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The distribution of financial burdens from heat pump investments: An empirical analysis for owner-occupiers in Germany

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Abstract

Albeit heat pumps are viewed as a key technology to decarbonize buildings, their upfront costs exceed investment costs for fossil boilers. These excess investment costs for heat pumps over fossil boilers are heterogeneously distributed across and within income groups, depending on building characteristics and local climate conditions. This paper investigates vertical and horizontal inequalities associated with investments in heat pumps as opposed to fossil heating systems, assessing them in absolute and income-relative terms. Using German survey data on building type, age, insulation condition, living area, and local climate, we estimate household-specific excess investment costs and analyze their relationship with income. In absolute terms, investment costs are equally distributed across income groups. However, when measured relative to income, distributional effects are regressive. Regarding the drivers of these effects, we show that lower-income households tend to live in smaller, older, and less well-insulated buildings than higher-income households. In contrast, for higher-income households, excess costs are largely driven by their comparatively larger living areas. Consequently, households across income groups face, on average, similar excess costs, albeit for different reasons. We also observe substantial horizontal inequalities in both absolute terms and relative to household income, reflecting considerable cost variations within income groups, depending on the combination of building type, building age, insulation condition and living area. Again, the drivers of these horizontal inequalities vary across income groups. We find that mitigating both vertical and horizontal inequalities requires targeted subsidies that take into account not only income differences but also substantial heterogeneity in building characteristics.

Keywords: Heat pump investment, Decarbonization, Cost distribution

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1. Introduction

According to the European Climate Law, the European Union aims to achieve net zero emissions in 2050 (regulation (EU) 2021/1119). Thus, all emitting sectors must significantly reduce their greenhouse gas emissions over the next years. In 2023, space heating accounted for about 16% of final energy consumption in the EU (eurostat, 2025). In order to reduce heating-related emissions, fossil-based technologies need to be replaced. Large-scale heat pump adoption has been suggested as a sustainable option for decarbonizing the European building sector (Weidner and Guillén-Gosálbez, 2023).

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While heat pumps have lower operating costs than fossil boilers, they entail higher upfront investment costs (Gaur et al., 2021, Li et al., 2025). At the same time, excess investment costs are likely to vary substantially across households, as heating system costs largely depend on building characteristics (Glaesmann, 2022). This in turn might translate into vertical and horizontal inequalities. Vertical inequalities would arise if lower-income households would systematically face higher excess costs while horizontal inequalities would occur if households with the same income face varying excess investment costs.

Those distributional effects are likely to influence heat pump adoption (Peñaloza et al., 2022). For instance, pertaining vertical distributional effects, lower-income households might have lacking financial capacities (Albrecht and Hamels, 2021, Vivier and Giraudet, 2024).

Moreover, distributional effects related to investing in heat pumps being incentivized by carbon pricing and regulation could have adverse effects on acceptance for climate policies and could increase polarization around climate-related topics. This, in turn makes more ambitious climate policies hard to implement (Schaffer, 2024). Lastly, distributional effects for heat pump investment have implications for the design of subsidy programs (Li et al., 2025).

Understanding distributional effects of heat pump excess investment costs thoroughly is therefore important to implement effective climate policy. Against this background, we address the following research questions:

- What are the vertical and horizontal distributional effects of replacing fossil boilers with heat pumps, in terms of absolute excess investment costs and excess costs relative to household income?
- Which building-specific factors drive the vertical and horizontal distributional effects of excess investment costs?

We focus on Germany as a case study due to data availability and its status as a population-rich European country. Also, we concentrate on owner-occupiers as they are directly exposed to the upfront investment costs of heating system replacements, whereas tenants are affected only indirectly through regulated cost-sharing mechanisms.

Previous research predominantly assesses the distributional effects of heating system transitions by analyzing total costs, defined as the sum of investment and operating costs, across alternative policy scenarios (Czock et al., 2025, Diefenbach and Cischinsky, 2024, Kuhn and Schlattmann, 2024, Vivier and Giraudet, 2024). However, aggregating investment and operating costs may mask the distinct role of upfront investment costs, which are particularly relevant as they can serve as major barrier to heat pump adoption and represent an important dimension for drawing policy implications.

Exceptions are Escribe and Vivier (2025) and Schumacher et al. (2024). Both studies use granular household decision models in which households can invest in new heating technologies and building shell insulation. While household decisions are based on total costs related to the technology switch, the authors analyze how the distributional effects can be attributed to investment and future energy costs.

Schumacher et al. (2024) investigate a baseline and policy scenario where the former includes German climate policies implemented until August 2022, and the latter measures that are planned but not yet enacted. Their distributional analysis compares annualized heating system investment, insulation investment and energy costs for owner-occupiers and tenants living in buildings with diverging building ages. Also, they show how those investment and energy costs are distributed within income deciles of German households.

Their analysis is based on a bottom-up energy system model that uses reference buildings, which they connect to micro-level German data from 2018. In contrast, we use empirical survey data which allows us to deliver a more precise representation of the German building sector.

Escribe and Vivier (2025) analyze the environmental and distributional effects of a gas boiler ban which is implemented in addition to the already existing policy mix in France. The authors compare the annual additional energy, heating system, and insulation costs of the ban for household quintiles. However, their investment cost assessment is not as granular as our approach. In fact, the authors do not estimate heating system costs as a function of building characteristics, but assume fixed costs for each respective renewable technology, with heat pump costs decreasing over time due to technical progress.

