carbon pricing." *Available at SSRN 3786030*,

Kaplan, Greg, Kurt Mitman, and Giovanni L Violante. 2020. "The housing boom and bust: Model meets evidence." *Journal of Political Economy* 128 (9): 3285–345.

Kerkhof, Annemarie C, Henri C Moll, Eric Drissen, and Harry C Wilting. 2008. "Taxation of multiple greenhouse gases and the effects on income distribution: A case study of the Netherlands." *Ecological Economics* 67 (2): 318–26.

Kotlikoff, Laurence, Felix Kubler, Andrey Polbin, Jeffrey Sachs, and Simon Scheidegger. 2021. "Making carbon taxation a generational win win." *International Economic Review* 62 (1): 3–46.

Krusell, Per, and Anthony A Smith Jr. 2022. "Climate change around the world."

Kuhn, Moritz, and Lennard Schlattmann. 2024. "Distributional Consequences of Climate Policies." *Distributional Consequences of Climate Policies*,

LCP Delta. 2021. "Heat pump costs projected to fall by 40 percent." URL: https://delta.lcp.com/press-release/heat-pump-costs-projected-to-fall-by-40/.

Lerbs, Oliver W. 2014. "House prices, housing development costs, and the supply of new single-family housing in German counties and cities." *Journal of Property Research* 31 (3): 183–210.

Lévay, Petra Zsuzsa, Yannis Drossinos, and Christian Thiel. 2017. "The effect of fiscal incentives on market penetration of electric vehicles: A pairwise comparison of total cost of ownership." *Energy Policy* 105: 524–33.

Miehe, Robert, Rene Scheumann, Christopher M Jones, Daniel M Kammen, and Matthias Finkbeiner. 2016. "Regional carbon footprints of households: a German case study." *Environment, Development and Sustainability* 18: 577–91.

Molloy, Raven, and Hui Shan. 2013. "The effect of gasoline prices on household location." *Review of Economics and Statistics* 95 (4): 1212–21.

Monras, Joan. 2018. "Economic shocks and internal migration."

Perobelli, Fernando Salgueiro, Weslem Rodrigues Faria, and Vinicius de Almeida Vale. 2015. "The increase in Brazilian household income and its impact on CO2 emissions: Evidence for 2003 and 2009 from input–output tables." *Energy Economics* 52: 228–39.

Rennert, Kevin, Frank Errickson, Brian C Prest, Lisa Rennels, Richard G Newell, William Pizer, Cora Kingdon, Jordan Wingenroth, Roger Cooke, Bryan Parthum, et al. 2022. "Comprehensive evidence implies a higher social cost of CO2." *Nature* 610 (7933): 687–92.

Rudik, Ivan, Gary Lyn, Weiliang Tan, and Ariel Ortiz-Bobea. 2022. "The economic effects of climate change in dynamic spatial equilibrium."

Ruhnau, Oliver, Clemens Stiewe, Jarusch Muessel, and Lion Hirth. 2023. "Natural gas savings in Germany during the 2022 energy crisis." *Nature Energy* 8 (6): 621–28.

Santos, Georgina, and Tom Catchesides. 2005. "Distributional consequences of gasoline taxation in the United Kingdom." *Transportation Research Record* 1924 (1): 103–11.

Stadler, Konstantin, Richard Wood, Tatyana Bulavskaya, Carl-Johan Södersten, Moana Simas, Sarah Schmidt, Arkaitz Usubiaga, José Acosta-Fernández, Jeroen Kuenen, Martin Bruckner, et al. 2018. "EXIOBASE 3: Developing a time series of detailed environmentally extended multi-regional input-output tables." *Journal of Industrial Ecology* 22 (3): 502–15.

Stawarz, Nico, Matthias Rosenbaum-Feldbrügge, Nikola Sander, Harun Sulak, and Vanessa Knobloch. 2022. "The impact of the COVID-19 pandemic on internal migration in Germany: A descriptive analysis." *Population, Space and Place* 28 (6): e2566. DOI: https://doi.org/10.1002/psp.2566. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/psp.2566. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/psp.2566.

Sun, Jeffrey E. 2024. "The Distributional Consequences of Climate Change: The Role of Housing Wealth, Expectations, and Uncertainty." Report.

Taruttis, Lisa, and Christoph Weber. 2022. "Estimating the impact of energy efficiency on housing prices in Germany: Does regional disparity matter?" *Energy Economics* 105: 105750.

Tomás, Manuel, Luis Antonio López, and Fabio Monsalve. 2020. "Carbon footprint, municipality size and rurality in Spain: inequality and carbon taxation." *Journal of Cleaner Production* 266: 121798.

Wadud, Zia, Daniel J Graham, and Robert B Noland. 2010. "Gasoline demand with heterogeneity in household responses." *Energy Journal* 31 (1): 47–74.

Wiedenhofer, Dominik, Dabo Guan, Zhu Liu, Jing Meng, Ning Zhang, and Yi-Ming Wei. 2017. "Unequal household carbon footprints in China." *Nature Climate Change* 7 (1): 75–80.

Appendix 3.A Additional empirical results

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

3.A.1 Regression equations and additional 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

$$
\begin{aligned}
gasoline_i &= \alpha_1 + \alpha_2 citysize_i + \alpha_3 y_i + \alpha_4 hhsize_i + \alpha_5 age_i + \epsilon_{c,i} \\
heating_i &= \beta_1 + \beta_2 citysize_i + \beta_3 y_i + \beta_4 hhsize_i + \beta_5 age_i + \beta_6 technology_i + \epsilon_{h,i} \\
logit(\mathbb{1}(technology_i = 1)) &= \gamma_1 + \gamma_2 citysize_i + \gamma_3 y_i + \gamma_4 hhsize_i + \gamma_5 age_i + \epsilon_{\lambda,i}.
\end{aligned}
$$

Table 3.A.1 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 3.A.2 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.

Finally, Figure 3.A.3 documents the predicted values shown in Figures 3.2.1 and 3.2.2 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 3.A.1. 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 3.A.2. 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.

Figure 3.A.3. Predicted values for different city sizes (baseline)

(a) Car energy

	Margin	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
_at						
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

	Margin	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
_at						
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

	Margin	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
_at						
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

	Margin	Delta-method Std. Err.	z	P>|z|	[95% Conf.	Interval]
_at						
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, a ge of the main earner, and the housing size.

3.A.2 Regression equations and additional results on 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:

$$\begin{aligned} ICF_i &= \alpha_1 + \alpha_2 citysize_i + \alpha_3 y_i + \alpha_4 hhsize_i + \alpha_5 age_i + \epsilon_{\alpha,i} \\ DCF_i &= \beta_1 + \beta_2 citysize_i + \beta_3 y_i + \beta_4 hhsize_i + \beta_5 age_i + \epsilon_{\beta,i} \end{aligned}$$

Figure 3.A.4 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. Figures 3.A.5 and 3.A.6 show the respective Figures for direct and indirect carbon footprints, when only tenants are included. Figures 3.A.5 and 3.A.6 resemble Figures 3.2.3a and 3.2.3b from the empirical part of this paper, but only include tenants. Again, the results are very similar to those on the overall population.

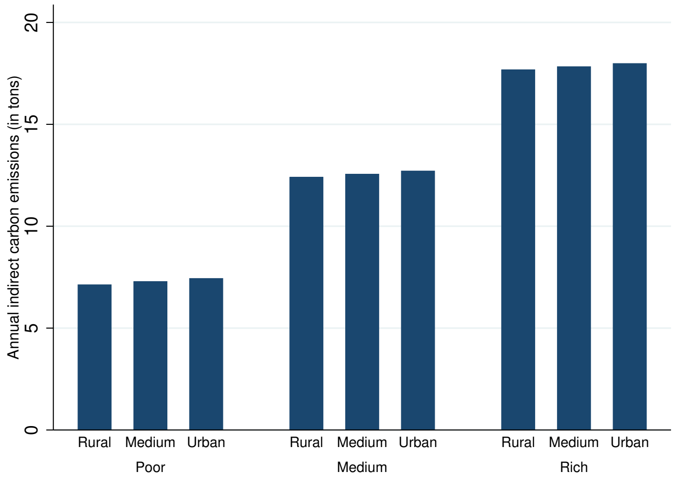
Figure 3.A.4. Regression outputs for indirect and direct carbon emissions

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

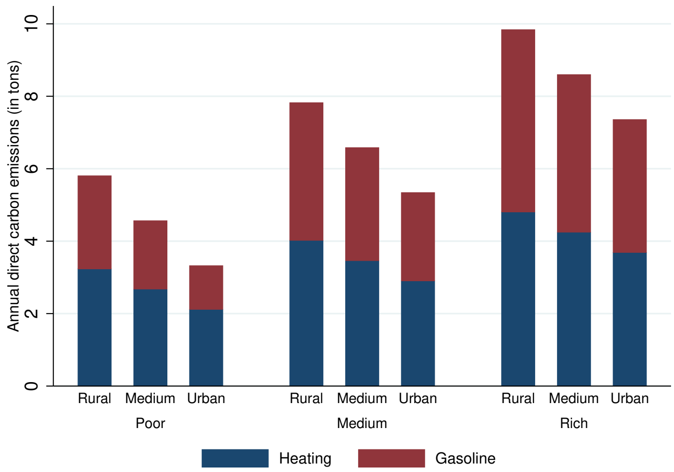
Notes: Notes: This figure shows the regression outputs for the different regressions on household carbon footprints. The first three columns show the results for indirect carbon footprint as well for direct carbon footprints for heating and car energy for the overall population. Columns 4 to 6 show the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

Figure 3.A.5. 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 3.A.6. 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.

