2119

Discussion Papers

Deutsches Institut für Wirtschaftsforschung

2025

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IMPRESSUM

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ISSN electronic edition 1619-4535

Prioritize to Decarbonize: Thermal Retrofits, Carbon Prices, and Energy Inequality

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May 9, 2025

Abstract

The energy crisis following Russia's invasion of Ukraine exposed the heightened vulnerability of low-income households to rising heating costs, particularly those in energy inefficient buildings. Using data from the German Socio-Economic Panel (SOEP), this study examines the distributional impact of heating costs across income deciles and evaluates the effectiveness of policy interventions. We find that low-income tenants are the most vulnerable segment of the population, with elevated risks of energy poverty. While carbon pricing with landlord-tenant cost splitting shields low-income households from carbon costs, it fails to offset overall energy price increases. In contrast, a "Worst-First" retrofit strategy, prioritizing upgrades in the least efficient buildings, substantially reduces heating costs and mitigates energy poverty. Our findings highlight the need for targeted retrofit policies to ensure both equitable decarbonization and economic relief for vulnerable households.

JEL: Q41, Q48, D31, D63
Keywords: Distributional effects, energy efficiency, retrofit, carbon prices, energy price crisis

1 Introduction

The energy price crisis in 2022 highlighted the risk of energy poverty across the European Union (EU). In 2023, more than 10% of EU households could not heat their homes adequately (Eurostat, 2025). However, this burden of high heat energy prices is not evenly distributed across income groups as particularly low-income households spend large shares of their disposable income on heat energy bills (Tovar Reaños & Wölfing, 2018). Spikes in heat energy prices, as observed during the crisis, therefore increase the risk of energy poverty. In Germany, for instance, energy poverty more than doubled from 3.3% to 8.2% in 2023 despite public subsidies to limit the cost increase (Eurostat, 2025). Government intervention in the form of lump-sum payments, as implemented in the past crisis, to mitigate these shocks can lead to high fiscal costs, while only partially alleviating household energy cost burdens (Kröger et al., 2023). Crucially, while this may provide some relief in the short-term, this type of government intervention discourages investments necessary to address the structural drivers of energy poverty, namely the level and variation of energy inefficiency of the existing building stock (Behr et al., 2023).

Addressing building energy inefficiencies is central to both reducing households' energy burdens and achieving climate targets. Heating and cooling activities are the main drivers of building emissions, comprising 26% of global energy-related emissions (IEA, 2023). Thermal retrofit is widely recognized as an effective strategy to reduce energy demand in buildings (IEA, 2024) and comes with numerous benefits, ranging from reducing energy poverty and improving well-being to reducing building emissions (Lou et al., 2022; Roberdel et al., 2023). Building retrofit offers varying levels of energy savings depending on the retrofit depth (Lidelöw et al., 2019). Several case studies illustrate how significant energy savings are achieved through comprehensive retrofit projects (Hamilton et al., 2013; La Fleur et al., 2018; Shamout et al., 2019; Thomsen et al., 2016; Vakalis et al., 2021).

Due to the climatic and economic benefits of building retrofits, they have gained increasing attention in the policy sphere. The Energy Performance of Buildings Directive (EPBD) establishes EU-wide standards that require nearly zero-energy new buildings, mandate energy performance assessments and upgrades for existing structures, and promote long-term renovation strategies to reduce energy use and carbon emissions. During its 2024 renewal, the focus shifted to the least energy efficient buildings, with targets set to prioritize the thermal retrofit of the worst 43% of the building stock. The revised EPBD states that 55% of emission reductions must come from these worst performing buildings (European Commission, 2024). While this focus is climate-driven, it also carries considerable socio-economic implications, given that low-income households are more likely to reside in energy inefficient buildings. This raises the question of the effect of the revised EPBD on socio-economic characteristics, in particular energy poverty.

In this paper, we investigate the distributional implications of heat energy price hikes in combination with carbon pricing and retrofit strategies. We use data from the German Socio-Economic Panel (SOEP) to study the distribution of heating costs across income deciles for the year 2024. We start by comparing the current situation, i.e. status quo of high heating costs, with a counterfactual specification in which the energy crisis had not occurred. We then analyze the role of home-ownership on energy expenditures, as tenants and homeowners face different constraints in relation to energy efficiency improvements. In addition to the immediate cost burden, we explore the implications of rising carbon prices. Specifically, we assess how different retrofit strategies could alleviate economic hardship. More precisely, we investigate how a strategic "Worst-First" retrofit strategy that aligns with the EPBD's prioritization goals can reduce unequal burdens of heating costs. By modeling the impact of these emission pricing policies and retrofit strategies, we provide insights into their effect on energy poverty.

Our results highlight the stark vulnerability of low-income households to high heating costs, particularly in energy inefficient buildings. In 2024, low-income households spent a disproportionately large share of their income on heating. Specifically, the median relative share of heat energy costs is between 12.9 and 16.7% for households in the lowest two income deciles. On the other hand, this share is between 4.7 and 5.9% for the top two income deciles. Strikingly, the share varies substantially more for lower income households. For instance, 25% of households in the lowest two income deciles spend more than 18.0% of their income on heating. This is the case despite low-income households living, on average, in significantly smaller dwellings than high-income households. In the status quo, depending on the definition, energy poverty ranges from 5.2% and 8.1%. We find that tenants live on average in less energy efficient homes and are more likely to face energy poverty. We find 7.1% to 10.6% of all tenants are energy poor. Our analysis shows that carbon pricing with landlord-tenant cost splitting works to protect the lowest income deciles from high carbon prices. However, it is not sufficient to protect these households from escalated heat energy prices, as seen during the 2022 crisis. In contrast, a Worst-First retrofit strategy substantially reduces heating cost burdens, particularly for low-income tenants. Our back-of-the-envelope calculation shows that if the energy efficiency of the most energy inefficient 30% (43%) of buildings is improved, 38.5% (57.9%) of heating costs could be saved on average. The share of tenants in the lowest two income deciles who spend more than 20% of their income on heating diminishes to 5 to 10% under the 30% retrofit scenario and disappears completely in the 43% retrofit scenario.

Our study contributes to the literature on household energy demand by examining distribution of heating costs across income deciles and assessing how different retrofit policy interventions could mitigate energy poverty. Our findings show that tenants in all income brackets experience higher average heating costs per square meter than homeowners, underscoring the persistent tenant-landlord dilemma that hinders retrofit investments. Closest to our paper are papers by George et al. (2023), who focus on the tenant-landlord dilemma, and by McCoy and Kotsch (2021), who quantify the benefits of retrofits. They find that especially low-income households profit less than estimated pre-retrofit, possibly due to higher room temperatures. This is one reason Roberdel et al. (2023) highlight that a lower fuel poverty comes at the expense of lower energy savings. Thus, how to evaluate retrofits from a welfare perspective is difficult. At the same time, George et al. (2023) find that carbon pricing and the modernization levy impact tenants regressively.

Our findings serve as a foundation for policies aimed at designing more equitable and effective decarbonization strategies. First, we claim that a retrofit strategy is not only a climate relevant strategy but also a social policy since it protects the most vulnerable segments of the population. Our findings show that, in the face of high energy prices, a targeted retrofit strategy protects low-income households and tenants who are most exposed to their adverse effects. Second, our analyses of the various specifications under different carbon prices, energy price increases, and retrofit strategies, highlight the importance of well-targeted retrofit policies to mitigate both energy poverty and carbon emissions effectively.

Findings in the literature suggest that optimal policy design for improving energy efficiency and equity remains unclear. For example, García-Muros et al. (2022) find that household rebates have progressive effects whereas efficiency-oriented policies, such as payroll tax reductions, are slightly regressive. As a result, these suggest combining the compensation of low-income households with a reduction of distorting taxes. In their literature review Gillingham et al. (2018) find that behavioral and informational programs are most cost-effective while also providing the smallest energy savings. Meanwhile, Saunders et al. (2021) provide an overview of energy efficiency research from 1980s through 2020s and show that, overall, energy efficiency efforts have been successful. In contrast, other work suggests policies only have a small impact on building energy efficiency (Eyre & Baruah, 2015; Peñasco & Anadón, 2023) indicating the need for better-designed interventions.

The remainder of this paper is structured as follows: Section 2 introduces our data and methodology. Section 3 presents our results and Section 4 discusses those with a focus on the relevant policies and their implications, while Section 5 concludes.

2 Data and Methodology

2.1 Primary Data Source

We employ the German Socio-Economic Panel (SOEP) in our empirical analysis, which is an annual representative longitudinal study of private households and individuals surveyed in Germany since 1984 (v.39, EU, Goebel et al. (2023)). The survey data covers a wide variety of topics including household composition, income, and wealth. The dataset is especially suitable in our context, as it provides micro-data on household characteristics, housing conditions, and heating expenditures. Our sample comprises private households in Germany, excluding institutionalized households. Our variables of focus include equalized household net income,[1] household wealth, homeownership, dwelling size, heating costs, and the primary energy source used for heating. We use heating costs per square meter as a measure of energy efficiency.[2] Our key measure is

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[1] We adjust for differences in household composition by applying the square root equivalence scale, as used by the OECD.

[2] The SOEP contains a question on whether the interviewed households' dwelling includes thermal insulation or not. However, this is a relatively broad question and does not provide detailed information on the degree of insulation.

the proportion of heating expenditure relative to the household income calculated by dividing the annual heating costs by the equivalent household net income.

Our main analysis is based on the SOEP responses from 2017, as that specific year also includes detailed information on household wealth. In combination with income, wealth is an additional measure that allows us to identify economically vulnerable households. Our primary measure of wealth is gross non-housing wealth.[3] Furthermore, we impute information on the primary energy source, which is available for 2015 and 2020. This is relevant for our analyses as the carbon and, thereby emission, intensity of various energy sources differ. The panel structure of the SOEP allows us to write the information forward from 2015 and backward from 2020 to obtain the energy source in 2017. Since we also observe if a household moved during this period, we drop them from the sample in order not to incorrectly assign them a particular primary energy source.