Our paper complements Escribe and Vivier (2025) and Schumacher et al. (2024) in three ways. Firstly, we provide a more detailed and empirically grounded understanding of the drivers for the distributional effects of heat pump investments by analyzing how building characteristics interact with heat pump excess investment costs. Secondly, we do not only look at vertical distributional effects, but also at horizontal effects. Lastly, both papers are limited to comparisons of specific policy scenarios and therefore only capture marginal differences between alternative policy designs. Our analysis instead focuses on the transition towards climate neutrality in the German building sector, explicitly assessing the associated cost burden relative to a no-policy baseline and its distribution across households.

2. Methods and Data

This section describes how we calculate the excess costs for households investing in heat pumps compared to fossil boiler technologies. We are interested in the excess investment costs as they can be interpreted as costs that households bear due to climate policies and the aim to reduce CO_2 emissions in the building sector.

In particular, we combine external investment cost functions for heating technologies from Deutsche Energie-Agentur GmbH (2025) with building data from the heating and housing panel (Frondel et al., 2023) to calculate hypothetical excess investment costs for 3,217 German households.

2.1. Excess cost functions

By combining different data sources, Deutsche Energie-Agentur GmbH (2025) suggest respective investment cost functions for heating technologies depending on their capacity size in kW as the latter is the main cost driver for heating systems (Glaesmann, 2022). Besides the equipment costs itself, the data also covers installation, costs for buffer tanks and low-cost measures related to insulation. From their catalog, we take cost functions covering heat pumps, oil and gas boilers. As air-sourced heat pumps are the most common heat pump type (Li et al., 2025), we disregard geo-thermal heat pumps. Among air-sourced systems, air-to-water heat pumps account for the majority of sales, while air-to-air heat pumps are only applicable to buildings with rather small heat loads (Glaesmann, 2022). Therefore, we focus only on air-to-water heat pumps.

Figure 1 displays the cost functions for each respective technology. Oil and gas boilers display steep marginal cost declines, leading to markedly concave cost functions. While these cost functions are similarly shaped, gas boilers are slightly cheaper for large capacity sizes. In contrast, the cost function for heat pumps does not exhibit strong marginal cost digressions, resulting in a steeper total cost curve compared to the fossil-based technologies. This reflects the large investment cost differences between heat pumps and fossil technologies.

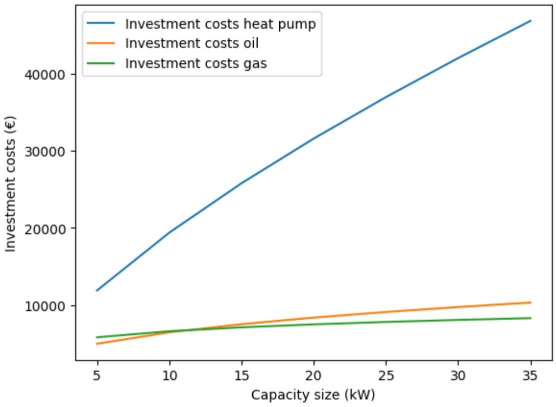

Figure 1: Investment cost functions

As we are interested in excess investment costs for heat pumps, we subtract the gas and oil boiler cost function from the heat pump cost function, respectively. The resulting excess cost functions depicted in Figure 2 are positively sloped. This again demonstrates the small marginal cost reductions for heat pumps in comparison to fossil boilers. Even for small capacity sizes of 5 kW corresponding to a well-insulated small single-family house, the excess costs are 5,000€. For an older, non-insulated building with a living area of 100 m^2, the heat load is approximately 12 kW (Glaesmann, 2022), resulting in excess costs of about 15,000€.

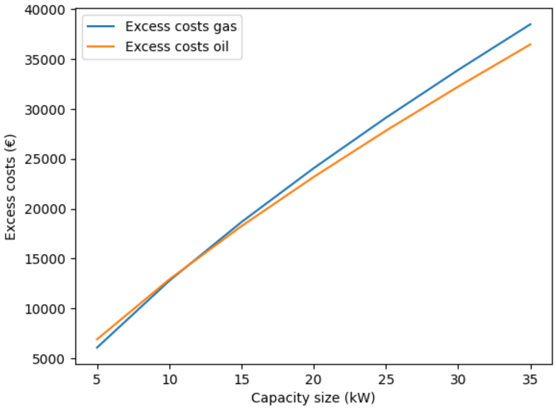

Figure 2: Excess investment costs

2.2. Heating and housing panel

The capacity size ultimately influencing the excess investment costs depend on building characteristics (Glaesmann, 2022). Thus, in this section, we present the building data we used from the 2021 German heating and housing panel wave (Frondel et al., 2023). This dataset is unique as it combines data on building characteristics with socio-economic data. Also, this panel exhibits oversampling of owner-occupiers

Table 1: Descriptive statistics

variable	relative frequency
construction year until 1958	0.3
construction year between 1959-1968	0.22
construction year between 1969-1977	0.15
construction year between 1978-1983	0.14
construction year between 1984-1994	0.11
construction year between 1995-2021	0.09
detached	0.61
one side adjacent	0.28
two side adjacent	0.11
insulated wall	0.56
insulated roof	0.7
insulated window	1
gas heating	0.75

and is therefore suited for answering our research questions. With regard to socio-economic variables, the data is representative on household level. What is particularly important for our analysis, the distribution of heating technology types is in line with German microcensus data from 2018 (Frondel et al., 2022).

Since we aim to simulate excess investment costs for owner-occupiers who still possess fossil heating technologies, particularly oil or gas boilers, we tailored the data to our requirements. For instance, we only look at single-family houses as insulation decisions in multiple-family houses have to be made by homeowner associations, where coordination frictions may play an important role, which are beyond the scope of this study. (Vivier and Giraudet, 2024).