Appendix 3.B Additional model derivations

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.

3.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 brown car (BCA) vs. buying a green car (GCA). The value function of not moving, not adjusting housing, and not buying a new car is given by

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

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

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

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

where

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

and further

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

and finally

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

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

3.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.

3.B.2.1 Housing construction

The representative construction firm has to decide how much brown and green 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

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

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 green or brown housing on the permitted land. To do this, it compares the profits in each case. Note, that the firm always build either green or brown houses. Therefore, the condition for building green housing is given by

$$
\begin{aligned}
\tau^{g} &> \tau^{b} \\
\Leftrightarrow\ q^{g}_{l,t} I^{h,g}_{l,t} - w^{g}_{l,t} N^{g}_{l,t} &> q^{b}_{l,t} I^{h,b}_{l,t} - w^{b}_{l,t} N^{b}_{l,t} \\
\Leftrightarrow\ q^{g}_{l,t} I^{h,g}_{l,t} - w^{g}_{l,t} \left(\psi^{h,b}_{l,t}\right)^{-\frac{1}{\alpha^{h}_{l}}} \left(I^{h,j}_{l,t}\right)^{\frac{1}{\alpha^{h}_{l}}} \overline{L_l}^{\frac{\alpha^{h}_{l}-1}{\alpha^{h}_{l}}} &> q^{b}_{l,t} I^{h,b}_{l,t} - w^{b}_{l,t} \left(\psi^{h,b}_{l,t}\right)^{-\frac{1}{\alpha^{h}_{l}}} \left(I^{h,j}_{l,t}\right)^{\frac{1}{\alpha^{h}_{l}}} \overline{L_l}^{\frac{\alpha^{h}_{l}-1}{\alpha^{h}_{l}}} \\
\Leftrightarrow q^{g}_{l,t}\left[\left(\alpha^{h}_{l}\frac{q^{g}_{l,t}}{w^{g}_{l,t}}\right)^{\frac{\alpha^{h}_{l}}{1-\alpha^{h}_{l}}}\left(\psi^{h,g}_{l,t}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\overline{L_l}\right] &- \quad w^{g}_{l,t}\left(\psi^{h,b}_{l,t}\right)^{-\frac{1}{\alpha^{h}_{l}}}\left[\left(\alpha^{h}_{l}\frac{q^{g}_{l,t}}{w^{g}_{l,t}}\right)^{\frac{\alpha^{h}_{l}}{1-\alpha^{h}_{l}}}\left(\psi^{h,g}_{l,t}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\overline{L_l}\right]^{\frac{1}{\alpha^{h}_{l}}}\overline{L_l}^{\frac{\alpha^{h}_{l}-1}{\alpha^{h}_{l}}} \\
> q^{b}_{l,t}\left[\left(\alpha^{h}_{l}\frac{q^{b}_{l,t}}{w^{b}_{l,t}}\right)^{\frac{\alpha^{h}_{l}}{1-\alpha^{h}_{l}}}\left(\psi^{h,b}_{l,t}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\overline{L_l}\right] &- \quad w^{b}_{l,t}\left(\psi^{h,b}_{l,t}\right)^{-\frac{1}{\alpha^{h}_{l}}}\left[\left(\alpha^{h}_{l}\frac{q^{b}_{l,t}}{w^{b}_{l,t}}\right)^{\frac{\alpha^{h}_{l}}{1-\alpha^{h}_{l}}}\left(\psi^{h,b}_{l,t}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\overline{L_l}\right]^{\frac{1}{\alpha^{h}_{l}}}\overline{L_l}^{\frac{\alpha^{h}_{l}-1}{\alpha^{h}_{l}}} \\
\Leftrightarrow\left(q^{g}_{l,t}\psi^{h,g}_{l,t}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\left(\frac{\alpha^{h}_{l}}{w^{b}_{l,t}}\right)^{\frac{\alpha^{h}_{l}}{1-\alpha^{h}_{l}}}\overline{L_l}-\left(\alpha^{h}_{l}\psi^{h,g}_{l,t}\frac{q^{g}_{l,t}}{w^{g}_{l,t}}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\overline{L_l} &> \left(q^{b}_{l,t}\psi^{h,b}_{l,t}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\left(\frac{\alpha^{h}_{l}}{w^{b}_{l,t}}\right)^{\frac{\alpha^{h}_{l}}{1-\alpha^{h}_{l}}}\overline{L_l}-\left(\alpha^{h}_{l}\psi^{h,b}_{l,t}\frac{q^{b}_{l,t}}{w^{b}_{l,t}}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\overline{L_l} \\
\Leftrightarrow\left(q^{g}_{l,t}\psi^{h,g}_{l,t}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\overline{L_l}\left[\left(\frac{\alpha^{h}_{l}}{w^{g}_{l,t}}\right)^{\frac{\alpha^{h}_{l}}{1-\alpha^{h}_{l}}}-\left(\frac{\alpha^{h}_{l}}{w^{g}_{l,t}}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\right] &> \left(q^{b}_{l,t}\psi^{h,b}_{l,t}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\overline{L_l}\left[\left(\frac{\alpha^{h}_{l}}{w^{b}_{l,t}}\right)^{\frac{\alpha^{h}_{l}}{1-\alpha^{h}_{l}}}-\left(\frac{\alpha^{h}_{l}}{w^{b}_{l,t}}\right)^{\frac{1}{1-\alpha^{h}_{l}}}\right] \\
\Leftrightarrow\ q^{g}_{l,t}\psi^{h,g}_{l,t} &> q^{g}_{l,t}\psi^{h,g}_{l,t} \\
\Leftrightarrow\ q^{g}_{l,t} &> q^{b}_{l,t}\left(\frac{\psi^{b}_{l,t}}{\psi^{g}_{l,t}}\right) \\
\Leftrightarrow\ q^{g}_{l,t}\Omega^{h}_{l,t} &> q^{b}_{l,t},
\end{aligned}
$$

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.

3.B.2.2 Housing renovations

For renovating brown into green housing, the construction firm solves the following problem:

$$
\max_{I^{ren}_{l,t}} q^{g}_{l,t} I^{ren}_{l,t} - w^{ren}_{l,t} N^{ren}_{l,t} - q^{b}_{l,t} h^{b}_{l,t} \quad \text{s.t} \quad I^{ren}_{l,t} = \Omega^{ren}_{l,t} \min\left\{\left(N^{ren}_{l,t}\right)^{\alpha^{ren}}, h^{b}_{l,t}\right\}.
$$

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

$$
h^{b}_{l,t} = \frac{I^{ren}_{l,t}}{\Omega^{ren}_{l,t}} \quad \text{and} \quad N^{ren}_{l,t} = \left(\frac{I^{ren}_{l,t}}{\Omega^{ren}_{l,t}}\right)^{\alpha^{ren}}.
$$

Hence, the construction firm solves

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

which gives the first-order-condition

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

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

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

Finally, the profits from renovations are given by

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

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

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

3.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 $\{V^{NM,NHA,NCA}, V^{NM,NHA,CA,GCA}, V^{NM,NHA,CA,BCA}, V^{NM,HA,NCA}, V^{NM,HA,CA,GCA}, V^{NM,HA,CA,BCA}$, $V^{M,NHA,NCA}, V^{M,NHA,CA,GCA}, V^{M,NHA,CA,BCA}, V^{M,HA,NCA}, V^{M,HA,CA,GCA}, V^{M,HA,CA,BCA}$, $V^{NM,NHA}, V^{NM,HA}, V^{M,NHA}, V^{M,HA}, V^{NM}, V^{M}, V\}$, prices $\{q^g_r, q^g_u, q^b_r, q^b_u, p^g_r, p^g_u, p^b_r, p^b_u, p^{c,g}$, $p^{c,b}, p^{ec}, p^{eh}, r\}$, aggregate variables $\{H^g_r, H^g_u, H^b_r, H^b_u, I^{h,g}_r, I^{h,g}_u, I^{h,b}_r, I^{h,b}_u, I^{ren}_r, I^{ren}_u, L_r, L_u$, $N, N^g_r, N^g_u, N^b_r, N^b_u, N^{ren}_r, N^{ren}_u, N^{c,g}, N^{c,b}, N^{eh}, N^{ec}, E^c, E^h, Y, C^g, C^b\}$, 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 $N^x = 1 - N_r^g - N_u^g - N_r^b - N_u^b - N_r^{ren} - N_u^{ren} - N^{c,g} - N^{c,b} - N^{eh} - N^{ec}$.
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.