Out of a total of 15,765 households in 2017, we exclude those with incomplete data on heating, income, or dwelling size, as these are key variables in our analysis. This reduces the sample by 1,103 observations. Additionally, we successfully impute the energy source for 12,256 households, which forms our working sample. Consequently, a further 2,102 observations are dropped due to missing information. [4]

To determine the status quo, household incomes and costs are adjusted to reflect the economic conditions of 2024. We assume a 100% increase in heating costs, which reflects the average increase from 0.06 to 0.12 EUR/kWh (Behr et al., 2024; Stede et al., 2018). During the same period, incomes have increased by 17% on average (Statistisches Bundesamt, 2024). Wealth is assumed to grow at the Euribor interest rate, which was at 4.6 % over the whole period.[5]

Table A1 presents the summary statistics for the key variables, separately for the full sample, and split by tenants and owners. The statistics for the entire sample mask the difference in terms of dwelling size, heating costs, and household equivalent income for tenants and home-owners. On average, homeowners occupy significantly larger dwellings (132.1 m^2) compared to tenants (79.9 m^2), with a higher median dwelling size as well. At the same time, homeowners tend to have lower heating costs per square meter. The real heating cost per square meter averages 28.73 EUR for tenants compared to 22.85 EUR for owners. Household equivalent income also differs substantially between the two groups. On average, homeowners have higher incomes (2,722 EUR) than tenants (1,984 EUR), with a larger spread in income, as indicated by the higher standard deviation among owners. Relative real heating costs, which reflect heating expenditures as a proportion of household income, appear slightly higher for tenants (11.10%) than for owners (10.29%). It is important to note that both the 2024 heating costs and income values are not directly observed but are estimated using projected growth rates from 2017. Finally, we also provide measures for the share of households that are income poor, wealth poor, or both. In both cases, a household is considered as poor if their income or wealth is below the

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[3] This includes financial assets, assets from private insurance policies, balance on savings account with a building and loan association, tangible assets, business assets, and value of vehicles.

[4] Descriptive statistics for the full sample are provided in Appendix A.1. The estimates align with those based on our working sample, such that our sample restrictions do not seem to incur substantial sample selection.

[5] This is measure is often applied as "risk-free" investment rate (European Central Bank, 2023).

poverty line, i.e., below 60 % of the median.[6] The estimates show that there are crucially more tenants than homeowners below the income and wealth poverty line. These descriptive patterns illustrate systematic economic differences between homeowners and tenants, which are explored further in the empirical analysis.

Variable	Mean	SD	Median
Working sample			
Relative real heating costs (%)	10.70	7.58	8.82
Dwelling size (m^2)	105.5	47.12	98.00
Real heating cost per m^2 (EUR)	25.85	13.58	23.53
Moderate heating cost per m^2 (EUR)	11.85	6.22	10.78
Household equiv. income (EUR)	2,346	1,176	2,082
Non-housing wealth (EUR)	109,559	228,670	34,002
Share income poor (%)	17.2	37.8	0
Share wealth poor (%)	36.8	48.2	0
Share income and wealth poor (%)	13.5	34.2	0
Tenants			
Relative real heating costs (%)	11.10	7.67	9.19
Dwelling size (m^2)	79.89	30.66	74.00
Real heating cost per m^2 (EUR)	28.73	13.64	26.15
Moderate heating cost per m^2 (EUR)	13.17	6.25	11.98
Household equiv. income (EUR)	1,984	1,002	1,767
Non-housing wealth (EUR)	51,591	138,762	12,557
Share income poor (%)	26.6	44.2	0
Share wealth poor (%)	56.1	49.6	1
Share income and wealth poor (%)	23.5	42.4	0
Home-owners			
Relative real heating costs (%)	10.29	7.46	8.49
Dwelling size (m^2)	132.1	46.48	125.00
Real heating cost per m^2 (EUR)	22.85	12.84	20.00
Moderate heating cost per m^2 (EUR)	10.47	5.89	9.17
Household equiv. income (EUR)	2,722	1,224	2,449
Non-housing wealth (EUR)	169,728	281,920	71,379
Share income poor (%)	7.48	26.3	0
Share wealth poor (%)	16.8	37.4	0
Share income and wealth poor (%)	3.13	17.4	0

SD is short for standard deviation.

Table 1: Summary statistics by ownership status.

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[6] While this is a commonly used measure for income poverty, wealth poverty definition can differ CITE (https://link.springer.com/article/10.1007/s11205-016-1529-5). For simplicity reasons, we use the main measure for wealth as for income.

2.2 Retrofit Scenarios

The 2024 EPBD requires prioritizing thermal retrofits of the 43% worst-performing residential buildings (European Commission, 2024). We adopt this definition in our analysis and refer to these buildings as "very energy inefficient." To investigate how a targeted approach in thermal retrofits of existing buildings would change the distribution of relative heating costs, we adopt two retrofit scenarios. In the "30% Retrofit Scenario," denoted as RF 30%, randomly chosen 70% of these very energy inefficient buildings are retrofitted, which corresponds to 30% of all buildings. In the "43% Retrofit Scenario," denoted as RF 43%, all 43% of very energy inefficient buildings are retrofitted. In terms of retrofit depth, analogous to the long-term scenarios of the German ministry for economic affairs, we assume that two-thirds of buildings undergo a comprehensive retrofit while one-third is partially retrofitted (Bundesministerium für Wirtschaft und Klimaschutz, 2022). Specifically, we assume that after a comprehensive retrofit, the heat energy consumption of a single-family home is 55 kilowatt hours per square meter (kWh/m^2) and 40 kWh/m^2 for a multi-family home. In the case of partial retrofits, we assume that the energy consumption of both single- and multi-family homes is reduced to 100 kWh/m^2. This means that, in both retrofit scenarios, the depth of retrofits across the retrofitted buildings is not the same as in both scenarios two thirds of the respective retrofitted buildings undergo a comprehensive and one third is only partially retrofitted.

2.3 Carbon Pricing

To investigate the effect of carbon pricing and its nexus with a Worst-First policy approach, we model their distributional effect. In 2021, Germany introduced a national CO_2 price for the heat and transport sectors. This CO_2 price has since been rising in yearly increments reaching a price of 45 Euros per ton of CO_2 (EUR/t) in 2024 (Bundesregierung, 2025). Crucially, tenants do not have to pay the entire share of the incurred costs. Rather, the share they have to pay depends on the energy efficiency of their home with the landlord having to pay the remainder. The less energy efficient the building, the higher the CO_2 cost share that the landlord must pay. Table 2 displays the proportion of the costs paid by the tenant and landlord given the CO_2 emissions from heating per square meter. We include this cost-sharing element in our analysis of the distributional effects of heat energy and CO_2 costs. Specifically, we combine the retrofit scenarios with the CO_2 splitting between tenants and landlords to scrutinize how it affects tenants' relative heating costs.

To model the CO_2 splitting in our data, we make use of the distribution of energy consumption by energy source. First, we calculate energy consumption per m^2 by dividing annual heat energy expenditures per m^2 by the price per m^2 for each energy source which are given in Column (1) of Table 3. In Germany, energy contracts typically comprise a fixed and variable cost component. To mirror this structure, we assume 0.4 EUR per m^2 fixed costs per month for each household. Thus, the mean energy consumption we calculate amounts to 131.4 kWh per m^2, which is in line with the 129.9 kWh per m^2 in 2017 estimated by Destatis (2023). As the last step, we use average CO_2 emissions per square meter for each energy source to impute the households carbon emissions from heating. The CO_2 emissions per square meter are depicted in Column (2) of Table 3.

CO_2 emissions range (kg/m^2)	Share paid by tenant (%)
$12 \leq CO_2 < 17$	90
$17 \leq CO_2 < 22$	80
$22 \leq CO_2 < 27$	70
$27 \leq CO_2 < 32$	60
$32 \leq CO_2 < 37$	50
$37 \leq CO_2 < 42$	40
$42 \leq CO_2 < 47$	30
$47 \leq CO_2 < 52$	20
$CO_2 \geq 52$	5

Source: Bundesministerium für Wirtschaft und Klimaschutz (2023)

Table 2: Proportion of costs paid by tenant based on CO_2 emissions.

Source (as in the SOEP)	Price per m^2	CO_2 emissions per m^2 (kg)
	(1)	(2)
Gas	0.668	0.201
Oil	0.668	0.288
District	1.132	0.280
Liquid gas	0.720	0.239
Electricity	1.114	4.350
Coal	0.617	0.335
Wood	0.610	0.027
Biomass	0.365	0.036
Heat pump	0.649	0.000
Solar	0.365	0.000

Sources include ista SE, C.A.R.M.E.N. e.V. (n.d.) and Rekord (2024) Bundesministerium für Wirtschaft und Klimaschutz (2019).

Table 3: Types of heating, costs, and CO_2 emissions.

2.4 Overview of Specifications

We provide three specifications, where we vary the increase in energy costs since 2017 (real, i.e. 100% increase, and moderate for a 10% increase) and the level of carbon pricing of 45 and 200 EUR/t CO_2. These are depicted in Table 4. Using the retrofit scenarios described above, we analyze Specifications 1 and 3 to investigate the interplay between carbon pricing and retrofit policies from a distributional perspective.