After data cleaning, 3,217 households remain. Half of the examined buildings are constructed before 1968 as Table 1 shows. Most houses are detached single-family houses. More than half of all captured buildings have insulated walls, whereas the insulation share for roofs is even 70%. Having insulated windows seems to be standard practice. Three quarter of all buildings are heated with gas, while one quarter uses oil boilers. Figure 3 depicts the distribution of the buildings' heated living areas in m^2. Most houses have heated living areas around 100 m^2, while only a minority of households lives on areas above 200 m^2.

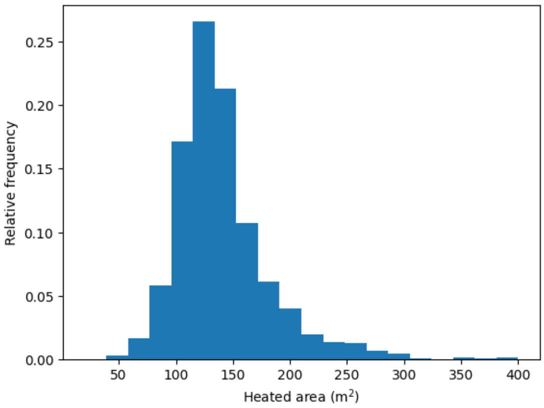

Figure 3: Living area distribution

2.3. Heat load calculation

To determine suitable heat pump capacities, a building's heat load is used. The latter indicates how much heating power must be delivered to meet certain room temperatures (Glaesmann, 2022).

In practice, there is a detailed procedure to determine a building's heat load via DIN EN 12831 (Glaesmann, 2022). To calculate the buildings' heat loads in the underlying sample, we use an approximate calculation. This is done with a heat load calculator from the German Heat Pump Association (Bundesverband Wärmepumpe)[1]. In particular, the heat load calculator combines building types, building ages, location-specific temperature conditions, and the insulation condition of windows, roofs, and walls in order to project buildings' specific heat loads given in W per m^2. For each combination of building type and construction year, the calculator assigns one particular value reported in Table A.1. Those values are adjusted by factors for temperature and insulation conditions. The correction factor for the standard outside temperature ranges between 0.84 to 1.04, while heat loads are again reduced by 15% for insulated roofs and at least double-glazed windows, respectively, and by 25% for insulated walls, as equation 1 shows. While the heating and housing panel includes data on building types, building ages and insulation conditions, we matched standard outdoor temperatures on the ZIP-code level based on DIN EN 12831-1. By multiplying each building's specific heat loads by their heated living areas, we calculate their final heat loads.

$$\begin{aligned}\text{heat load } (kW) = &(\text{specific heat load} \left(\frac{W}{m^2}\right) * \text{location } (\%) * \text{insulation } (\%) \\ &* \text{heated area } (m^2))/1,000\end{aligned} \tag{1}$$

Figure 4 shows that the heat load distribution is right-skewed, with most heat loads being smaller than 5 kW. Very little buildings are projected to have heat loads larger than 20 kW.

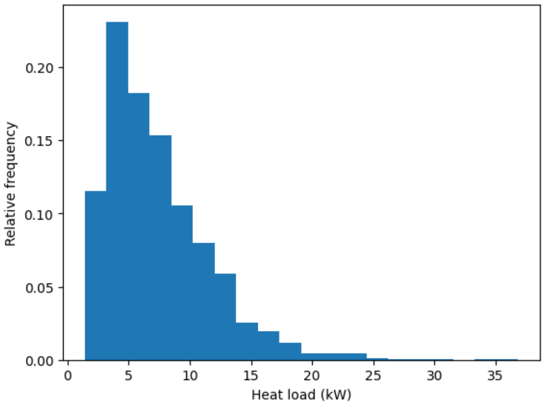

Figure 4: Heat load distribution

2.4. Final cost calculation

Finally, we can put together the heat load calculation and excess cost functions by setting the calculated heat load equal to the hypothetical capacity size of the household's heating technologies. Glaesmann

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[1] version December 2024

(2022) argues that heat load calculations usually already include some buffer, such that this simplification is reasonable.

Based on all previous steps, we can calculate the excess investment costs. In the absence of climate policy, we assume that households would re-invest in their current boiler technology. Notably, households that previously used gas boilers would invest in new gas boilers. While gas boilers are more cost-efficient than oil boilers (Czock et al., 2025), households often are reluctant to invest in new technologies (Achtnicht and Madlener, 2014) and access to gas infrastructure is not universally available. That justifies our assumption that oil-using households would re-invest in their current technology. Beyond that, excess investment cost functions for the two fossil technologies are very similar, implying that this assumption is unlikely to affect our results.

As the excess costs are a function of heat load, Figure 5 is similarly shaped as Figure 4. Most excess costs range between 5,000 and 10,000€, whereas only a few projections are above 20,000€.

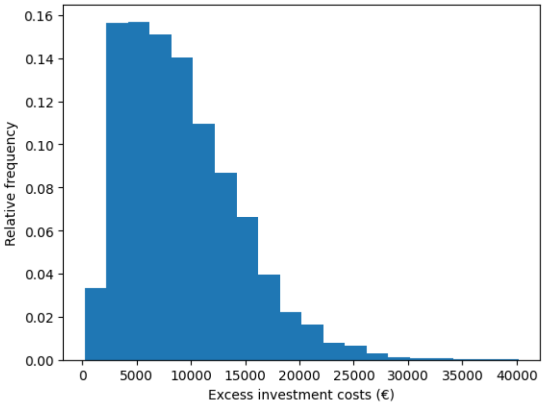

Figure 5: Excess cost distribution

2.5. Distributional analysis

Finally, we can analyze whether the calculated excess investment costs systematically vary with income. As the heating and housing panel data (Frondel et al., 2023) also includes income data, we can compare households' estimated excess investment costs with their reported incomes and evaluate systematic patterns.