Appendix 3.C Additional model results

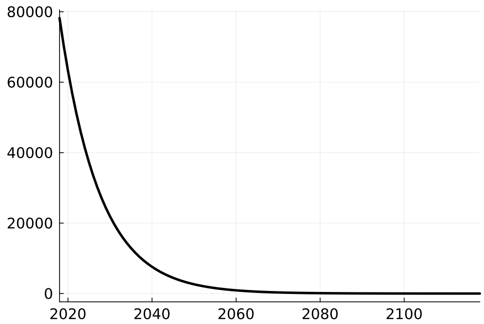
This section provides more details on the results of the quantitative analysis. First, I show details on the calibration and additional results for the baseline specification. Thereafter, I check the robustness of the baseline results by providing an extensive sensitivity analysis.

3.C.1 Additional results for the baseline model

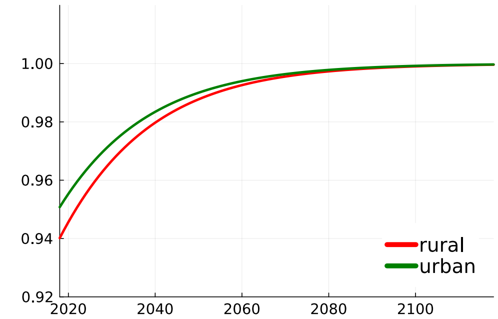
Figure 3.C.1 plots the convergence of the productivity levels and prices for green technologies along the transition. Subfigure 3.C.1a shows the price premium for green cars. I calibrate this price premium to match the observed adoption rates for electric vehicles from 2019 to 2023. Initially, prices for green cars are around 76,000 Euros higher than those for brown 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 green cars.

Figure 3.C.1. Convergence of productivities and prices of green technologies

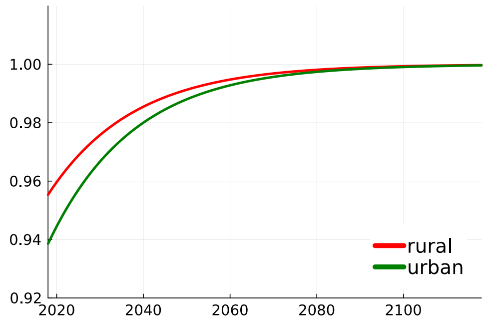
(a) Price premium for green cars



(b) Relative productivity green housing construction



(c) Productivity for housing renovations

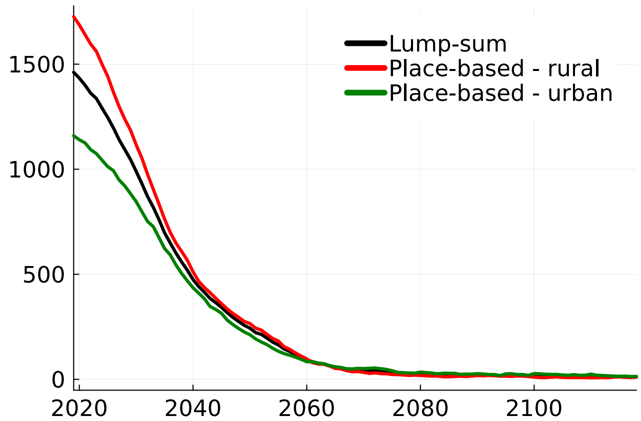


Notes: Panel (a) shows the price premium of green cars relative to brown cars in Euros over the transition period. Similarly, Panel (b) shows the productivity of green housing construction relative to brown housing construction over the transition period. Finally, Panel (c) shows the productivity of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

Subfigures 3.C.1b and 3.C.1c show the discount in the productivity of producing green relative to brown houses and the productivity of renovations. The initial productivity levels are calibrated to match the observed difference in production costs for green and brown housing construction and the observed renovation rate, respectively. The initial productivity of green 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 green and brown 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 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 3.C.2 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.

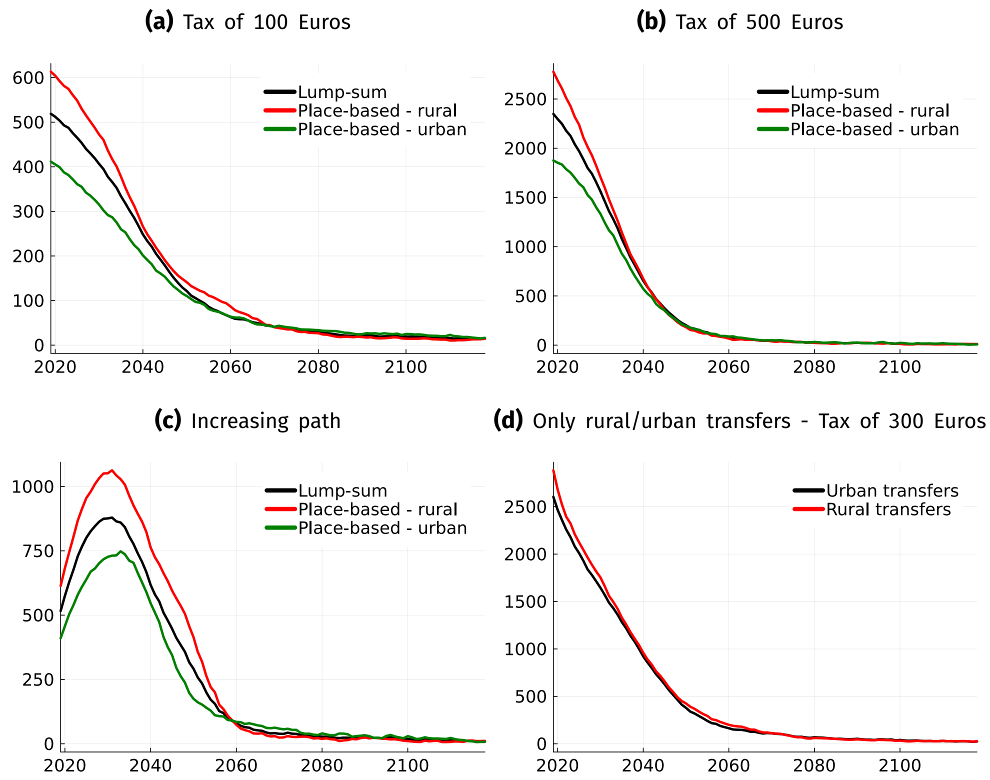
Figure 3.C.2. Transfer levels for different carbon taxes and policies



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.

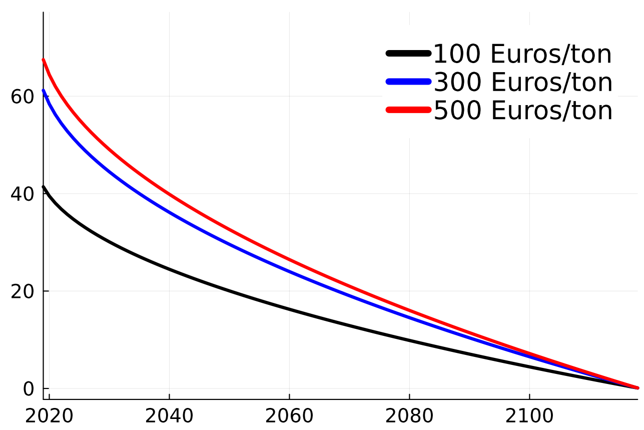
Figure 3.C.3 shows how the level of transfers change with different levels of carbon taxes and rebating policies. With lower (higher) carbon taxes the level of transfers naturally decreases (increases). Note that with carbon taxes of 500 Euros per ton, the level of transfers decreases faster than with carbon taxes of 100 Euros, as carbon emissions decrease faster with higher carbon taxes. With an increasing carbon tax path, as specified in Figure 3.C.18, 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 3.C.3. 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 3.C.4. Subsidy level on housing renovations (%)



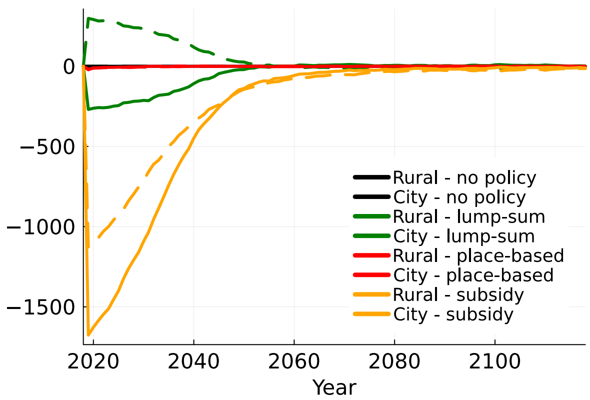
Notes: This figure shows the percentage subsidy on housing renovations for carbon taxes of 100, 300, and 500 Euros per ton of carbon.

Figure 3.C.4 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.