In the main analysis, we assume no behavioral adjustments to price increases by setting the price elasticity of demand to zero. This is a strong assumption that heat energy demand is typically inelastic in Germany but not perfectly so, especially in the short run. For instance, Behr et al. (2025) estimate a short-term price elasticity for heat energy of -0.07 during the 2022 crisis, while controlling for non-monetary conservation motives. Without such controls, Ruhnau et al. (2023) report a larger short-term elasticity of -0.3. In the long run, demand is more responsive, with elasticity estimates ranging from -0.15 (Bissiri et al., 2019) to -0.9, depending on household characteristics (Schulte & Heindl, 2017). Schmitz and Madlener (2020), for instance, find elasticities between -0.31 and -0.43. However, the extent to which households can and do respond to large, abrupt price increases, such as those in our specifications, remains empirically uncertain. This is particularly true for the carbon price as the carbon price elasticity might differ from normal price elasticities. While some studies find stronger behavioral effects for carbon taxes than for market-driven price shifts (Li et al., n.d.; Rivers & Schaufele, 2015), others find no significant impact on residential energy consumption (Ott & Weber, 2022). To address concerns about this assumption, we conduct a sensitivity analysis using a linear elasticity gradient: from -0.2 for lower-income households to -0.3 for higher-income households (see Appendix A.3).

Specifications		Energy costs	CO_2 price (EUR/t)
1	Status quo	Actual	45
2	No crisis	Moderate	45
3	High carbon price, moderate energy prices	Moderate	200

Table 4: Specification for energy costs and CO_2 pricing

2.5 Quantifying Energy Poverty

To quantify the prevalence of energy poverty in the status quo, in the other specifications, as well as in the retrofit scenarios, we rely on three different energy poverty indicators. How to statistically identify energy poverty is long debated in the literature with several definitions of energy poverty being commonly employed (Castaño-Rosa et al., 2019; Drescher & Janzen, 2021; Heindl, 2018; Herrero, 2017; Hills, 2012; Thomsen et al., 2016). Validating our results by these three different indicators allows for a more robust analysis.

Our first energy poverty indicator, referred to as Indicator I, considers income in addition to heating expenditures. We follow the recommended measurement of fuel poverty Hills (2012) with the exception of focusing on heat energy only. Specifically, we consider a household to be energy poor if their heat energy expenditure is above the median while their residual income after heating expenditures are deducted is smaller than 60% of the median income.

The second energy poverty indicator, referred to as Indicator II, is based on the UK LILEE indicator, which comprises two components. A household is classified as energy poor if they live in a building with a low fuel poverty energy efficiency rating (FPEER) and if their residual income is below the official poverty line (UK Government, 2024). Germany does not use the FPEER metric, which is why we instead define the 33% worst-performing buildings as the first component of this indicator. As a second step, we consider the residual income analogous to the second definition. Therefore, this indicator defines energy poverty based on both living conditions and disposable income.

As a third and last indicator, referred to as Indicator III, we define a new measure that includes wealth in addition to income. We define households to be wealth poor if their wealth lies below 60% of the median wealth. Note that this does not include wealth from owning property. We add this wealth component to Indicator II. In other words, this indicator has an even stronger focus on the very vulnerable segments of the population.

3 Escalated Vulnerability in Times of Energy Crises

We find that low-income households spend substantially larger shares of their income on heating costs in comparison to high-income households. In addition, the within decile variation is higher for low-income households than for high-income ones. This is exacerbated further by considerable price increases that German households faced during the recent energy price crisis. This is demonstrated by Figures 1a and 1b showing heating expenditure relative to income by income deciles for 2024. The former figure depicts the status quo with real high energy costs and the latter does so for a counterfactual specification with moderate energy costs.

Even if energy prices had only risen moderately, low-income households would spend a large proportion of their income on heating. The median relative share of heat energy costs under a moderate price increase specification is between 7.2 and 9.4% for the lowest two income deciles in contrast to being between 2.6 and 3.3% for the highest two income deciles. Most importantly, these shares vary significantly for the lowest two income deciles as these households spend more than 10% of their income on heating costs.[7]

Introducing the status quo of actual high energy prices (see Figure 1b) to the counterfactual situation, two things become apparent. First, while households in all income deciles are affected by higher prices, the change in median relative share of income spent on heating is the highest for the low-income households. Precisely, this share increases to 12.9 to 16.7% for households in the lowest two income deciles. This increase is not as high for the top two income deciles, which are between 4.7 and 5.9%. Second, the variation in relative heating expenditures increases dramatically for low-income households. Given increased prices, 25% of households in the lowest two income deciles spend now more than 18% of their income on heating costs.

Although they live in significantly smaller dwellings than higher-income households in the median, low-income households are disproportionately burdened (see Figure 2a). For instance, median dwelling size for the lowest two income deciles is between 60 and 69 m^2, while this range is between 110 and 126 m^2 for the highest two income deciles. At the same time low-income households do not only spend more on heating relative to their income but also in absolute terms per square meter (see Figure 2b). The lowest two income deciles spent between 25.7 and 27.0 EUR/m^2 on heating in comparison to high-income households, which only spend between 20.6 and 21.5 EUR/m^2. This implies that low-income households are more likely to live in less energy efficient buildings than high-income households. Consequently, they are affected more severely during the crisis. This highlights the importance of protecting low-income households from high energy prices.

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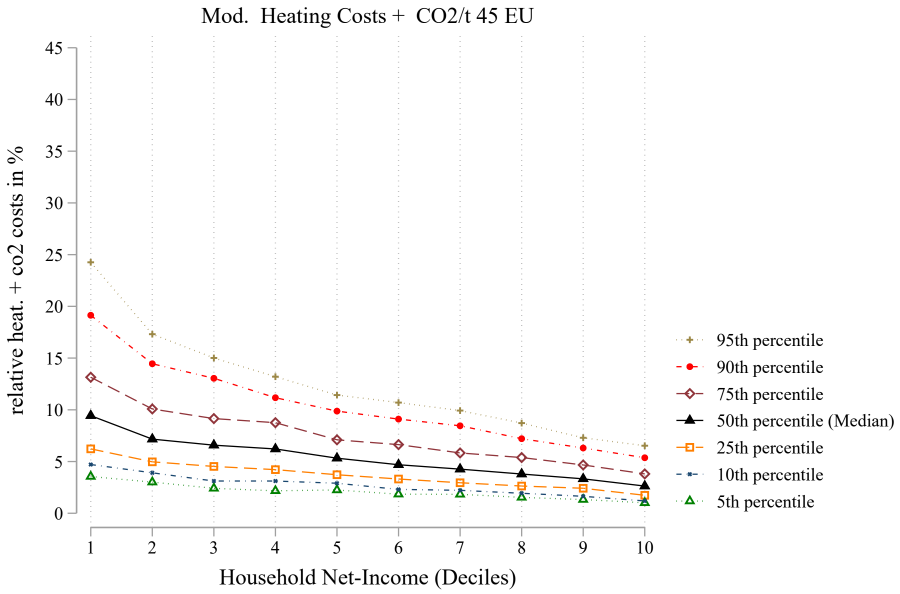
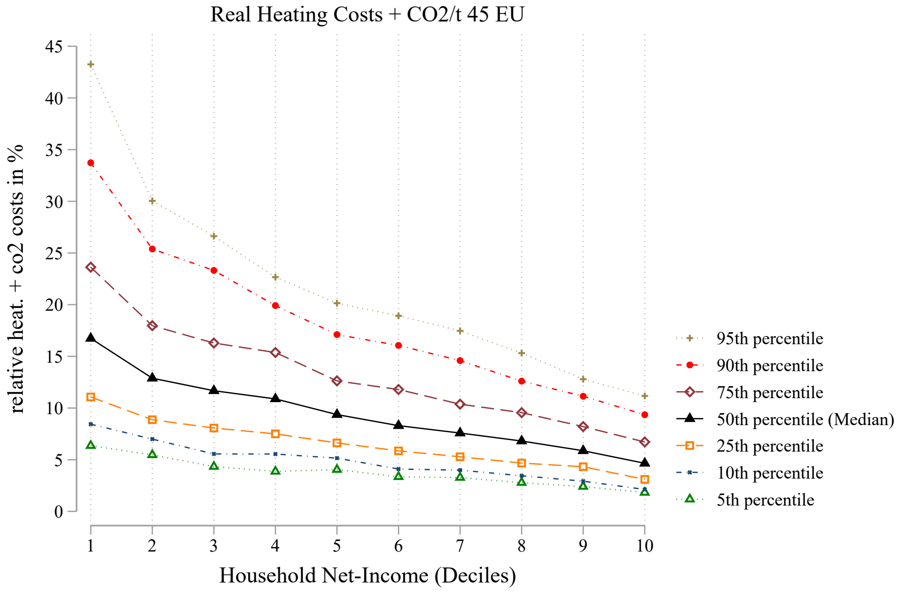
[7] Figure 1a shows this in the purple 75th percentile line, which depicts a share of 10% (13%) for the second (first) income decile.



(a) No-crisis specification in 2024. Moderate increase in energy prices. Heating costs relative to income (%) by household net-income deciles.

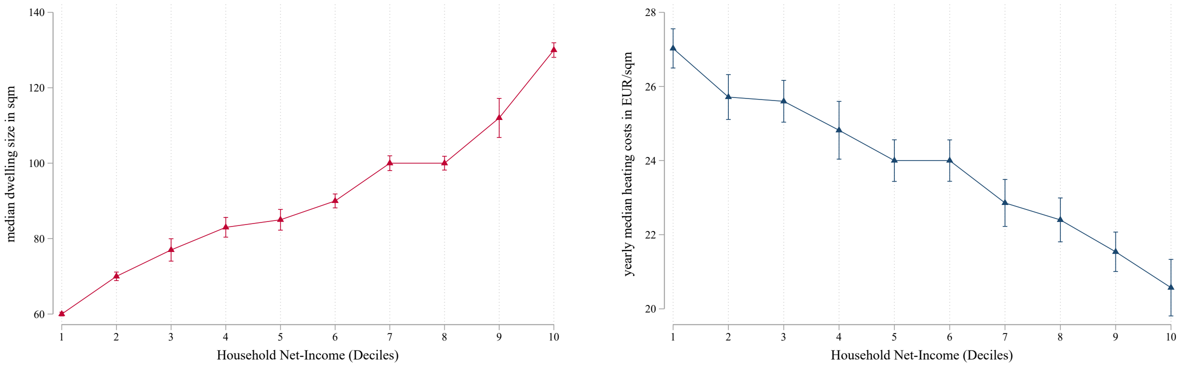


(b) Status quo specification in 2024: Real energy price increase. Heating costs relative to income (%) by household net-income deciles.