This is done on two dimensions. On the one hand, we investigate vertical distributional effects associated with inequalities between income groups and horizontal distributional effects corresponding to inequalities within income groups. The second dimension relates to absolute and income-relative excess investment costs, resulting in the following combinations: (1) absolute vertical, (2) absolute horizontal, (3) relative vertical, and (4) relative horizontal distributional effects. Lastly, we also investigate the drivers for the respective excess cost distributions by inspecting how building characteristics, income, and heat load are related.

As the income data is given in intervals in the heating and housing panel, we use the upper and lower bounds' mean of the given income intervals. Also, the lowest income category with a value of 1,224 was constructed from three intervals due to a lack of observations in those intervals, respectively. Ultimately, the households are approximately uniformly distributed across income groups as Table A.2 shows.

To investigate the degree to which a building's insulation drives the distributional effects of heat pump investment, we first used agglomerative clustering to construct four insulation categories to avoid depicting all combinations of window, wall, and roof insulation. Hereby, buildings within the same cluster entail similar heat loads. Cluster 1 mainly reflects buildings with insulated windows, walls, and roofs, and therefore includes buildings with the lowest average heat load. Cluster 2 mostly includes buildings with insulated windows and walls, while cluster 3 is represented by buildings with lacking wall insulation, but with roof and window insulation. Cluster 4 predominantly comprises buildings with window-only insulation and therefore includes buildings with the highest heat loads.

3. Results

3.1. Vertical distributional effects

Figure 6 shows how the absolute costs are distributed across income groups. There is no clear pattern as to which household groups incur the highest median excess costs. Rather, excess costs are evenly distributed across income groups in absolute terms with median costs of around 8,000€.

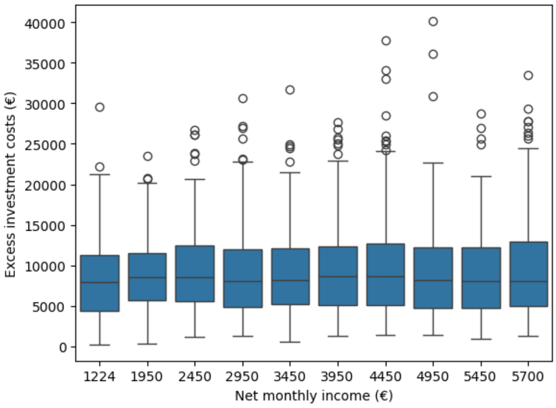

Figure 6: Absolute distributional effects

Figure 7 sets households' net incomes in relation to the required excess investment by dividing the latter by the former. Therefore, the y-axis represents the number of monthly incomes households must spend to cover the excess investment costs between heat pumps and fossil boilers. The median household from the lowest income interval must spend 6.5 times of its monthly income. Whereas the second and third lowest income groups, in medians, still require about 3.5 and 4.5 monthly household incomes to finance the excess costs, the median household from the highest income interval only needs to invest 1.5 monthly incomes. The absence of vertical inequalities in absolute terms translates into relative vertical inequalities due to income differences as lower-income households must spend a larger share of their incomes. Therefore, the excess investment cost distribution in relative terms is regressive.

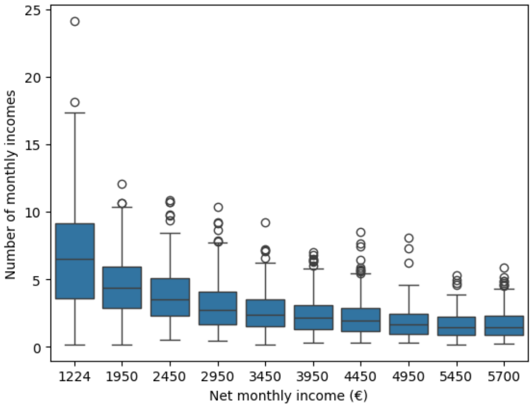

Figure 7: Relative distributional effects

In the following, we identify the drivers for the absolute cost distribution by investigating how income and heat loads are related to building characteristics.

The left panel of Figure 8 shows that detached buildings have, on average, higher heat loads. At the same time, there is no clear correlation between the distribution of building type and income as the right panel of Figure 8 shows.