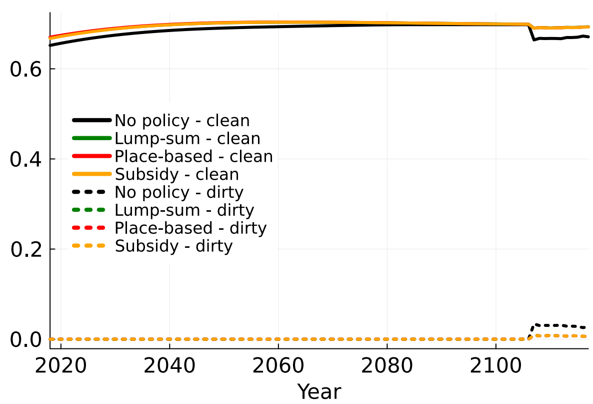
Figure 3.C.5 shows the spatial redistribution for the baseline specification with carbon taxes of 300 Euros per ton of carbon. Without policy and with place-based transfers, there is no redistribution by construction. Figure 3.4.3a in the main text shows the corresponding case with lump-sum transfers. 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 3.C.5. 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 3.C.6. Housing construction by housing type

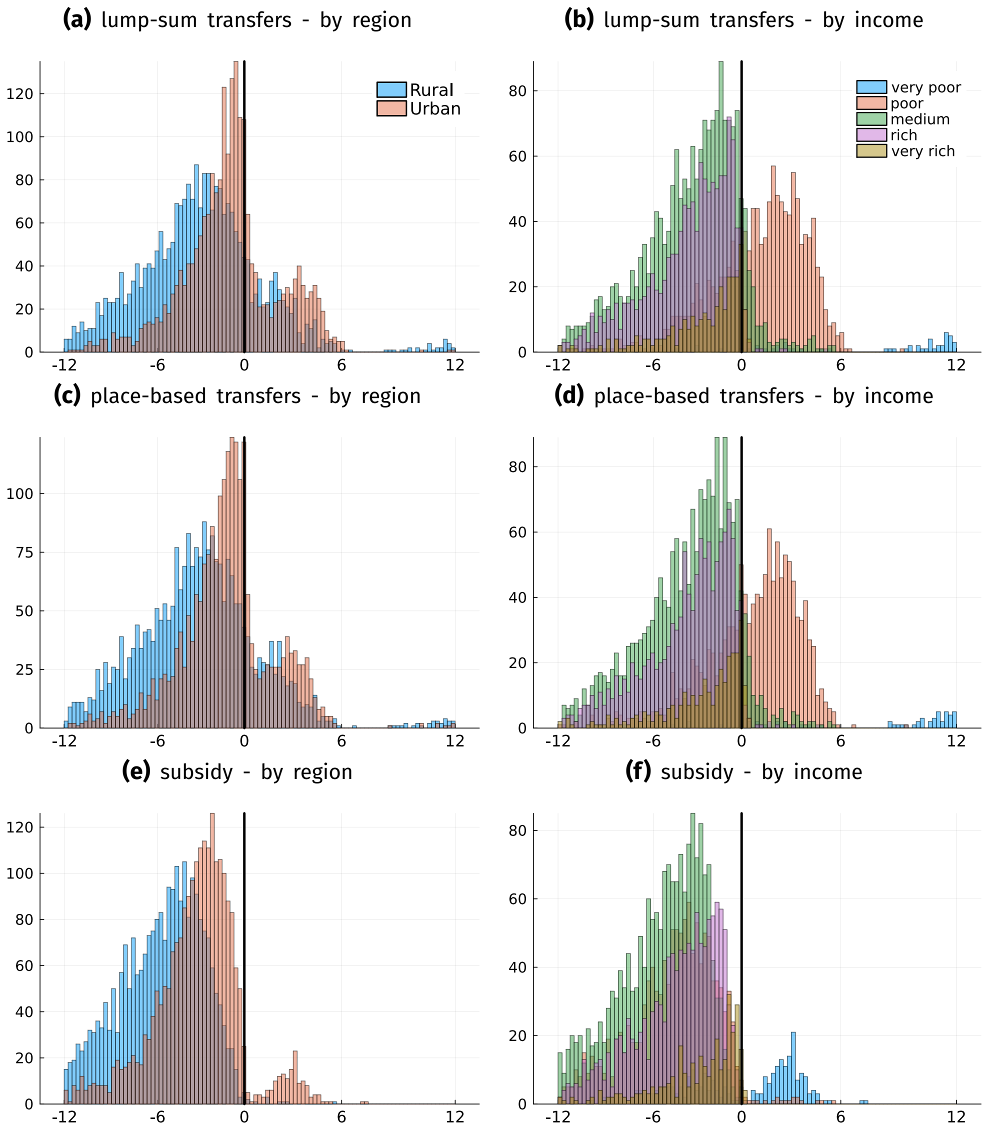


Notes: This figure shows the construction rates, being defined as the share of newly build housing units relative to the total housing stock in the initial steady state, for both housing types and the different policy scenarios.

Figure 3.C.6 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 green houses, as their prices are higher.

Finally, Figure 3.C.7 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 3.C.7. 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.

3.C.2 Sensitivity analysis

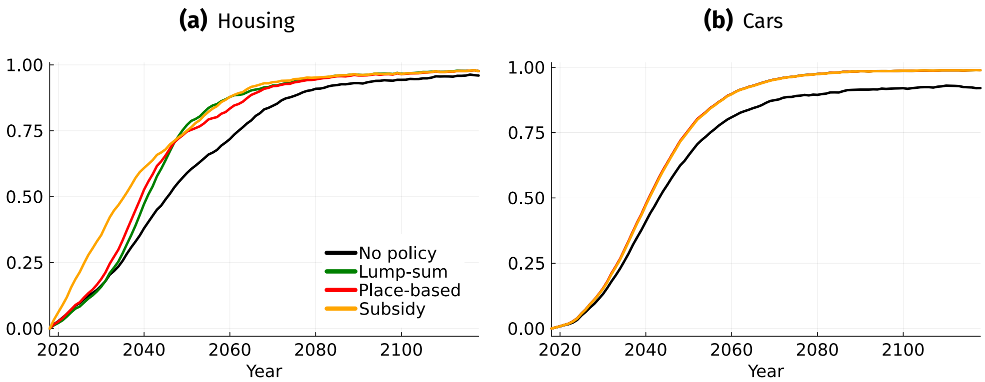
For the policy analysis in the main part, I focus on a constant carbon tax of 300 Euros per ton of carbon emissions. Within the European ETS2, there is, however, no fixed price per ton of emissions but rather a given number of issued certificates which allow firms to emit carbon emissions. These certificates will be 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 period.

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.

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

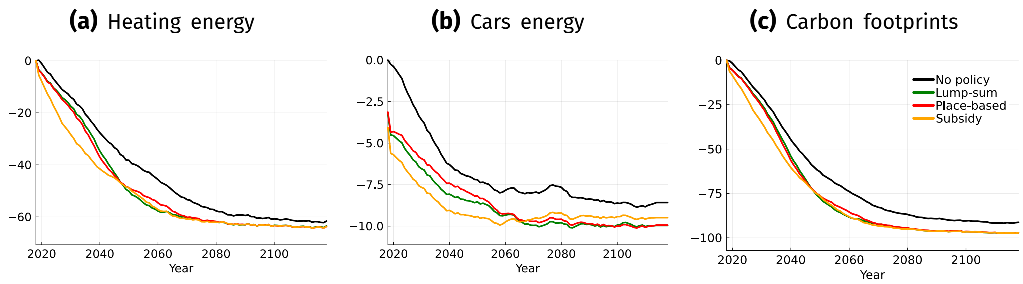
Figure 3.C.8 shows the share of households with green technologies along the transition. As expected, a carbon tax of 100 Euros per ton of carbon speeds up the transition less than the baseline tax of 300 Euros.

Figure 3.C.8. Share of green technologies along the transition - carbon tax of 100 Euros per ton



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

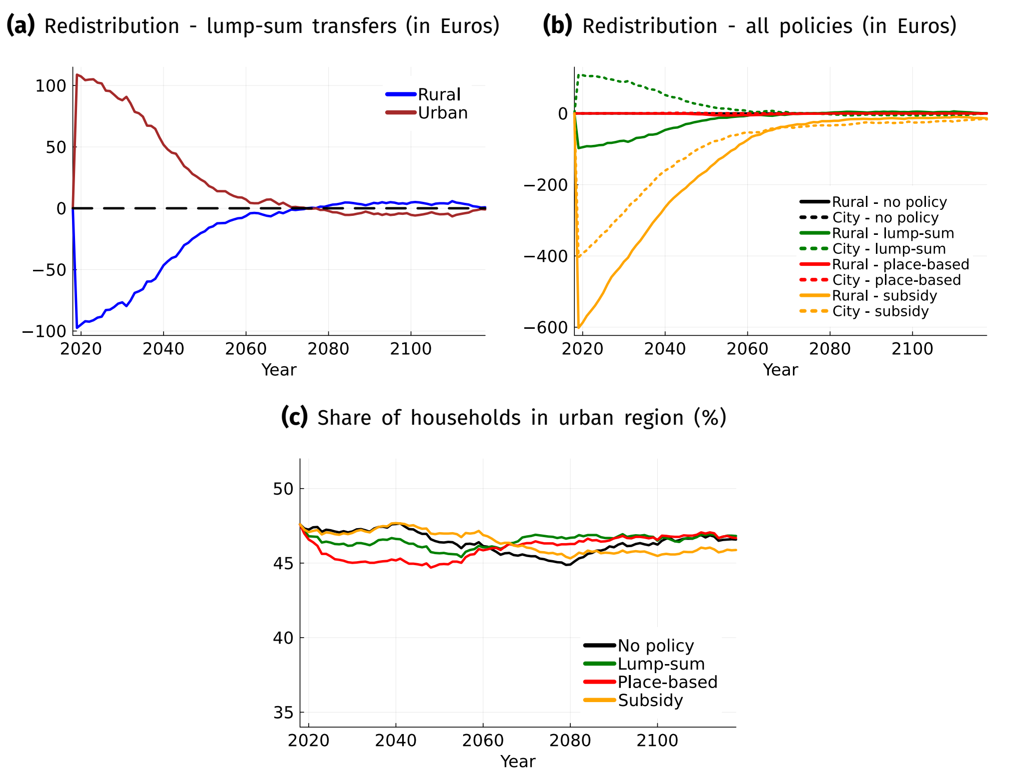
Figure 3.C.9. Percentage changes over the transition - carbon tax of 100 Euros per ton