Figure 1: Heating costs relative to net income by net-income decile (in %). Includes the full working sample.

3.1 Homeowners vs. Tenants

A major difference in heating expenditure arises when we compare tenants with homeowners. Tenants, in the median, pay significantly higher heating costs per square meter than homeowners across all income brackets (see Figure 3). This gap is larger for higher income deciles. A



(a) Median dwelling size in square meters by income decile.

(b) Median heating costs in Euros per square meters by income decile.

Figure 2: Median dwelling size in and heating costs per meter square. Includes the full working sample.

likely reason for this observation is that tenants typically live in less energy efficient buildings than homeowners. This might be surprising as tenants often live in multi-family homes, which are more energy efficient than single family homes. However, since we are comparing tenants and homeowners within the same income decile, effects of different building types should be negligible. Even tenants in the top deciles pay substantially higher heating costs than their homeowner counterparts.

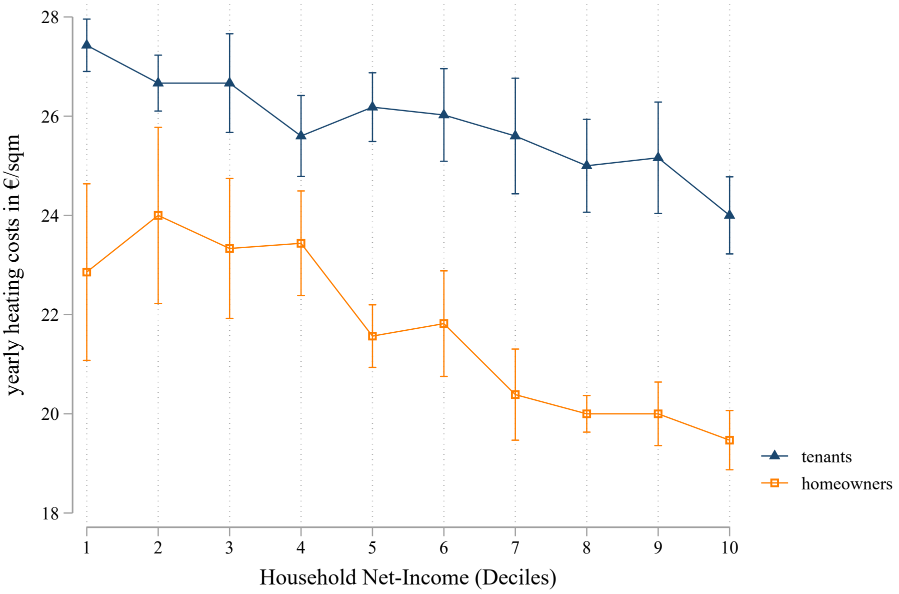


Figure 3: Heat energy costs for homeowners and tenants by net-income decile (Euros per square meter).

The observation that rental housing appears to be much less energy efficient than those homes owned by homeowners points to a widely discussed topic: the tenant-landlord dilemma.[8] This dilemma arises due to miss-aligned incentives for tenants and homeowners and is typically attributed to a number of factors (Ahlrichs & Rockstuhl, 2022; Gornig & Klarhöfer, 2023). On the one hand, tenants suffer from high energy costs due to energy inefficient buildings, but they are not the ones to decide whether the building is retrofitted. Landlords, on the other hand, do not profit from savings in energy costs but rather from an increased value of their property, which does not translate into a cash flow.

To combat the energy inefficiency of rental buildings, Germany has two policies in place. Since 2019, 8% of the thermal modernization investments and up to a maximum of 3 EUR/m^2 per year can be passed on from the landlord to the tenant Bürgerliches Gesetzbuch (BGB) (n.d.). Thus, landlords can financially benefit directly from retrofits through the modernization levy. The second policy introduced with the German national carbon pricing refers to the tenant-landlord splitting of carbon costs (see above). This is another incentive for landlords to improve the energy efficiency of their buildings. However, it is questionable whether the amount is sufficient to incentivize large investments. The question about effectiveness of investment incentives is an important topic, but beyond the scope of this study as we focus on the distributional implications of hypothetical retrofit scenarios.

3.2 Energy poverty

An unequal burden on low-income households raises the question about energy poverty. We compare the three specifications presented above (see Table 4) to understand the implications of energy price increases and carbon prices on the share of households affected by energy poverty. Table 5 presents the shares of energy poverty according to the three indicators for the entire population, as well as to tenants and homeowners separately. Regardless of which energy poverty indicator we use, tenants always exhibit a larger share of energy poor households than homeowners. Unsurprisingly, a situation with moderate heating costs and no carbon pricing leads to the lowest level of energy poverty. For the full population, the share of energy-poor households ranges between 5.3% and 8.5%. Tenants are affected more strongly, with a range of 7.9% to 12.8%, while homeowners exhibit shares between 2.7% and 6.8%.

In Specification 1 the share of households affected by energy poverty increases noticeably. In the full population, the share of energy-poor households rises to 10.2% under Indicator I. Indicators II and III, which are closest in line with the numbers from Eurostat, show 9.7% and 6.5%, respectively. Tenants experience a significantly higher energy burden, with 11.5% under Indicator I, 14.4% under Indicator II, and 9.6% under Indicator III. Meanwhile, homeowners are affected to a lesser extent, at 8.9%, 5.1%, and 3.4%, respectively. For Specification 3 these shares vary more across indicators. Notably, the share of energy-poor tenants is particularly high in this situation. For example, under Indicator II, 18.6% of tenants are energy poor, whereas only 6.5% of homeowners fall into this category.

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[8] Here we use homeowners and landlords interchangeably.

The results on the shares of households affected by energy poverty provide two insights. Comparing Specifications 1 and 2 shows that energy price increases significantly increase the share of households affected by energy poverty. Comparing Specifications 1 and 3, on the other hand, shows that even in a situation of stable energy prices, the increase in carbon prices alone is sufficient to push a significant share of households into energy poverty. These results are much more pronounced for tenants than for homeowners, highlighting their additional vulnerability.

	Full Population	Tenants	Homeowners
Specification 1 - Real heating costs and a CO_2 price of 45 EUR/t			
Indicator I	10.2	11.5	8.9
	(0.33)	(0.40)	(0.28)
Indicator II	9.7	14.4	5.1
	(0.40)	(0.47)	(0.31)
Indicator III	6.5	9.6	3.4
	(0.28)	(0.31)	(0.25)
Specification 2 - Moderate heating costs and a CO_2 price of 45 EUR/t.			
Indicator I	8.0	9.3	6.8
	(0.28)	(0.33)	(0.33)
Indicator II	8.5	12.8	4.3
	(0.32)	(0.40)	(0.47)
Indicator III	5.3	7.9	2.7
	(0.25)	(0.28)	(0.31)
Specification 3 - Moderate heating costs and a CO_2 price of 200 EUR/t.			
Indicator I	10.6	12.8	8.4
	(0.33)	(0.40)	(0.47)
Indicator II	12.5	18.6	6.5
	(0.47)	(0.47)	(0.28)
Indicator III	7.1	10.8	3.5
	(0.31)	(0.25)	(0.28)

Bootstrapped standard errors in parentheses. Focus on the full working sample.

Table 5: Energy poverty under different specifications.

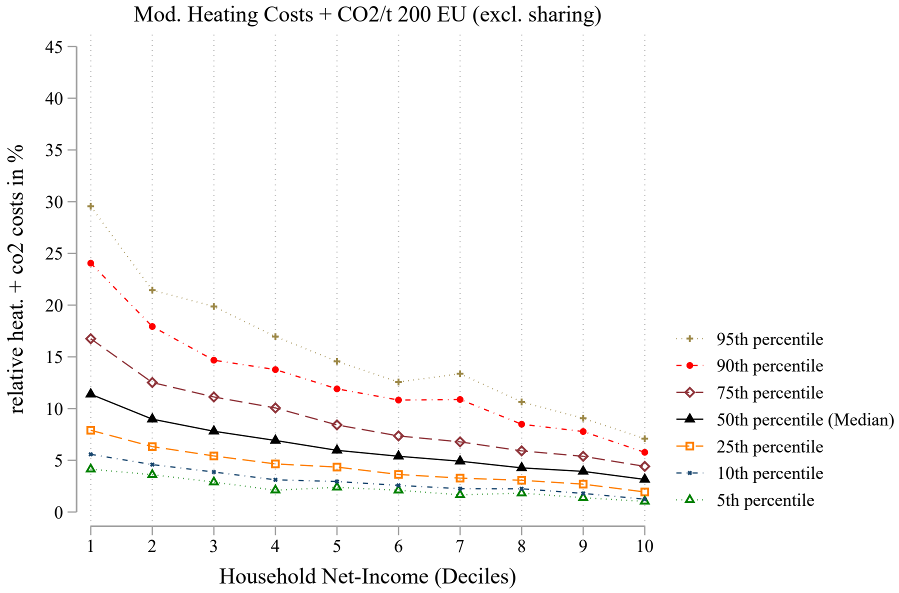
4 Policy Options to Reduce Vulnerability

In response to energy crises, most governments intervened to avoid unequal burdens on the population in one of the following three ways. The first intervention option involves lump-sum payments and is a comparatively fast-acting measure that attempts to alleviate immediate burdens. The German government followed this strategy in the winter 2022/23 following the price spikes due to the Russian invasion of Ukraine. All German residents received one-off payments to cover their December 2022 heat energy bills. However, as there are large variations in households' heat energy expenditures, lump sum payments cannot alleviate the burden on the lowest income deciles residing mostly in the least energy efficient houses. This is in line with Kröger et al. (2023), who show that lump sum payments are costly and energy inefficient. So far, our analysis demonstrates that low-income households – particularly tenants – are disproportionately impacted by high heating costs and therefore vulnerable. In this section, we investigate the distributional implications of two additional government interventions, that are carbon pricing and thermal retrofits while focusing on tenants only.