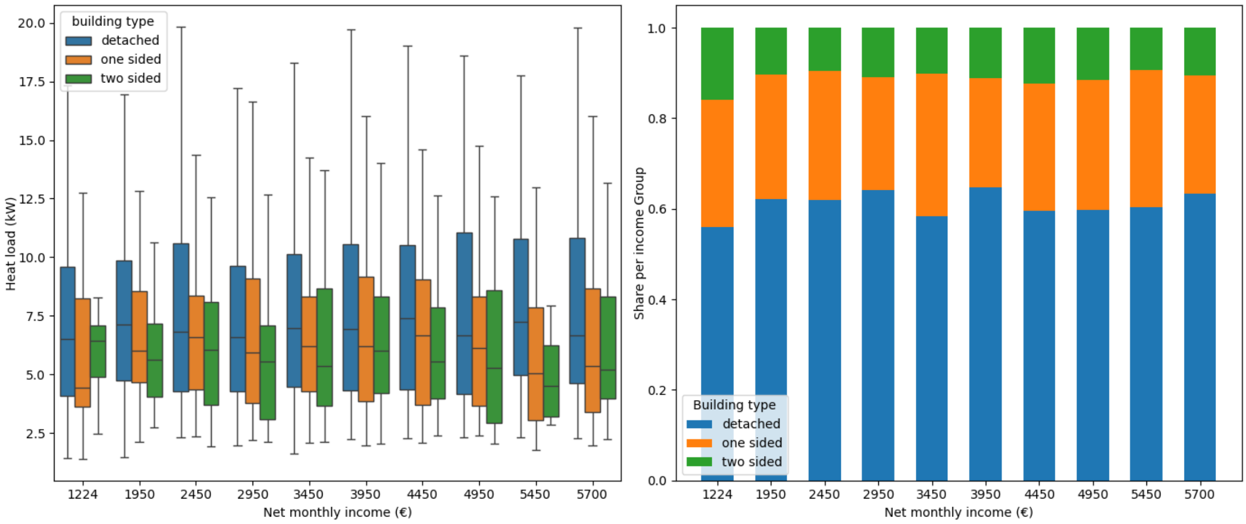

Figure 8: Building type

In combination with building types, construction years deliver the basis for heat load calculation. Therefore, the left panel of Figure 9 examines the extent to which construction time influences heat load. Buildings built before 1978 especially have higher heat loads compared to buildings constructed after 1977. This can be attributed to the introduction of the first Heat Insulation Ordinance enacted in 1977 (El-Shagi et al., 2017). While the oldest three construction year intervals have similar median heat loads respectively, median heat loads decrease with every construction interval for the three remaining construction year intervals. The right panel of Figure 9 shows how building ages are connected to income. What stands out is that the share of buildings older than 1977 decreases the larger the household income gets. Almost 60% of households from the lowest income group live in buildings from those categories, whereas for the highest income group, it is only 40%. In contrast, the share of households living in buildings classified in the newest category differs by more than 15 percentage points between the lowest and highest income class.

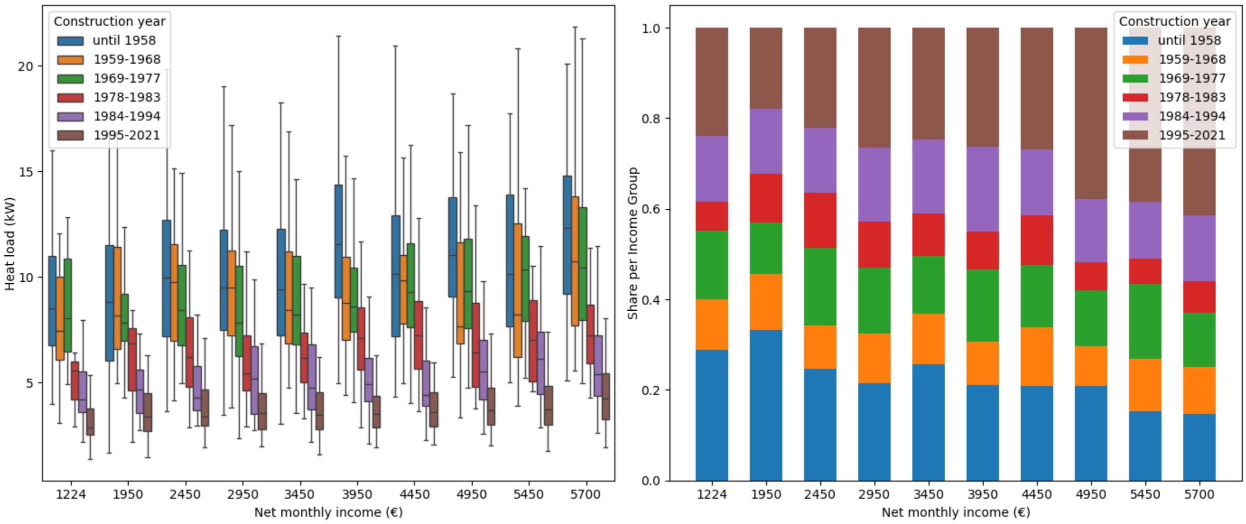

Figure 9: Construction year

As window, wall, and roof insulation is used for correcting the calculated specific heat load, Figure 10 shows how a building's insulation influences its heat load. As described in more detail in section 2.5, we constructed insulation clusters for this analysis where cluster 1 corresponds to the most and cluster 4 to the least insulated buildings. The left panel of Figure 10 displays that median heat load differences between neighboring insulation clusters are approximately 2 kW across all income groups. The right panel of Figure 10 suggests that the share of people living in badly insulated buildings decreases throughout income classes. Especially the two highest-income classes differ from the remaining income groups as almost 50% of them live in cluster 1 renovated buildings. For all remaining groups, only shares between 33 and 45 % live in such buildings.