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 3.C.10 shows that carbon taxes of 100 Euros lead to shares of households with green houses and cars of around 75 percent for both goods by 2050, while in the baseline the shares were of around 88 and 85 percent, respectively. As

Figure 3.C.10. Location choices and redistribution over the transition - carbon tax of 100 Euros per ton

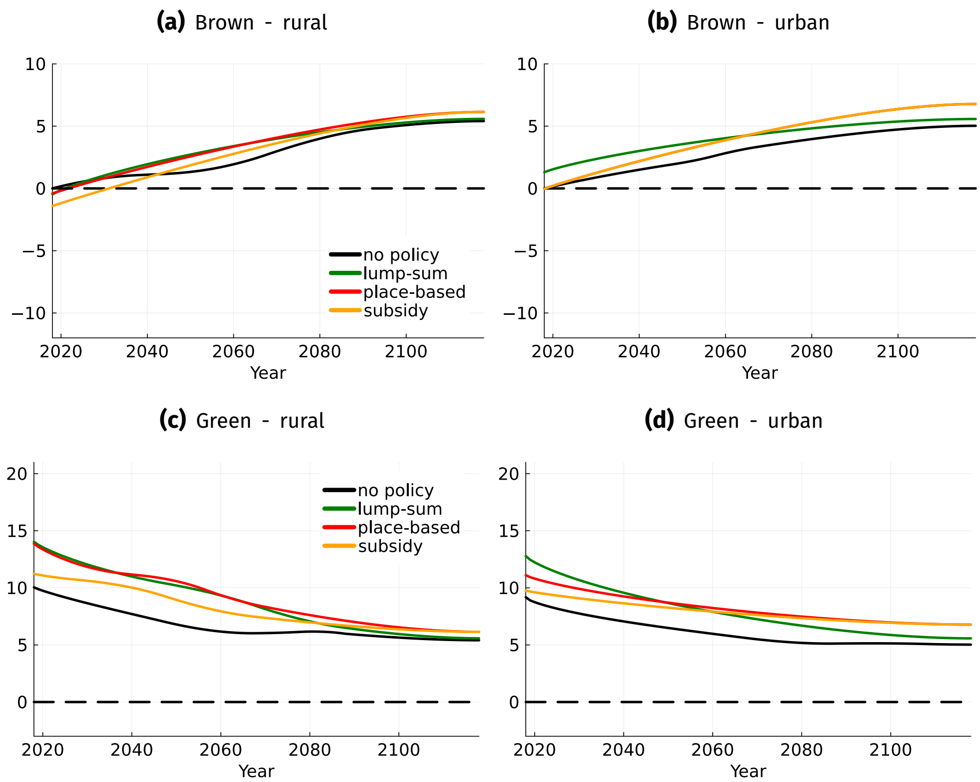


Notes: Panel (a) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers. Panel (b) shows the share of the population living in the urban region along the transition for the different policy scenarios.

a result, also the declines 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.

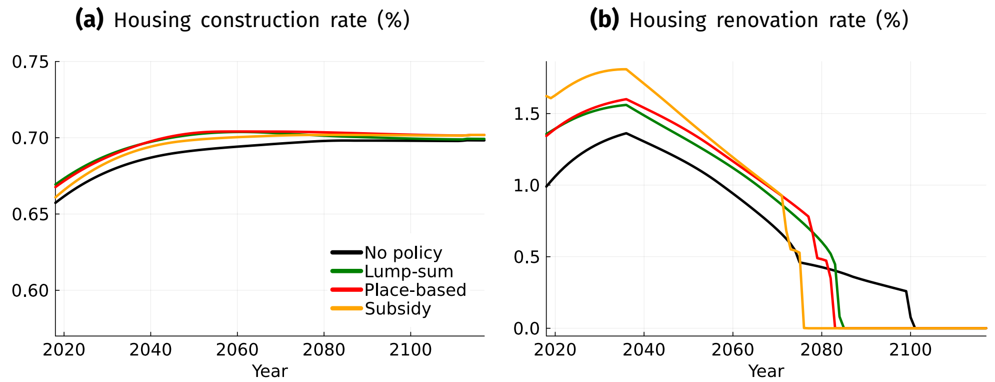
Figure 3.C.10 shows that the level of spatial redistribution, and the net migration flows are considerably smaller. The difference in the present value of net transfers between rural and urban households is 3,000 Euros, compared to the 8,000 Euros in the baseline. The changes in housing prices are also smaller with carbon taxes of 100 Euros per ton of carbon. Figure 3.C.11 documents that the initial price premium of green 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 brown houses is only around 1 percentage point with carbon taxes, while it was around 5 percentage points in the baseline. Finally, housing construction still reacts very little in response to the carbon tax and housing renovations react less strong, as Figure 3.C.12 documents.

Figure 3.C.11. Housing price changes over the transition - carbon tax of 100 Euros per ton



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

Figure 3.C.12. Housing construction and renovations over the transition - carbon tax of 100 Euros per ton

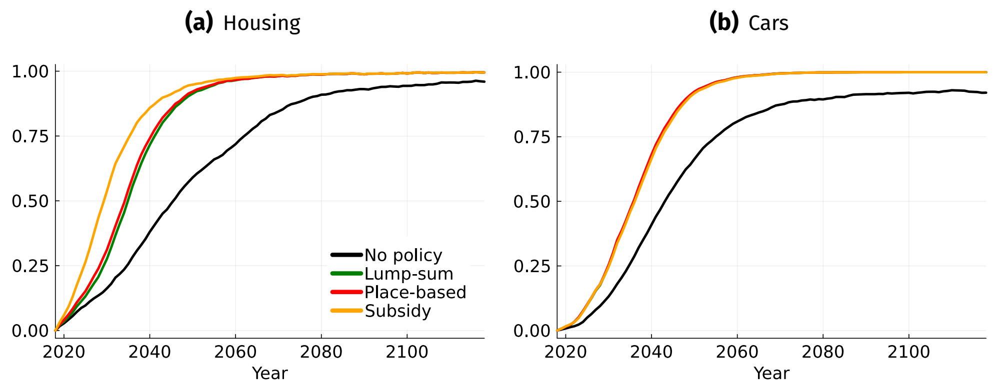


Notes: Panel (a) shows the share of newly constructed housing relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition. Panel (b) shows the share of housing renovations relative to the stock of housing in the initial stationary equilibrium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

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

The results for the high-carbon tax scenario of 500 Euros per ton of carbon lead to a faster transition to green goods. While in the baseline around 88 to 90 percent of households use green 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.

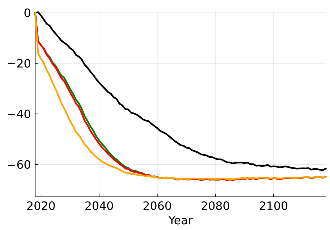
Figure 3.C.13. Share of green technologies along the transition - carbon tax of 500 Euros per ton



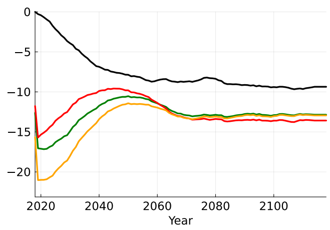
Notes: Panel (a) shows the share of households with green houses along the transition period for the different policy scenarios considered. Panel (b) shows the corresponding share of households with green cars along the transition.