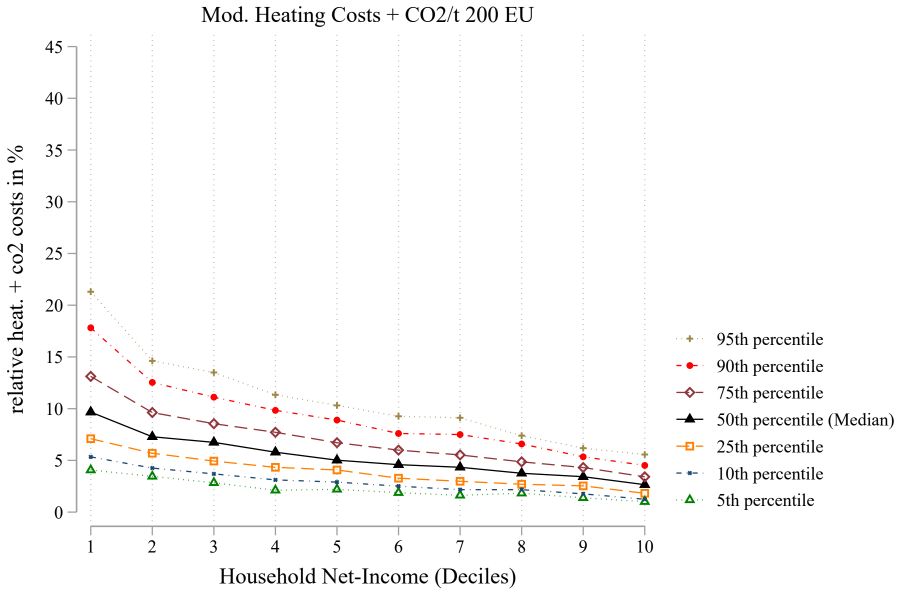
4.1 Carbon Pricing with Tenant-Landlord Cost Splitting

The implementation of carbon pricing with tenant-landlord cost splitting was initiated in Germany in 2021. This policy has two main objectives. First, to reduce the externality of high CO_2 emissions from fossil fuel heating, and, second, to shift part of the increased energy costs to the landlord, thereby incentivizing thermal retrofits. Consequently, if tenants are living in energy inefficient homes, a *higher* share of the cost of the emissions tax is placed on the owners. The tenant-landlord split is unique to Germany.

Figure 4 presents tenants' relative heating cost under moderate price increases and a carbon price of 200 EUR/t for two cases: without and with tenant-landlord cost splitting. The comparison of Figures 4a and 4b depicts a clear picture of how cost splitting substantially reduces the relative heating costs across all income deciles. Especially the variation of relative heating costs reduces at the lower end of the income distribution. Even without a hypothetical thermal retrofit scenario assumed, tenant-landlord cost splitting protects significantly lower income households.



(a) Moderate increase including a carbon price of 200 Euro per ton of CO_2 increase, excluding landlord-tenant cost splitting.



(b) Moderate increase including a carbon price of 200 Euro per ton of CO_2 increase, including landlord-tenant cost splitting.

Figure 4: Relative heating and CO_2 cost expenditure for heating for tenants by net-income decile (in %).

4.2 Retrofit Scenarios: Worst-First

A Worst-First approach aims at alleviating unequal burdens of residential heat energy costs by retrofitting the most energy inefficient buildings first. Retrofitting is a sustainable, long-term approach, that targets the roots of elevated energy consumption due to wasted energy. Prioritizing the retrofitting of inefficient buildings has the potential to ensure vulnerable households against energy price shocks. The EU's renewal of the EPBD strengthens the Worst-First policy approach. Thus, in this section, we study the distributional effects of such a prioritized retrofit strategy, varying the degree of energy and carbon prices by focusing on Specifications 1 and 3.

Specification 1 considers real heat energy prices with a carbon price of 45 EUR/t. We compare distributional outcomes under three scenarios: no retrofit, a 30% retrofit, and a 43% retrofit. Figure 5 illustrates the distribution of relative heating expenditures across income deciles for each scenario – no retrofit (left panel), 30% retrofit (middle panel), and 43% retrofit (right panel).

The results show that prioritizing retrofits for highly energy-inefficient buildings significantly reduces relative heating costs across all income groups, with households facing high heating expenses benefiting the most. For instance, in the lowest two income deciles, the median share of heating costs (black line) drops from 11.4%–15.1% to 7.0%–8.6% under the 30% retrofit and to 2.3%–2.9% under the 43% retrofit. The gap between the lowest and highest income deciles also narrows, as the median share in the top two income deciles declines more modestly from 4.2%–5.4% to 2.5%–3.1% (30% retrofit) and to 1.6%–1.7% (43% retrofit). Additionally, as shown by the purple 75th percentile line, 25% of households in the lowest two deciles currently spend more than 15.5% to 21.4% of their income on heating without retrofits. This share decreases to 11.1%–14.0% with a 30% retrofit and to 8.4%–10.0% with a 43% retrofit. Overall, average heating costs decline by 38.5% in the 30% retrofit scenario and 57.9% in the 43% retrofit scenario, demonstrating the considerable impact potential of retrofitting in line with the new EPBD on heating expenditures.

Turning to Specification 3, we consider how a Worst-First approach protects low-income households when energy prices would have been stable but CO_2 prices would have increased to 200 EUR/t instead. This is depicted in Figure 6. As above, the panel on the left shows Specification 3 without retrofit, while the middle and right panels plot the 30% and 43% retrofit scenarios, respectively. Again, both retrofit scenarios reduce the relative heating and CO_2 costs across all income deciles. However, the reduction is slightly smaller compared to Specification 1 because the tenant-landlord sharing already reduces the burden for tenants in the non-retrofit specification, as discussed in the previous section. Here, average heating costs decline by 31.7% in the 30% retrofit scenario and 49.0% in the 43% retrofit scenario. Specification 3 shows that the retrofit strategies do not just reduce differences in relative heating costs, but also further insures tenants against increases in carbon prices.

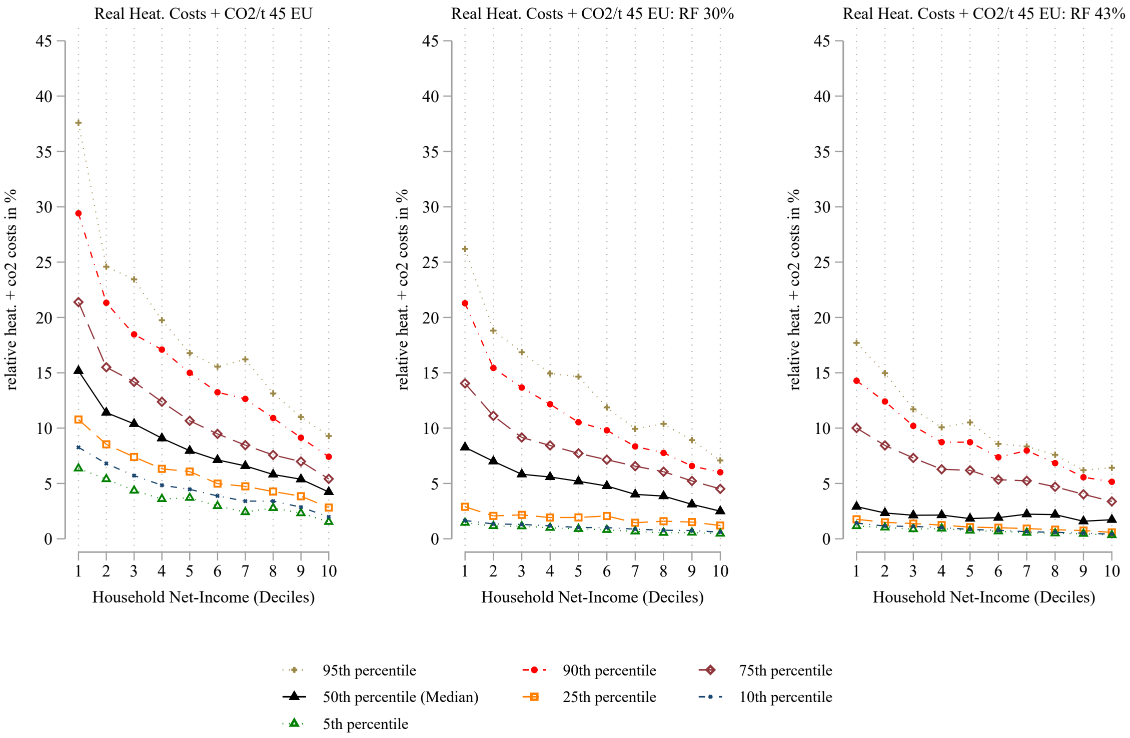


Figure 5: Relative heating and CO_2 costs for tenants in the status quo specification and the different retrofit scenarios (in %). Left panel: status quo. Middle panel: 30% Retrofit Scenario. Right panel: 43% Retrofit Scenario.