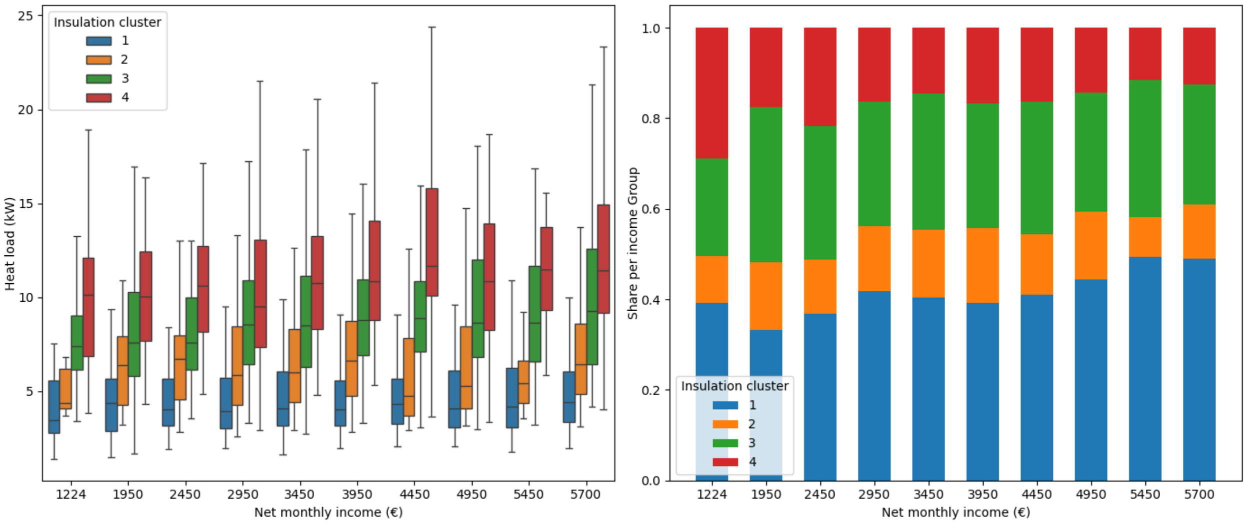

Figure 10: Insulation

Lastly, the heated area is a major factor in determining heat loads as it scales the specific heat load given in W per m^2. The left panel of Figure 11 shows that heat load increases with heated areas. Only buildings with large heated areas will exceed certain heat loads. The right panel of Figure 11 shows that median heated areas per income group increase with income.

Even though all income groups face the same median excess costs and therefore have the same median heat loads, we find divergent heat load drivers between income groups. In fact, higher-income households are inclined to live in newer and better insulated buildings, on average, reducing their buildings' heat load. At the same time, they also live on larger heated areas, counteracting the first effect. In contrast, lower-income households tend to live in older and not well-insulated buildings. As those households live on smaller living areas, their higher heat loads per m^2 are offset in total terms.

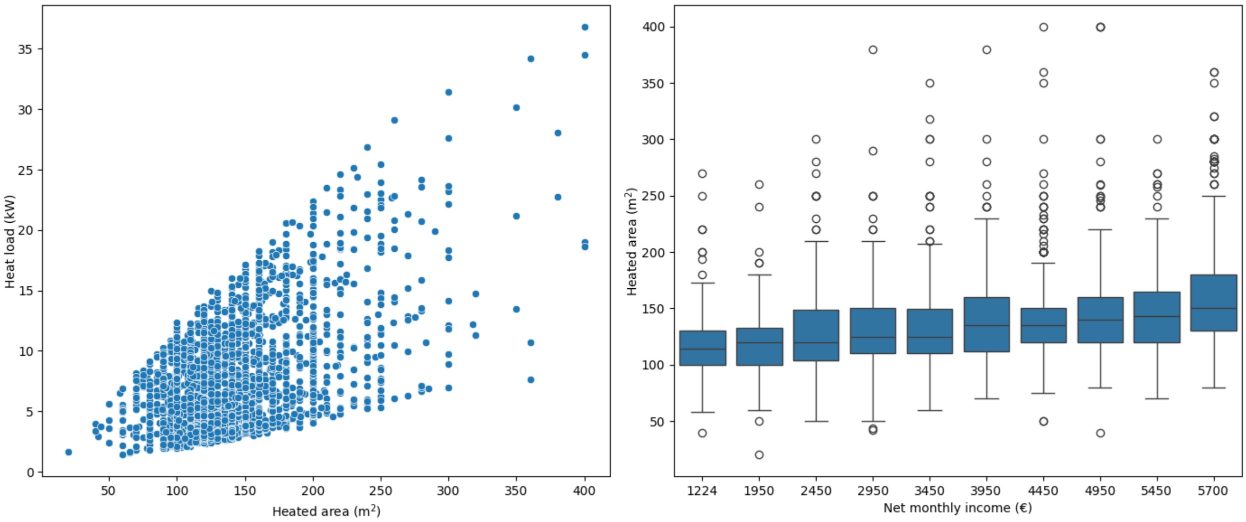

Figure 11: Heated area

3.2. Horizontal distributional effects

With regard to horizontal distributional effects, Figure 6 depicts how the absolute costs are distributed within income groups. Whereas the median excess costs are 8,000€ across all income groups, some households face excess investment costs up to 40,000€. In fact, in every income group, some households can be classified as outliers, as they incur costs exceeding 20,000€. Looking at the data between the 25th and 75th percentile, the costs range between 4,000€ and 13,000€. This pattern reveals horizontal inequalities across all income groups since the calculated absolute excess costs differ to a large extent within income groups.

The outliers outlined in Figure 6 translate into outliers in relative terms, depicted in Figure 7. For instance, two households from the lowest income group need to invest 18 or 24 monthly incomes for purchasing a heat pump instead of a fossil boiler, whereas the median household from that income group only has to pay 6.5 monthly incomes. At the same time, no outlier household from the five highest income groups would have to pay more than ten monthly incomes. Also, with regard to the data ranging between the 25th and 75th percentile, the interquartile range of the lowest income group is strikingly larger than that of the remaining income intervals. Therefore, the horizontal inequality effects in relative terms are more pronounced for lower-income households predominantly driven by income differences, reflecting the fact, that it is more challenging for low-income households to absorb higher excess investment costs.