Figure 3.C.14. Percentage changes over the transition - carbon tax of 500 Euros per ton

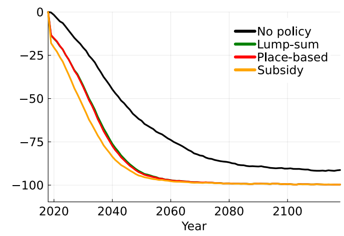
(a) Heating energy



(b) Cars energy



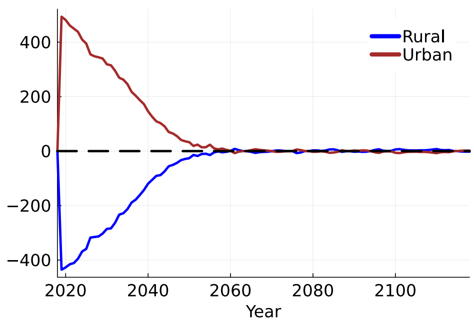
(c) Carbon footprints



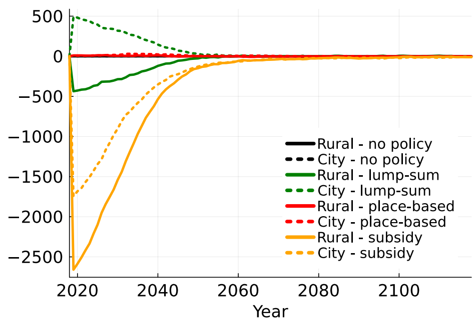
Notes: Panel (a) and Panel (b) show the percentage change in heating and car energy along the transition for the considered policy scenarios. Panel (c) depicts the resulting path of carbon footprints. Finally, Panel (d) shows the annual level of net transfers for rural and urban households if the carbon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

Figure 3.C.15. Location choices and redistribution over the transition - carbon tax of 500 Euros per ton

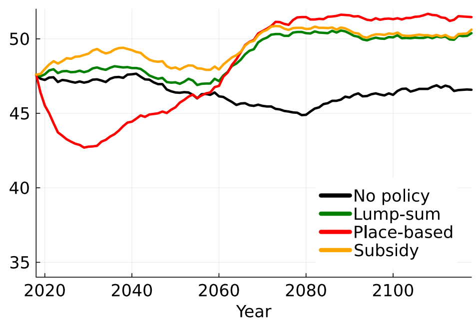
(a) Redistribution - lump-sum transfers (in Euros)



(b) Redistribution - all policies (in Euros)



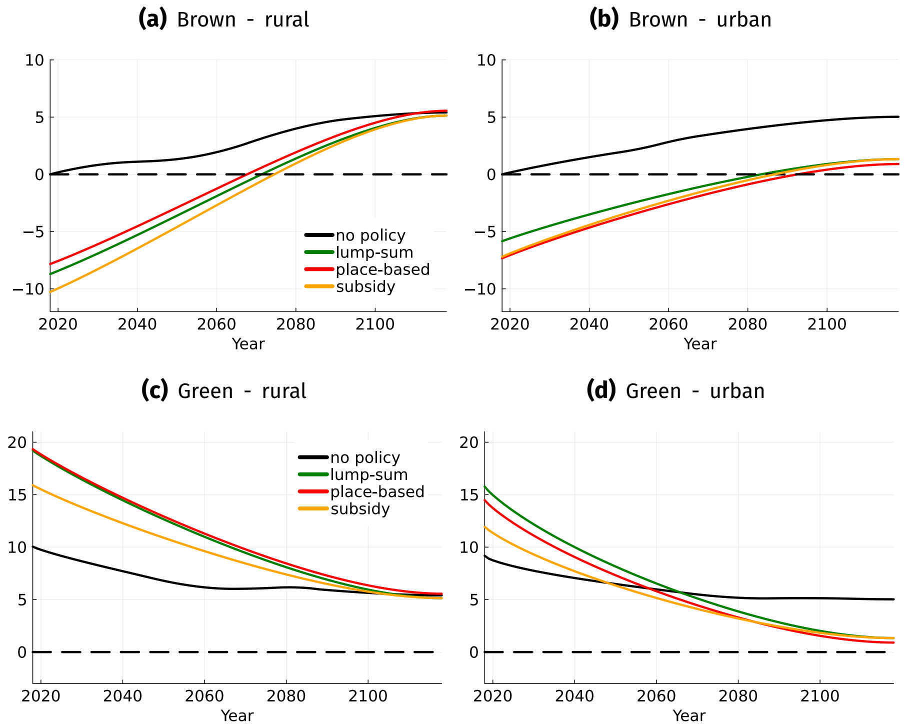
(c) Share of households in urban region (%)



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.

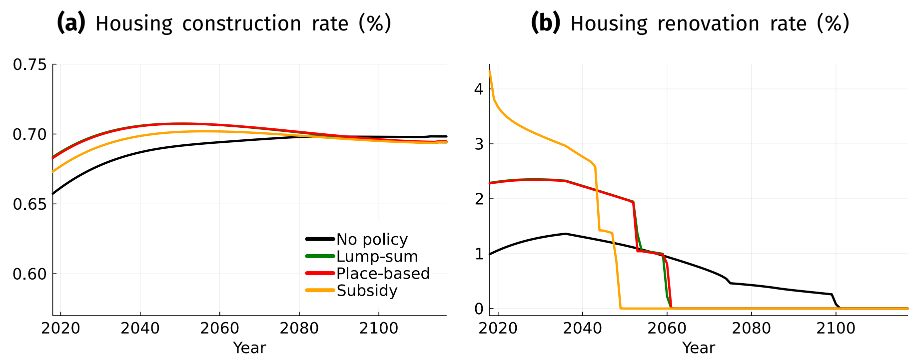
The reaction of the housing prices is much stronger, too. While the premium for green houses with lump-sum and place-based transfers was around 14 to 15 percent, it increases to 15 to 19 percent with carbon taxes of 500 Euros. Also the initial price drop for brown houses is with 6 to 10 percent larger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

Figure 3.C.16. Housing price changes over the transition - carbon tax of 500 Euros per ton



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

Figure 3.C.17. Housing construction and renovations over the transition - carbon tax of 500 Euros per ton



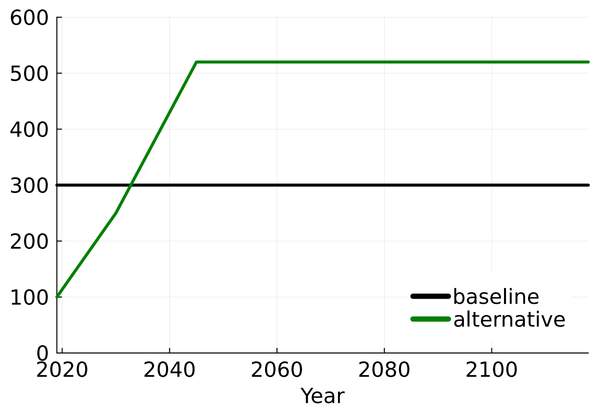
Notes: Panel (a) shows the share of newly constructed housing relative to the stock of housing in the initial stationary equilibrium for the different policy scenarios along the transition. Panel (b) shows the share of housing renovations relative to the stock of housing in the initial stationary equilibrium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

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 green and brown houses and as the lead to higher percentage subsidies, the around 4 percent of the initial brown housing stock is renovated in the first years of the transition.

3.C.2.3 Increasing path of carbon emissions

Figure 3.C.18 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.

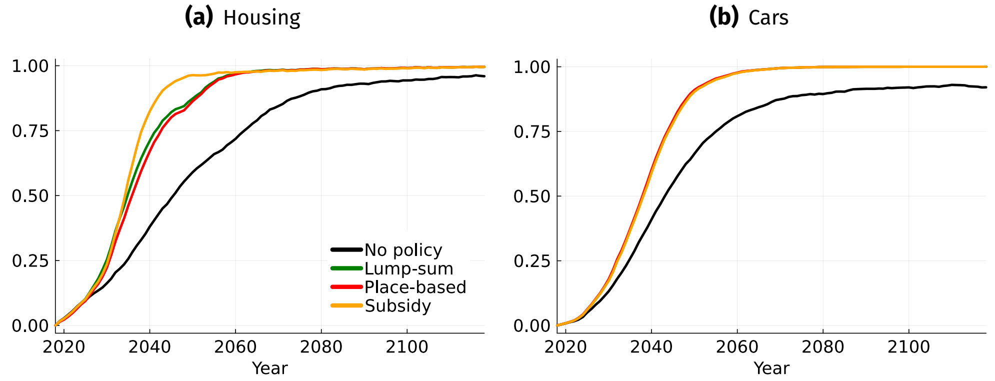
Figure 3.C.18. Alternative increasing path of carbon taxes