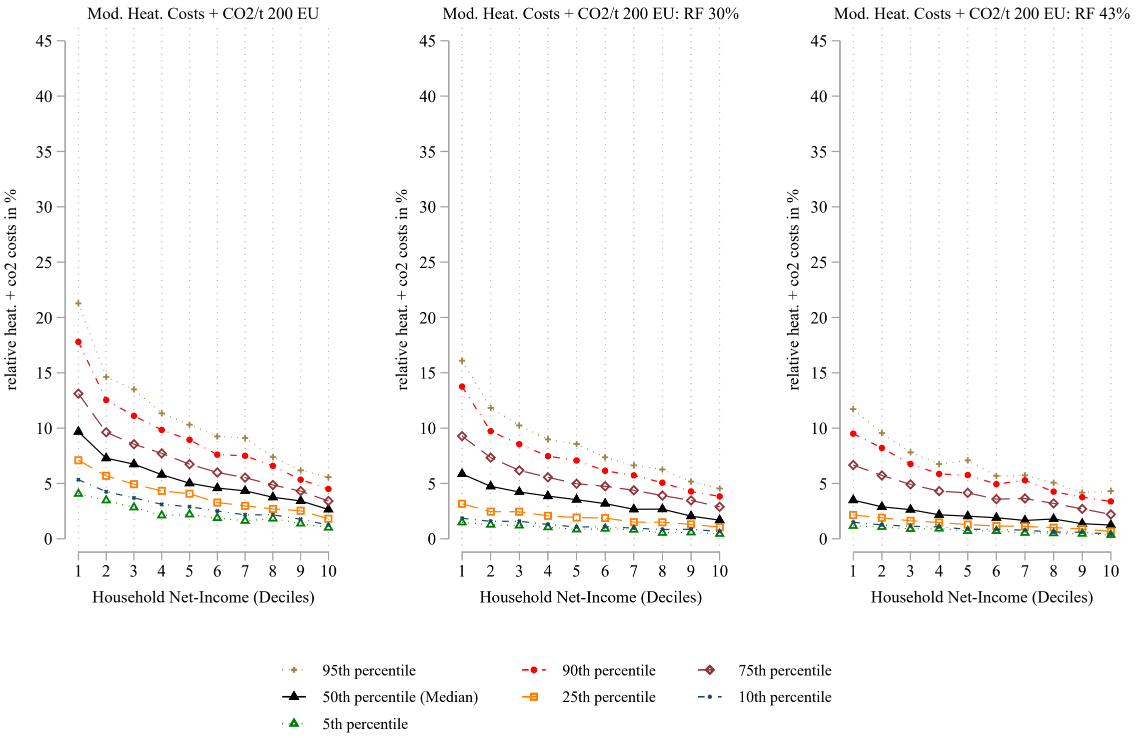


Figure 6: Relative heating and CO_2 costs for tenants in a specification with moderate energy costs and a high CO_2 price (in %). Left panel: no crisis specification 4b. Middle panel: 30% Retrofit Scenario. Right panel: 43% Retrofit Scenario.

4.3 Energy Poverty with a Worst-First Approach

We learned that a Worst-First approach has distributional benefits, but how does it affect the most vulnerable tenants? We study this question by examining the energy poverty rates in our different specifications with and without retrofit strategies.

The estimates of the energy poverty rates are provided in Table 6.[9] What stands out is that retrofit scenarios reduce energy poverty rates for tenants drastically under both retrofit scenarios regardless of the indicator used. During the energy crisis, a 30% retrofit scenario would have lowered energy poverty rates from a range of 9.6% to 14.4% down to 3.7% to 4.6%. A 43 % retrofit scenario would have reduced this range even further to 0.4% to 1.4%. Even in the case of moderate heating costs, however, with elevated carbon prices of 200 EUR/t, energy poverty rates decrease from a range of 10.8% to 18.6% down to 4.8% to 7.1% and to 2.0% to 2.5% under the 30% and 43% retrofit scenario, respectively.

These findings underscore that retrofitting programs are a highly effective tool for reducing energy poverty among tenants. Thus, implementing large-scale retrofits can serve as a socially equitable climate policy, balancing environmental goals with economic protections for low-income households.

	No Retrofit	Retrofit 30%	Retrofit 43%
Real heating costs and a CO_2 price of 45 EUR/t			
Indicator I	11.5	4.6	1.4
	(0.37)	(0.21)	(0.12)
Indicator II	14.4	4.4	0.4
	(0.42)	(0.24)	(0.06)
Indicator III	9.6	3.7	1.0
	(0.30)	(0.19)	(0.08)
Moderate heating costs and a CO_2 price of 200 EUR/t			
Indicator I	12.8	5.8	2.5
	(0.34)	(0.21)	(0.13)
Indicator II	18.6	7.1	2.5
	(0.42)	(0.29)	(0.17)
Indicator III	10.8	4.8	2.0
	(0.32)	(0.20)	(0.13)

Bootstrapped standard errors in parentheses. Focus on tenants only.

Table 6: Energy poverty scenarios and retrofit effects.

5 Conclusion

The European Energy Price Crisis heightened awareness of heating cost risks across Europe, particularly in countries highly dependent on Russian gas imports, such as Germany. Its effects underscored the urgent need to reduce reliance on energy imports while simultaneously protecting households from energy price volatility and advancing emission reduction goals.

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[9] Note that this table focuses on tenants. Hence, the no-retrofit energy poverty rates correspond to the third column in Table 5.

This study details the burden caused by the energy price increases on the broader population living in Germany. We find that low-income households spend a significantly higher share on their heating costs than high-income households. Specifically, the median relative share of heating costs is between 12.9% and 16.7% for households in the lowest two income deciles, while this ranges from 4.7% to 5.9% for the top two income deciles. As low-income households mostly live in less energy efficient buildings, they are relatively more exposed to energy price shocks. An energy price crisis exacerbates the burden of energy costs increasing the share of the population facing energy poverty from a range of 5.3% to 8.5% up to a range of 6.5% to 10.2%.

Investigating heat energy costs for tenants and homeowners separately, shows us that tenants are especially at risk, with 9.6% to 14.4% of them facing energy poverty at times of elevated prices. Specifically concerning low-income tenants, the median relative share of heat energy costs masks the vast disparity on income spent on heating. While median relative heat energy cost is 11.4% to 15.1%, 25% of the lowest two income deciles pay more than 15.5% to 21.4%. Although tenants typically inhabit smaller apartments, this is not suffice to counterbalance the increased costs from the energy inefficient buildings they reside in.

We examine how government interventions, such as tenant-landlord cost-sharing for carbon pricing and thermal retrofits, impact the distribution of energy costs amid rising prices for tenants. We find that carbon splitting reduces the burden of potential carbon price increases for all tenants but especially low-income ones. However, it does not protect them from energy price increases. Therefore, we investigate how thermal retrofits would alter the unequal energy cost burden using two hypothetical retrofit strategies. Our findings show that if 30% and 43% of the worst performing buildings were retrofitted, relative heating costs would decline by 38.5% and 57.9%, respectively. Energy poverty rates would reduce from a range of 9.6% to 14.4% under a no-retrofit scenario to a range of 3.7% to 4.6% and 0.4% to 1.4% under a 30% and 40% retrofit scenario, respectively. Not only does a Worst-First approach reduce the unequal burden of heat energy costs under energy price hikes but also for the case when prices increase moderately no matter how high carbon prices are. In such a case, with 30% and 43% retrofitting, energy poverty rates drop from a no-retrofit range of 10.8% to 18.6% down to a range of 4.8% to 7.1% and 2.0% to 2.5%, respectively.

We conclude that our analysis provides evidence for concern about the challenges of energy and carbon price increases. We identify low-income tenants as the most vulnerable group. Our findings show that allowing prices to escalate, whether due to carbon prices or energy crises, would put a substantial shares of the population at risk of energy poverty. While internationally less common measures, like carbon-cost splitting, cushion the effect of increased carbon prices, improving building energy inefficiencies goes even further and protects against energy crises. More importantly, targeted thermal retrofitting addresses the root cause of the unequal vulnerabilities to energy price increases.

We acknowledge that while a Worst-First strategy might be a solution to the problem, it raises questions about implementation. Currently, a combination of standards, incentives, and subsidies provide financial support for the thermal retrofit of buildings (Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2025). However, on the one hand, despite these support programs, the retrofit rate in Germany has stagnanted since 2013 Behr et al. (2023). On the other hand, evidence from the US shows that high-income households profit disproportionately more from retrofit subsidies (Allcott & Greenstone, 2017; Allcott et al., 2015; Borenstein & Davis, 2016). Additionally, building standards also affect low-income households more negatively than high-income households (Bruegge et al., 2019). Hence, the avenues for the most effective implementation pathways of a Worst-First strategy remain unexplored and comprise avenues for future research.