In the following, we discuss how the building characteristics influence the horizontal inequalities and how the drivers differ across income groups. Figure 8 shows that especially detached buildings exhibit substantial heat load variations. Figure 9 and Figure 10 demonstrate that the heat load dispersion is the largest for buildings built before 1978 and less-insulated buildings. Lastly, Figure 11 points out, that heat load dispersion increases with increasing heated areas. What this analysis shows is that the factors of living in detached, old, not well-insulated and large building area seems to serve as scaling factor leading to high heat loads across all income groups. Those above-average heat loads, in turn, generate above-average excess costs and thereby generate the observed within-group excess cost variation.

As lower-income households are more likely to live in older, poorly insulated buildings, while higher-income households tend to occupy larger dwellings and include a subset of outliers with exceptionally large living areas, the factors driving horizontal inequalities differ across income groups. However, the composition of building characteristics is very individual within income groups. Overall, this shows once again how heterogeneous the German building sector is (Moritz et al., 2025).

4. Discussion

4.1. Findings

Placing our results in the context of the existing literature, the level of the additional costs associated with fuel switching is higher in our study compared to Escribe and Vivier (2025) and Schumacher et al. (2024). This can be attributed to the fact that these papers compare specific policy scenarios, both of which already include building sector policies. Both papers use status quo building sector policies as a baseline and compare this against an additional gas boiler ban (Escribe and Vivier, 2025) or the requirement that 65% of the energy consumption in the heating system comes from renewable sources (Schumacher et al., 2024). Therefore, the cost difference between both policies is only up to 50€ in annualized terms for both comparable studies translating into about 1,000€ in total terms.

Concerning vertical distributional effects in a policy–baseline comparison primarily inducing heat pump investments, Schumacher et al. (2024) find progressive patterns across German household income deciles. This is driven by the ownership structure as higher-income deciles exhibit a higher share of owner-occupied dwellings which are directly affected by investment costs in contrast to renters. However, the authors highlight, that the main reason for the progressivity is that higher-income households live on larger areas. Although the authors apply differentiated investment cost rates per m^2 for heating technology renewal, where buildings constructed before 1949 exhibit about twice the costs of those built after 2000, this effect is outweighed by the influence of the total living area. Since Schumacher et al. (2024) do not explicitly account for a building's insulation condition, our results diverge showing regressive investment cost patterns. As shown in section 3.1, this is explained by the fact that lower-income households, on average, live in less well-insulated buildings, which increases their excess investment costs.

Escribe and Vivier (2025) also find increasing average annual investment costs by income quintile. The authors explain this pattern by differences in heating system choices. Instead of focusing on heat pumps as future technology, their model lets households choose between heat pumps, wood boilers, and direct electric heaters. Also, their simulation includes income-dependent subsidies explaining the progressive distributional investment cost pattern. Lastly, Escribe and Vivier (2025) do not calculate heating system costs based a building's heat load, but they take average costs for each heating system. Taken together, these assumptions create the progressive investment cost pattern.

The greater granularity of our approach, particularly the explicit consideration of building insulation conditions, explains the divergence in distributional results between our study and Schumacher et al. (2024) and Escribe and Vivier (2025).

Additionally, the differences in distributional effects between our study and Schumacher et al. (2024) and Escribe and Vivier (2025) can be explained by the fact that both studies are restricted to specific policy comparisons not capturing the full-scale transformation of the building sector towards climate neutrality. Consequently, distributional outcomes are driven by scenario-specific switching behavior. That is, some households may be induced to switch to renewable heating systems only under stringent policy packages, whereas others would already do so under less ambitious measures. Depending on which income groups switch to renewable heating systems only under stringent policies and therefore bear the associated additional costs, the resulting cost distribution will be regressively or progressively shaped.

Neither Escribe and Vivier (2025), nor Schumacher et al. (2024) systematically examine horizontal distributional effects for single-family owner-occupiers. Also, given that two specific policy scenarios are compared, cost differences within income groups may be small, as the additional policy measures not necessarily induces behavioral responses. Therefore, our paper provides a novel estimate of horizontal inequality associated with heat pump investments, also identifying the interplay of living area, insulation condition, and building age as key drivers of heterogeneously distributed excess investment costs within income groups.

4.2. Limitations

While this paper provides valuable insights, it is subject to certain limitations. First, the literature covers a wide range of different heating system cost functions reflecting the uncertainties associated to the excess costs and the extent of their distributional effects (Frings and Helgeson, 2023, Jagnow and Wolff, 2020, Moritz et al., 2025). As our analysis shows, the absolute excess investment costs between income groups is uniformly distributed. Thus, the distributional effects in vertical, absolute terms does not depend on the cost functions. Only the median costs for all income groups could become larger or smaller, and therefore, the distribution of relative costs between income groups could become more or less regressive. Also, depending on how steep the cost function is, the horizontal inequality effect could become smaller or larger as well. However, as the cost functions we use (Deutsche Energie-Agentur GmbH, 2025) falls within the range of existing cost functions in Frings and Helgeson (2023), Jagnow and Wolff (2020) and Moritz et al. (2025), we expect our results to remain largely unchanged.

Secondly, cost reductions are likely to materialize for heat pumps in the next decades. The International Renewable Energy Agency (2022) project heat pump investment costs to fall such that they are cost-efficent in comparison to fossil boilers within the next five to 10 years, and Kuhn and Schlattmann (2024) estimate heat pump prices to fall by 25% within the next 10 years. While assuming a learning rate would be in line with the literature, the underlying paper is based on a static approach to assessing investment costs. If the heat pump costs would fall, the excess cost gap would close and consequently relative vertical inequalities as well as horizontal inequalities in absolute and relative terms would decrease, up to the point where costs are fully equalized.