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

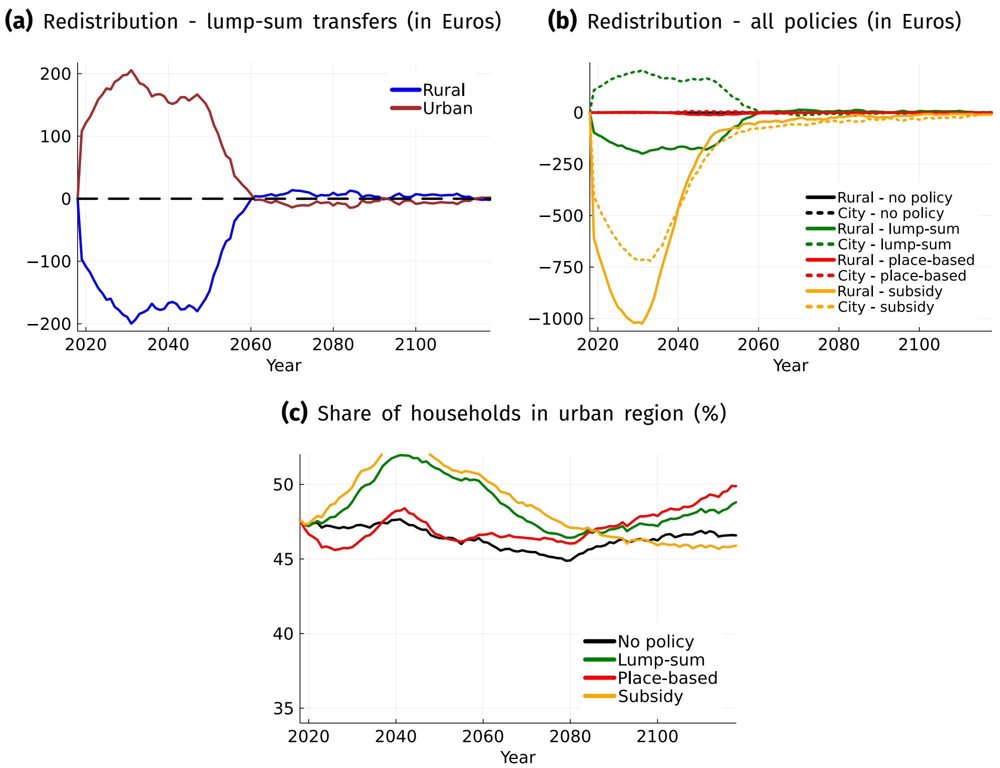
Figure 3.C.19 shows that the adoption of green technologies happens slower than in the baseline due to the lower initial carbon tax. As carbon taxes increase, the share of green technologies is very similar to the one in the baseline by 2050. As a result, also the reduction in emissions by 2050 is very 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 very similar to the baseline, too.

Figure 3.C.19. Share of green technologies along the transition - increasing carbon tax path



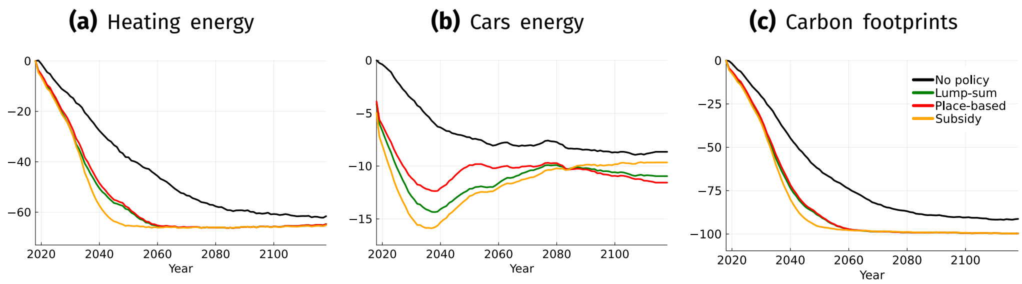
Notes: Panel (a) shows the share of households with green houses along the transition period for the different policy scenarios considered. Panel (b) shows the corresponding share of households with green cars along the transition.

Figure 3.C.20. Location choices and redistribution over the transition - increasing carbon tax path



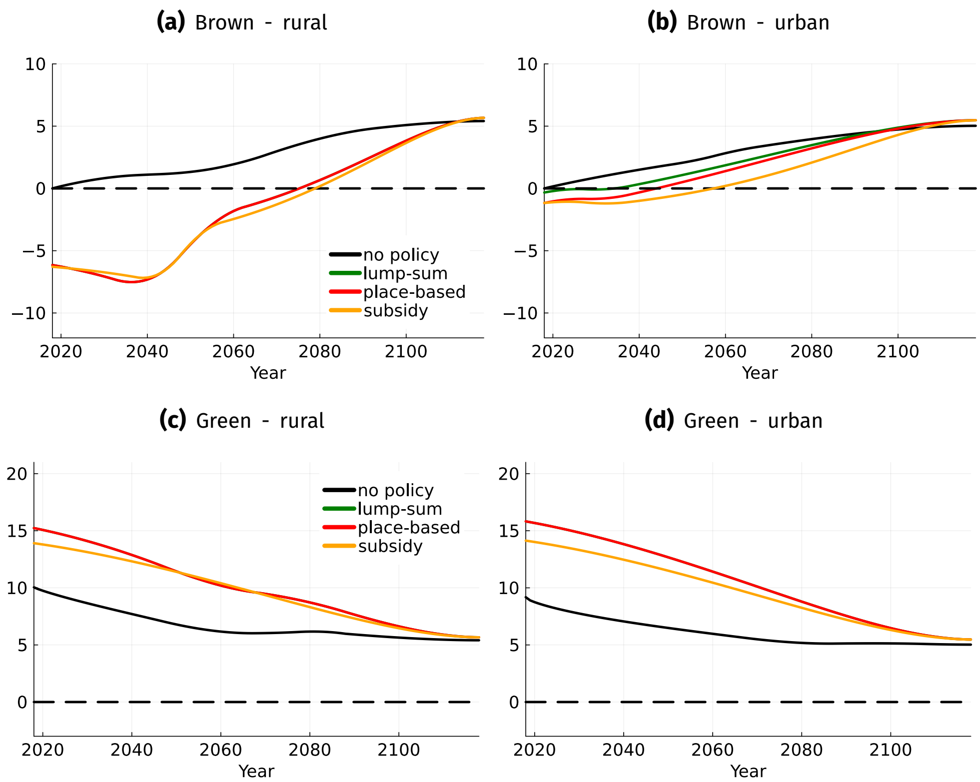
Notes: Panel (a) shows the annual level of net transfers for rural and urban households if the carbon tax revenues are used for lump-sum transfers. Panel (b) shows the share of the population living in the urban region along the transition for the different policy scenarios considered.

Figure 3.C.21. Percentage changes over the transition - increasing carbon tax path



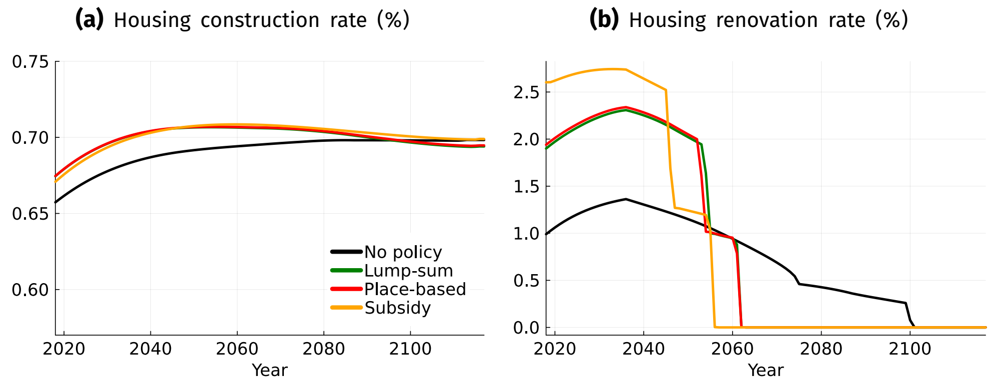
Notes: Panel (a) and Panel (b) show the percentage change in heating and car energy along the transition for the considered policy scenarios. Panel (c) depicts the resulting path of carbon footprints. Finally, Panel (d) shows the annual level of net transfers for rural and urban households if the carbon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

Figure 3.C.22. Housing price changes over the transition - increasing carbon tax path



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

Figure 3.C.23. Housing construction and renovations over the transition - increasing carbon tax path



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.

Tables 3.C.1 and 3.C.2 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.

Table 3.C.1. 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 3.C.2. Political support for climate policies - welfare decision - increasing carbon tax path

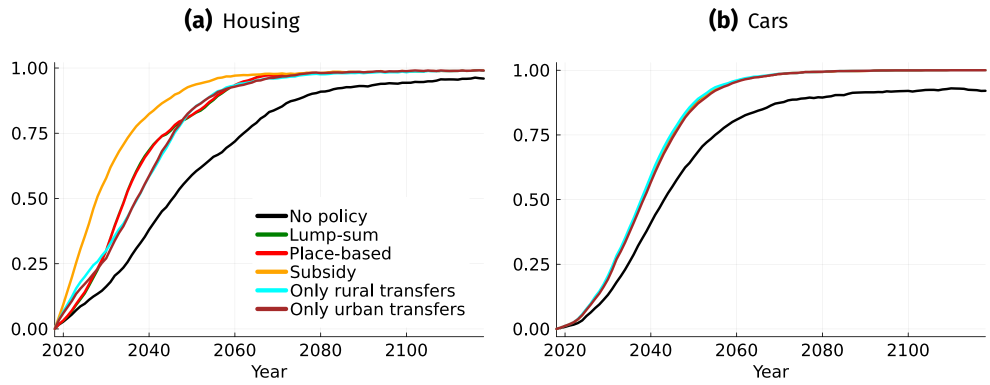
	Lump-sum				Place-based			
$\tau =$	100	300	500	Rising	100	300	500	Rising
Baseline								
All	36.3	29.1	17.3	30.2	40.2	32.4	18.0	33.4
Rural	31.1	22.3	11.0	23.5	38.8	30.2	15.0	31.2
Urban	41.1	36.1	23.8	37.2	42.9	34.1	21.2	35.2
Positive ext.								
All	46.2	39.9	20.3	40.8	50.1	41.9	22.1	42.3
Rural	41.2	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.