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A Appendix

A.1 Descriptive statistics for the full sample

Variable	Mean	SD	Median
Working sample			
Relative real heating costs (%)	10.72	7.70	8.81
Dwelling size (m^2)	102.9	47.25	94.00
Real heating cost per m^2 (EUR)	26.08	13.83	23.82
Moderate heating cost per m^2 (EUR)	11.95	6.34	10.92
Household equiv. income (EUR)	2,301	1,172	2,061
Non-housing wealth (EUR)	102,874	218,946	29,817
Share income poor (%)	17.1	37.7	0
Share wealth poor (%)	39.6	48.9	0
Share income and wealth poor (%)	13.6	34.3	0
Tenants			
Relative real heating costs (%)	11.05	7.81	9.06
Dwelling size (m^2)	79.28	31.86	74.00
Real heating cost per m^2 (EUR)	28.81	14.03	26.09
Moderate heating cost per m^2 (EUR)	13.21	6.43	11.96
Household equiv. income (EUR)	1,971	1,013	1,767
Non-housing wealth (EUR)	49,601	135,819	11,508
Share income poor (%)	25.1	43.4	0
Share wealth poor (%)	57.8	49.4	1
Share income and wealth poor (%)	22.2	41.6	0
Home-owners			
Relative real heating costs (%)	10.32	7.56	8.49
Dwelling size (m^2)	132.1	46.83	125.00
Real heating cost per m^2 (EUR)	22.82	12.85	20.00
Moderate heating cost per m^2 (EUR)	10.46	5.89	9.17
Household equiv. income (EUR)	2,707	1,226	2,415
Non-housing wealth (EUR)	168,440	276,493	70,620
Share income poor (%)	7.27	26.0	0
Share wealth poor (%)	17.3	37.8	0
Share income and wealth poor (%)	3.06	17.2	0

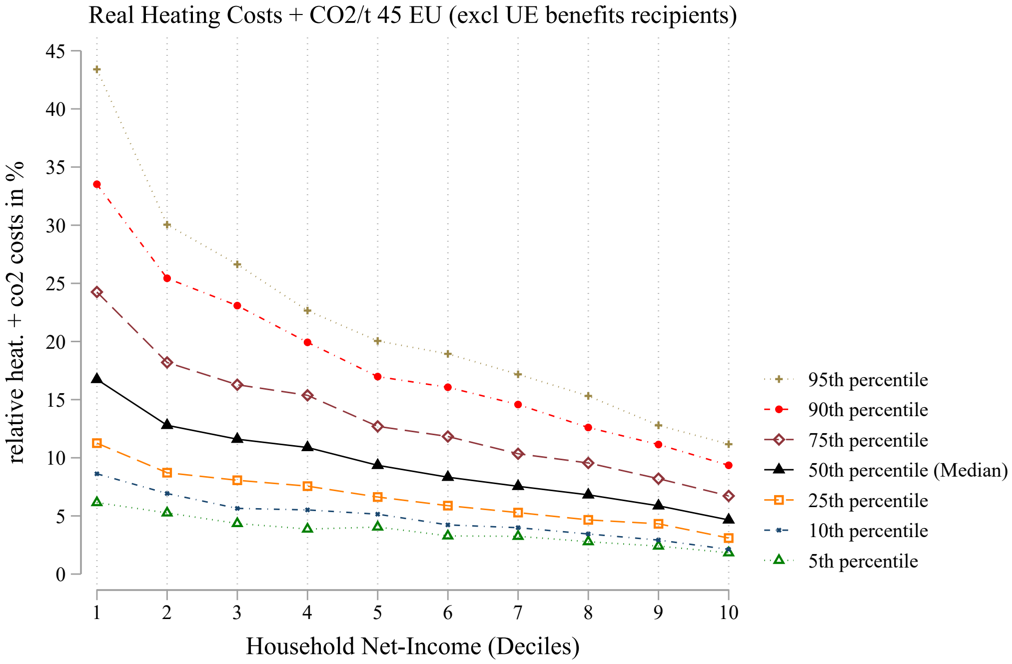
SD is short for standard deviation.

Table A1: Summary statistics by ownership status.

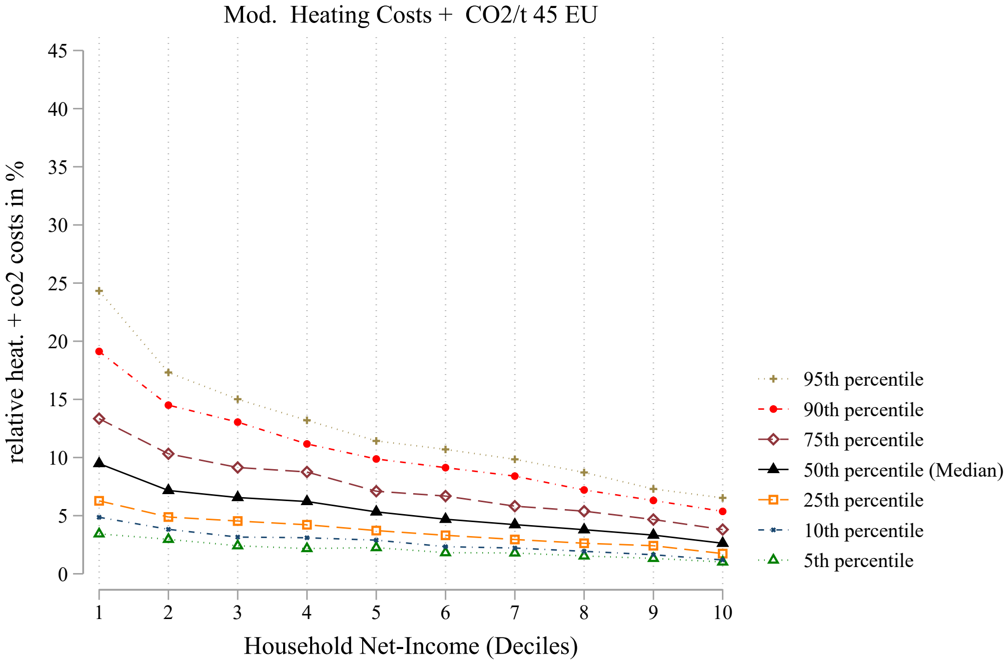
A.2 Excluding unemployment benefits recipients

Table A2: Full tables

Inc Decile	**p5**	**p10**	**p25**	**p50**	**p75**	**p90**	**p95**	**mean**
Real heating costs and a CO_2 price of 45 EUR/t								
1	6.36	8.44	11.07	16.74	23.63	33.73	43.28	19.47
2	5.47	7.00	8.87	12.89	17.97	25.39	30.05	14.60
3	4.34	5.56	8.07	11.68	16.29	23.31	26.63	13.10
4	3.87	5.55	7.50	10.89	15.37	19.90	22.66	11.99
5	4.04	5.16	6.63	9.37	12.63	17.11	20.15	10.45
6	3.35	4.11	5.86	8.30	11.79	16.06	18.93	9.38
7	3.27	3.99	5.29	7.58	10.37	14.59	17.47	8.51
8	2.79	3.45	4.68	6.81	9.55	12.61	15.32	7.54
9	2.41	2.93	4.32	5.87	8.20	11.14	12.79	6.63
10	1.84	2.13	3.10	4.66	6.72	9.36	11.17	5.33
Real heating costs and a CO_2 price of 45 EUR/t (Excl. ALG 2)								
1	6.15	8.62	11.26	16.74	24.26	33.52	43.41	19.47
2	5.26	6.93	8.72	12.79	18.20	25.44	30.05	14.57
3	4.35	5.65	8.07	11.60	16.28	23.08	26.63	13.07
4	3.87	5.52	7.56	10.89	15.37	19.91	22.66	12.00
5	4.04	5.15	6.63	9.35	12.70	16.98	20.04	10.44
6	3.28	4.23	5.89	8.33	11.83	16.06	18.94	9.41
7	3.25	3.99	5.29	7.55	10.35	14.58	17.18	8.48
8	2.79	3.45	4.66	6.81	9.55	12.61	15.32	7.53
9	2.41	2.93	4.32	5.87	8.20	11.14	12.79	6.63
10	1.84	2.13	3.10	4.66	6.72	9.36	11.17	5.33
Mod. heating costs and a CO_2 price of 45 EUR/t								
1	3.56	4.71	6.23	9.44	13.15	19.13	24.26	10.94
2	3.01	3.91	4.97	7.17	10.08	14.45	17.31	8.22
3	2.41	3.12	4.53	6.58	9.15	13.05	15.02	7.39
4	2.17	3.12	4.22	6.22	8.76	11.17	13.20	6.79
5	2.25	2.90	3.73	5.33	7.10	9.87	11.43	5.91
6	1.85	2.31	3.31	4.69	6.64	9.10	10.70	5.31
7	1.83	2.22	2.95	4.27	5.83	8.46	9.90	4.81
8	1.53	1.94	2.63	3.79	5.39	7.21	8.72	4.26
9	1.33	1.64	2.42	3.33	4.67	6.31	7.30	3.75
10	1.02	1.19	1.74	2.63	3.81	5.37	6.53	3.02
Mod. heating costs and a CO_2 price of 45 EUR/t (Excl. ALG 2)								
1	3.43	4.86	6.28	9.48	13.34	19.13	24.33	10.95
2	2.97	3.83	4.89	7.17	10.32	14.50	17.31	8.21
3	2.41	3.16	4.54	6.56	9.14	13.05	15.02	7.38
4	2.17	3.10	4.22	6.22	8.76	11.17	13.20	6.79
5	2.25	2.90	3.72	5.33	7.10	9.87	11.43	5.90
6	1.81	2.33	3.31	4.69	6.69	9.13	10.70	5.32
7	1.79	2.22	2.95	4.23	5.82	8.40	9.85	4.79
8	1.53	1.94	2.63	3.80	5.39	7.21	8.72	4.25
9	1.33	1.64	2.42	3.33	4.67	6.31	7.30	3.75
10	1.02	1.19	1.74	2.63	3.81	5.37	6.53	3.02



(a) Status quo scenario in 2024 excluding unemployment benefits recipients: Real energy price increase. Heating costs relative to income (%) by household net-income deciles.



(b) No crisis scenario in 2024 excluding unemployment benefits recipients: Moderate increase in energy prices. Heating costs relative to income (%) by household net-income deciles.

Figure A1: Heating costs relative to net income by net-income decile (in %).

A.3 Behavioral Response to Heating Cost Increases

When households face increased heating costs, economic theory suggests that they would reduce their energy consumption. However, the extent of this reduction is uncertain and depends on various factors.