Regarding the technology choice, we only focus on air-to-water heat pumps even though hydrogen boilers or air-to-air heat pumps might become a cost-efficient alternative (Moritz et al., 2025). Also, for some owner-occupiers, it might be cost-efficient with regard to operational costs to combine their heat pumps with solar technologies, battery storage systems (Czock et al., 2025) or even back-up heating systems (Wüllhorst et al., 2022).Depending on a household's technology choice, investment costs differ substantially across technology packages, with additional technologies driving up excess investment costs. This in turn influences vertical and horizontal distributional effects, depending on which household groups are incentivized to combine their heat pumps with additional technologies to reduce operational costs.

Lastly, heat pump switches are likely to be accompanied by conducting additional insulation, such as wall or roof insulations to increase heat pump efficiency and, in turn, reduce operational costs (Junghans, 2015, Lingard, 2020). Although improving building shell insulation also decreases heat load and therefore lowers investment costs of heating systems, these savings are likely to be superseded by the costs of insulation measures. In fact, investments in energetic insulation tend to be two to six times larger than for the heating technology switch itself (Schumacher et al., 2024). As lower-income households, on average, live in less insulated buildings, they tend to be more affected by this cost burden. At the same time, fewer high-income households are affected as a larger share of this group already resides in well-insulated buildings. However, high-income households living in non-insulated buildings may face higher insulation costs, particularly as they tend to occupy larger dwellings. As these opposing mechanisms partially offset each other, the absolute vertical distributional effects are likely to remain ambiguous. In contrast, relative vertical inequality is expected to increase, as median investment costs rise overall. Horizontal inequality is also likely to increase once insulation costs are taken into account, as not all households will undertake insulation improvements.

To account for a learning rate, comprehensive insulation, alternative and additional technologies, applying a dynamic approach where households optimize over time such as in Frings and Helgeson (2023) and Vivier and Giraudet (2024) is needed. Thus, extending this study by including household optimization behaviors could offer important insight for future household excess investment costs in achieving climate neutrality in the German and European building sector.

5. Conclusion and policy recommendations

This study analyzes the vertical and horizontal distributional effects of excess investment costs for heat pumps compared to fossil boilers among German single-family owner-occupiers, both in absolute terms and relative to household income. It aims to assess the extent to which such investments incentivized or triggered by climate policy may generate social burdens and potentially contribute to opposition against climate policy. To counteract those effects, this paper lays the foundation for a societal debate about the design of climate policies, in particular subsidies in the building sector.

Regarding the vertical inequalities, all ten considered income groups face similar absolute excess costs. Thus, there are no vertical inequalities according to this approach. This result masks substantial differences in the underlying drivers across income groups. We show that lower-income households live in smaller, older, and less insulated buildings compared to higher-income households, which in turn drives their excess costs. In contrast, excess costs among higher-income households are primarily driven by their larger average living areas. As median excess costs do not differ between income groups, this effect translates into regressive vertical distributional effects in relative terms. That is, lower-income households must spend a larger share of their monthly incomes than higher-income households.

Absolute excess costs vary considerably within income groups as a subset of households within each income group face considerable above-average excess investment costs, revealing horizontal inequalities. This is particularly driven by the interplay of building type, building age, insulation condition and living area. In fact, every single factor serves as scaling factor for excess investment costs explaining how horizontal inequalities emerge. Within lower-income households, horizontal inequalities mainly stem from combining the scaling factors of living in old, not well-insulated buildings. In contrast, the scaling factor for higher-income households is rather the fact that these income groups live, on average, on larger areas and also include outlier households living on exceptionally large areas. Horizontal heterogeneity in relative terms is more pronounced among lower income households due to their lower income.

Translating these results into policy design options, the effectiveness of carbon pricing is compromised as households facing exceptionally high excess costs might not be financially able to switch their heating systems. Regulatory approaches imposing mandatory investments into renewable heating systems expose some households to substantial financial burdens as well. In particular, low-income and credit constrained households are affected. However, as excess costs are heterogeneously distributed within income groups, even middle-households might be disproportionally affected. Such dispersion increases the risk of extreme financial strain for specific households and may raise concerns regarding the social acceptability of regulatory policies.

These considerations suggest that carbon pricing and regulatory instruments need to be completed to ensure socially balanced and effective implementation. While income-based, staggered subsidies can address vertical inequalities, we suggest to also take into account building characteristics such as insulation and building age to determine subsidy design. This could also be implemented by expressing subsidies as a percentage of total investment costs.

Additionally, renovation subsidies might become necessary to enable efficient heat pump operation while decreasing a building's heat load resulting in reduced excess investment costs. Especially, lower-income households living on average in less insulated buildings would benefit from this measure.

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Appendix

	detached	one-side adjacent	Two-side adjacent
until 1958	140	130	120
1959 - 1968	130	120	115
1969 - 1973	120	115	110
1974 - 1977	115	105	100
1978 - 1983	95	90	85
1984 - 1994	75	70	65
from 1995	60	55	50

Table A.1: specific heatloads by building age and building type

Note: The second and third categories "1969-1973" and "1974-1977" are merged to match it with the Heating and housing panel data. For this combined building age category, the specific heat load means are taken to calculate the sample's heat loads.

income category	relative frequency
1,224	0.04
1,950	0.06
2,450	0.08
2,950	0.12
3,450	0.13
3,950	0.11
4,450	0.11
4,950	0.11
5,450	0.06
5,700	0.18

Table A.2: income intervals