3.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 3.C.24 shows that the transitions to green 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 3.C.25c.

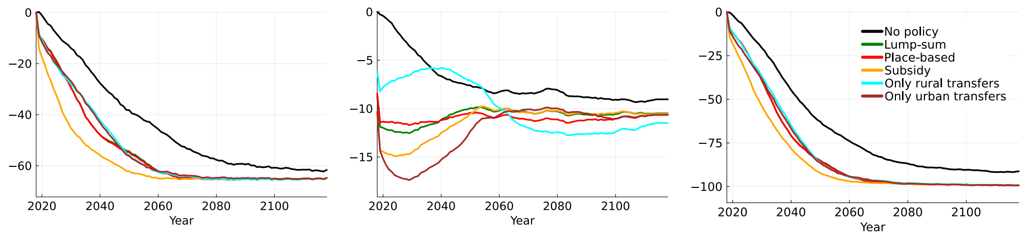
Figure 3.C.24. Share of green technologies along the transition - only rural/urban transfers



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

Figure 3.C.25. Percentage changes over the transition - only rural/urban transfers

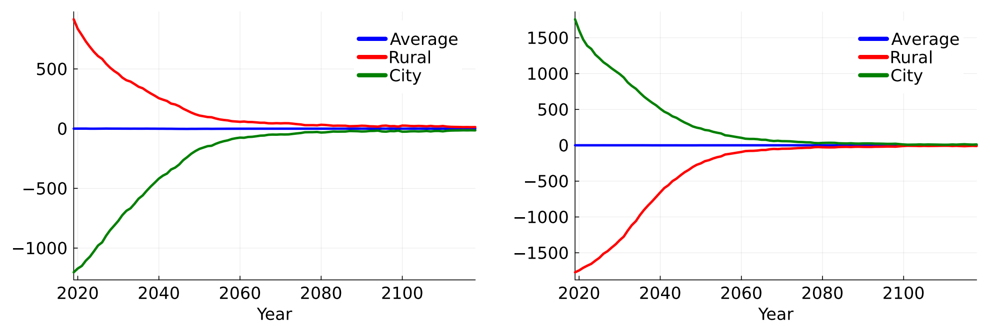
(a) Heating energy **(b)** Cars energy **(c)** Carbon footprints



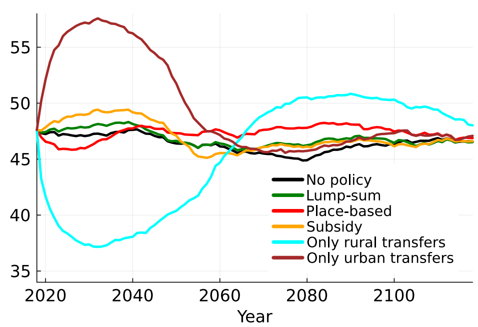
Notes: Panel (a) and Panel (b) show the percentage change in heating and car energy along the transition for the considered policy scenarios. Panel (c) depicts the resulting path of carbon footprints. Finally, Panel (d) shows the annual level of net transfers for rural and urban households if the carbon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

Figure 3.C.26. 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)



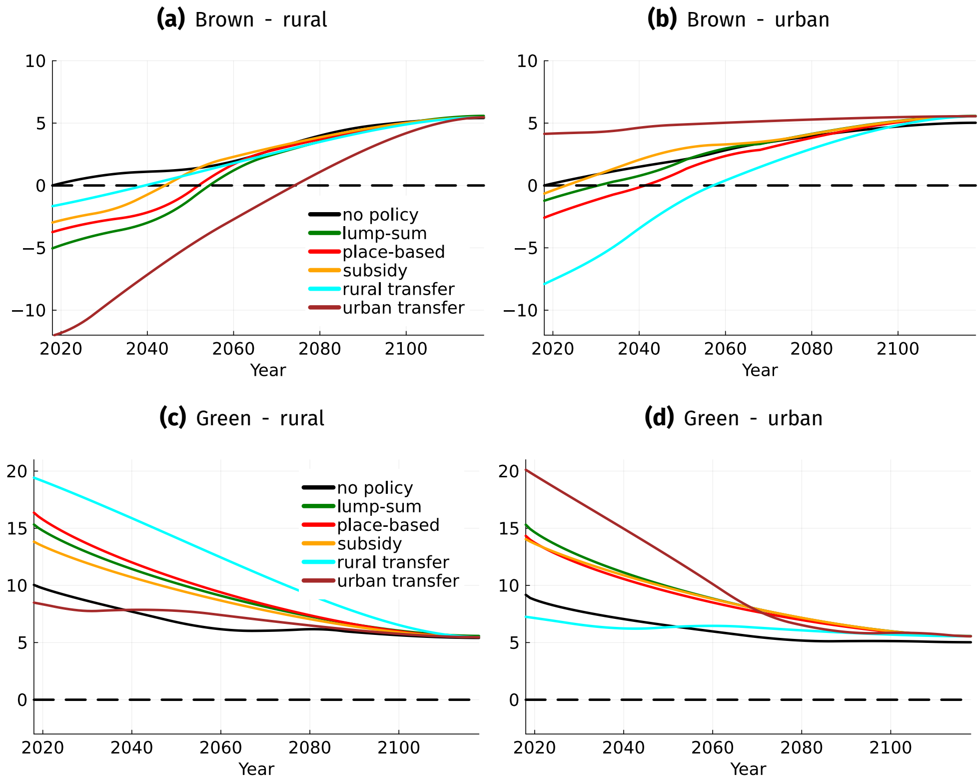
(c) Share of households in urban region (%)



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.

But the level of spatial redistribution increases substantially, as Subfigure 3.C.26a shows. 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 (Subfigure 3.C.26b). 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 3.C.26c documents.

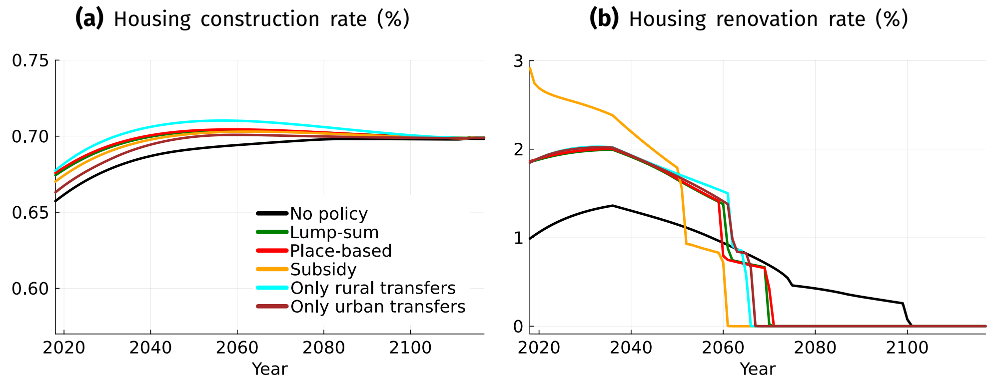
Figure 3.C.27. Housing price changes over the transition - only rural/urban transfers



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

The housing prices do also change substantially with these extreme ways of redistribution, as Figure 3.C.27 shows. If only paying transfers to rural households, the initial price drop for brown, urban houses amounts to 8 percent, while brown 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. Brown houses in the rural region loose around 12 percent in value, while brown houses in the urban region even gain around 4 percent in value. The initial price premium of green 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 3.C.28).

Figure 3.C.28. 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.

Tables 3.C.3 and 3.C.4 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 3.C.3. 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 3.C.4. 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.

References

Holland, Stephen P, Erin T Mansur, and Andrew J Yates. 2021. "The electric vehicle transition and the economics of banning gasoline vehicles." *American Economic Journal: Economic Policy* 13 (3): 316–44.

Kalkuhl, Matthias, Maximilian Kellner, Tobias Bergmann, and Karolina Rütten. 2023. "CO2-Bepreisung zur Erreichung der Klimaneutralität im Verkehrs- und Gebäudesektor: Investitionsanreize und Verteilungswirkungen."

LCP Delta. 2021. "Heat pump costs projected to fall by 40 percent." URL: https://delta.lcp.com/press-release/heat-pump-costs-projected-to-fall-by-40/.

Lévay, Petra Zsuzsa, Yannis Drossinos, and Christian Thiel. 2017. "The effect of fiscal incentives on market penetration of electric vehicles: A pairwise comparison of total cost of ownership." *Energy Policy* 105: 524–33.