Baseline Elasticity Estimates In non-crisis times , the demand for heating energy is relatively inelastic, particularly in the short run. In the long run, demand becomes more responsive, with elasticity estimates ranging from -0.15 (Bissiri et al., 2019) to -0.9, depending on household characteristics (Schulte & Heindl, 2017). For instance, Schmitz and Madlener (2020) find long-run elasticities between -0.31 and -0.43.

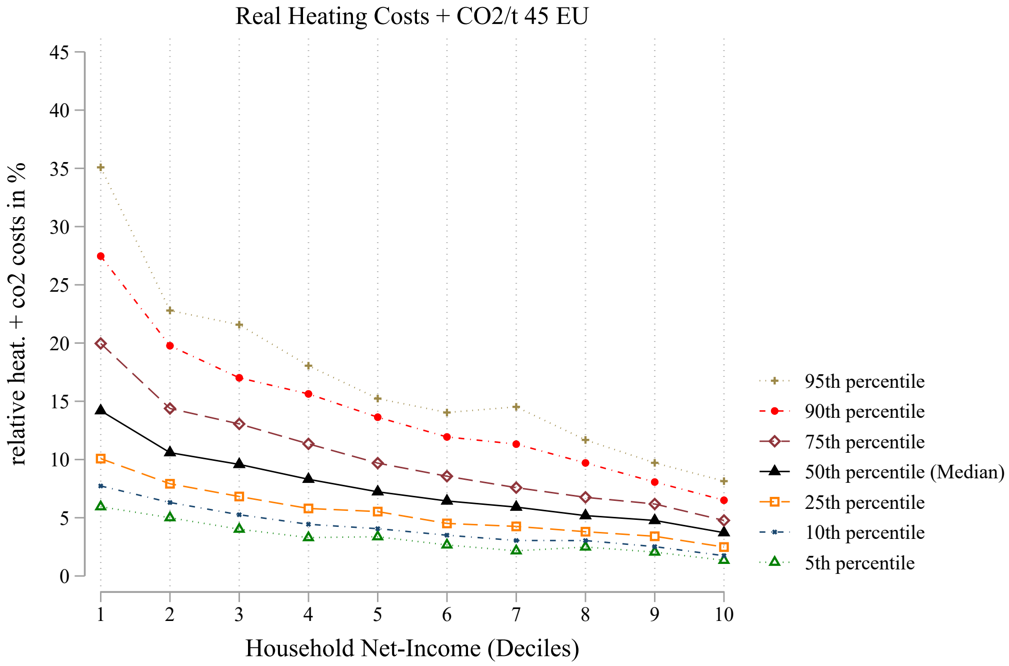
Adjustments in Crisis Periods During economic crises or periods of extreme price volatility, the response to increases in heating costs can deviate from the standard elasticity estimates. Binding savings constraints: In contrast, some households, particularly those in the lower income brackets, may have limited financial flexibility and may not be able to reduce consumption beyond a certain threshold without compromising basic heating needs (Roberdel et al., 2023). Given our research context, these crisis-induced behavioral adjustments are particularly relevant. For sharp increases in energy prices, the standard estimates are potentially too large. **behr_understanding_nodate<empty citation>** find an elasticity of -0.07 in the recent energy crisis as response to large energy price increases.

Heterogeneity Across the Income Distribution The price elasticity may also vary across income groups. According to Schulte and Heindl (2017), lower-income households tend to be less responsive to price changes due to their constrained ability to adjust consumption. This has direct implications for policy interventions aimed at mitigating energy poverty.

To test the robustness of our findings, we implement a sensitivity analysis where the assumed elasticity follows a linear pattern, with a lower-bound elasticity of -0.2 for lower-income households and a gradual increase up to -0.3 for higher-income households. This approach accounts for two key aspects: First, it introduces a dampened increase in heating expenditures, as households partially offset cost increases by reducing consumption. Second, it allows heterogeneity in response across income deciles, reflecting differences in behavioral flexibility. When translated into the cost increase scenario, where the heating cost doubles in the main analysis, this adjustment results in a revised cost increase of 1.86 under an elasticity of -0.1, and 1.74 under an elasticity of -0.2.

Figure A2a replicates Figure 1afrom the main analysis, displaying the relative heating cost burden for the whole population in the real scenario. The figure shows a persistent variation in lower income deciles, although extreme values within the first decile decrease. For example, the values in the 90th and 95th percentiles drop from 34% and 43% to approximately 26% and 33%, respectively. Reduced increase in relative heating costs for upper deciles, reflecting our assumption of a stronger consumption response among higher-income households.

Focusing on tenants only, Figure A3 reproduces Figure 5 from the main analysis. We still observe a strong reduction in relative costs from both retrofit strategies, particularly at the lower end of the income distribution.



(a) Status quo scenario in 2024 excluding unemployment benefits recipients: Real energy price increase. Heating costs relative to income (%) by household net-income deciles.

Figure A2: Heating costs relative to net income by net-income decile (in %) assuming price elasticities between -0.1 and -0.2.

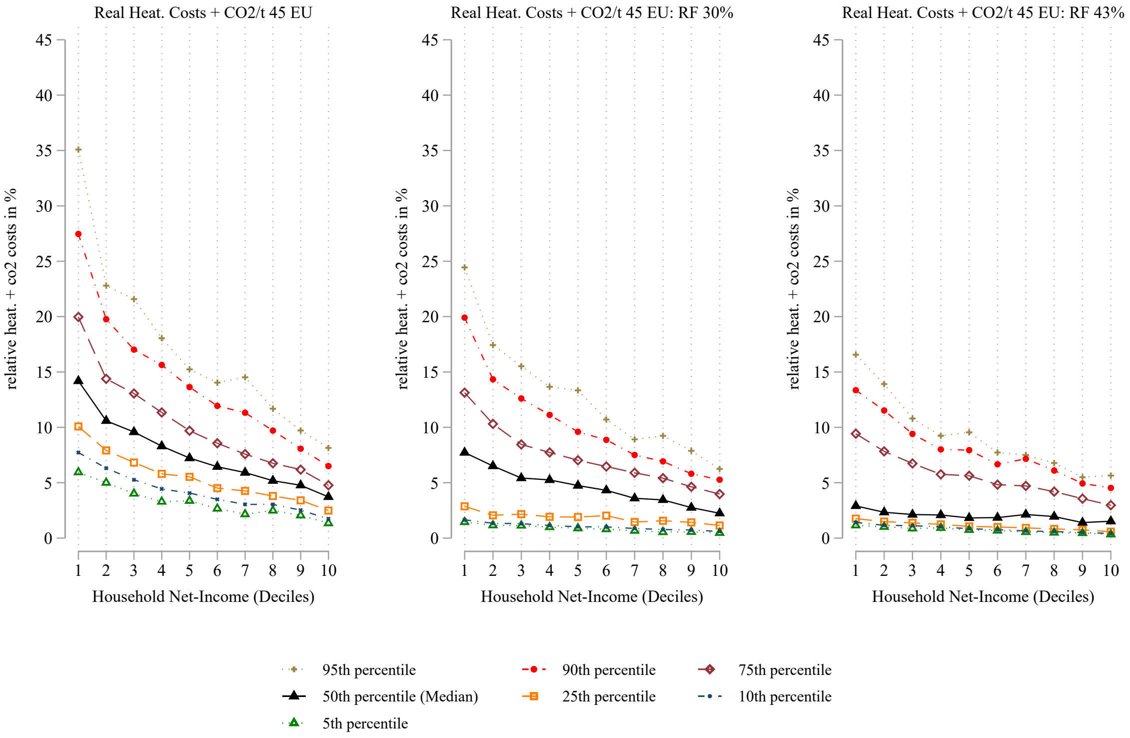


Figure A3: Relative heating and CO_2 costs for tenants in the status quo vs. retrofit scenarios (in %) assuming price elasticities between -0.1 and -0.2. Left panel: status quo as in Figure 1b. Middle panel: 30% Retrofit Scenario. Right panel: 43% Retrofit Scenario.

Lastly, Table A3 reproduces Figure 6 from the main analysis, presenting adjusted poverty indicators under different scenarios. In all cases, the poverty rates appear slightly lower compared to the main analysis. This outcome aligns with expectations, as the assumed behavioral response prevents some households from crossing poverty thresholds due to lower effective heating expenditures.

Overall, our findings confirm that incorporating behavioral responses does not fundamentally alter our main conclusions. The potential for reducing energy poverty through a Worst-First retrofit strategy remains robust to these adjustments.

	No Retrofit	Retrofit 30%	Retrofit 43%
Moderate heating costs and a CO_2 price of 45 EUR/t			
Ind: I	9.1	3.7	1.2
	(0.29)	(0.20)	(0.11)
Ind: II	12.4	3.8	0.4
	(0.33)	(0.22)	(0.06)
Ind: III	7.7	2.9	0.9
	(0.26)	(0.15)	(0.08)
Real heating costs and a CO_2 price of 45 EUR/t			
Ind: I	10.1	4.0	1.3
	(0.31)	(0.20)	(0.10)
Ind: II	12.1	3.8	0.3
	(0.36)	(0.22)	(0.06)
Ind: III	8.5	3.1	0.9
	(0.29)	(0.19)	(0.09)
Moderate heating costs and a CO_2 price of 200 EUR/t			
Ind: I	12.6	5.7	2.4
	(0.34)	(0.23)	(0.15)
Ind: II	18.1	6.6	2.0
	(0.40)	(0.29)	(0.17)
Ind: III	10.6	4.7	1.9
	(0.30)	(0.22)	(0.13)

Table A3: Energy poverty scenarios and retrofit assuming price elasticities between -0.1 and -0.2.